# Solar electricity every hour of every day is here and it changes everything

Batteries are now cheap enough to unleash solar’s full potential, getting as close as 97% of the way to delivering constant electricity supply 24 hours across 365 days cost-effectively in the sunniest places.

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Lead author: Kostantsa Rangelova
Other authors: Dave Jones

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# About

This report unpacks the concept of 24-hour electricity supply with solar generation — how solar panels, paired with batteries, can deliver clean, reliable electricity around the clock. It compares cities across the world, showing how close they can get to solar electricity 24 hours across 365 days (24/365 solar generation), and at what price. Focused on project-level applications like industrial users and utility developers, the report shows how batteries are now cheap enough to unlock solar power's full potential.

# Key highlights

**17 kWh**

1 kW of stable solar power across 24 hours of the day can be achieved on an average day in a sunny place like Las Vegas with 5 kW of fixed solar panels and a 17 kWh battery.

**97%**

The sunniest regions in the world can get as close as 97% of the way to 24/365 solar - stable supply every hour of every day of the year.

**104 $/MWh**

Achieving 97% of the way to 24/365 solar in very sunny regions is now affordable at as low as $104/MWh, cheaper than coal and nuclear and 22% less than a year earlier.

# 24-hour solar generation is here — and it changes everything

**Solar electricity is now highly affordable and with recent cost and technical improvements in batteries — 24-hour generation is within reach. Smooth, round-the-clock output every hour of every day will unleash solar's true potential, enabling deeper penetration beyond the sunny hours and helping overcome grid bottlenecks.**

On June 21st — the Northern Hemisphere summer solstice — the "midnight sun" circles the sky continuously, providing 24 hours of daylight and theoretically, 24 hours of solar electricity generation. Thanks to advances in battery storage, this phenomenon is no longer limited to the Arctic.

Rapid advances in battery technology, especially in cost, have made near-continuous solar power, available every hour of every day of the year, an economic and technological reality in sunny regions.

Industries like data centres and factories need uninterrupted power to function. At the same time, the rising push for hourly-matched carbon-free energy goals — pursued largely through corporate Purchase Power Agreements (PPAs) — is increasing the demand for clean electricity every hour of the day. While solar is now extremely affordable and widely available, its real value will only be realised when it can deliver power consistently to meet the demands of a growing economy, even when the sun isn't shining.

24-hour solar generation enables this by combining solar panels with sufficient storage to deliver a stable, clean power supply, even in areas without grid access or where the grid is congested or unreliable. While this may not solve every challenge at the grid level, since not all places are as sunny and the electricity demand varies hourly and seasonally, it provides a pathway for solar to become the backbone of a clean power system in sunny regions and to play a much bigger role in less sunny regions.

This report explores how close we are to achieving constant, 24-hour solar electricity across 365 days in different cities around the world, and what it would cost to get there.

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01 **24-hour solar generation is possible - just 17 kWh of battery storage is enough to turn 5 kW of solar panels into a steady 1 kW of 24-hour clean power.** TATEMENT TO BE VERIFIED.

On an average day in a sunny city like Las Vegas, US, providing 1 kW of stable, round-the-clock power requires 5 kW of fixed solar panels paired with a 17 kWh battery. This combination can deliver a constant 1 kW of solar electricity every hour over a full 24-hour period – and this amount of battery will be sufficient for most regions across the world.

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02 **It is possible to get 97% of the way to constant solar electricity every hour of every day of the year (24/365) in the sunniest cities.**

Cloudy days mean that 24/365 solar generation - maintaining the same constant solar output every hour of every day of the year - would need so much solar and battery that it is likely uneconomical. However, in sunny cities it is possible to get more than 90% of the way. Las Vegas can reach 97% of the way to 1 GW constant supply and Muscat in Oman - 99%, using 6 GW solar panels and 17 GWh battery. Even cloudier cities like Birmingham can get 62% of the way to a constant supply every hour of every day across the year.

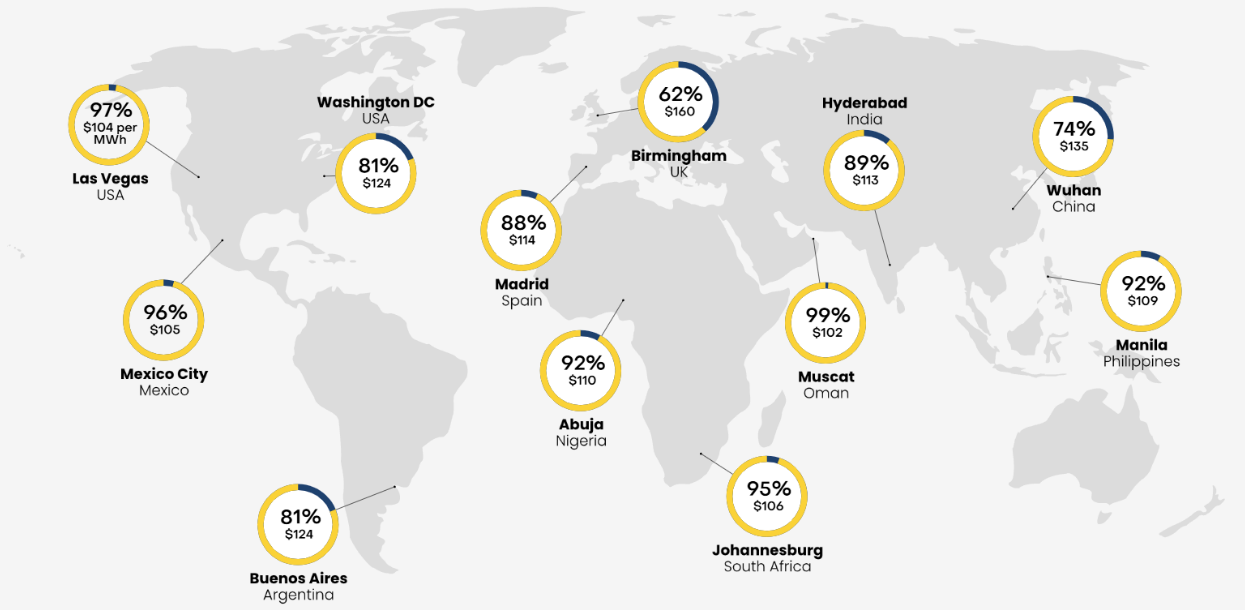
03 **The economics are great in sunny cities - just \$104/MWh to get 97% of the way to 24/365 solar, 22% lower cost than just a year earlier and cheaper than new coal or new nuclear.**

In a sunny city like Las Vegas, the estimated Levelised Cost of Electricity (LCOE) at this 97% benchmark is \$104/MWh. This is already 22% lower than the \$132/MWh estimate based on global average capital costs of solar and battery a year earlier. It is also more cost-effective than coal in many regions (\$118/MWh) and far cheaper than nuclear (\$182/MWh).

60万kW?

**Many sunny places can get at least 90% of the way to constant 24/365 solar generation from around $100/ MWh**

Share of 1GW constant electricity supplied, using 6 GW solar with 17 GWh battery (2005-2023 average), and Levelized cost of electricity, USD/MWh




Source: Ember analysis of JRC hourly solar radiation data
Key assumptions: CAPEX - $388/kW solar, $165/kWh battery; Other costs: $76/kW grid connection; $48/kW inverter; 10% total cost markup for soft costs; 7.7% discount rate over 20 years lifetime; losses: 3.8% PV to grid; 5.6% PV to grid via battery; 90% usable battery capacity

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The emergence of 24-hour solar generation marks a fundamental shift in how solar fits into the broader power system. With the ability to deliver electricity around-the-clock, solar can now support 24/7 clean energy contracts (PPAs) for industries which require continuous power, not just daytime supply. This is extremely valuable for emerging economies, where solar-powered industrial and economic zones can emerge in sunny areas far from existing grid infrastructure. At the same time, it can also bring substantial potential savings on grid expansion costs - allowing up to five times as much solar capacity to be installed behind the same grid connection, maximizing existing assets and deferring costly upgrades.

As costs continue to fall and deployment accelerates, solar-plus-storage is emerging as the default model for clean power in the sunniest parts of the world — both on and off the grid. To fully realise its potential, energy policy must now catch up, by integrating 24-hour solar generation into planning frameworks, electricity market design and infrastructure development strategies.

This is a turning point in the clean energy transition. Around-the-clock solar is no longer just a technical possibility and distant dream, but an economic reality. It unlocks game changing opportunities for energy-hungry industries like data-centres and manufacturing. Solar will be unleashed. The change is new - the costs and quality of grid batteries have improved so much in the last 12 months. Now it’s time for policy and investment to catch up.

**Kostantsa Rangelova**
Global electricity analyst, Ember

Chapter 1

# How batteries will unlock solar's true potential

**24-hour solar generation is not a dream — it is already within reach. With today's battery technologies, delivering clean, round-the-clock electricity is simple and affordable. No breakthroughs needed — just scaling what already works.**

Rapid advances in battery technology are making the delivery of round-the-clock solar electricity increasingly feasible. Modern lithium iron phosphate (LFP) batteries are a game changer and have taken over Nickel Manganese Cobalt (NMC) in the grid battery storage market, as they are cheaper, safer, and longer-lasting.

24-hour solar generation can unlock huge savings by helping overcome one of the biggest challenges to clean energy — building more grid. Batteries let solar be used when and where it is needed — without waiting years for costly grid expansions. That is a game changer for data centres, factories and remote infrastructure, where grid access is often delayed, restricted, or entirely unavailable. Battery-backed solar offers a fast, flexible way to overcome grid bottlenecks and get clean power online without being held back by the need to build more grid.

This is already happening. From the world's first gigawatt-scale 24-hour solar project in the UAE to solar-powered data centres in Arizona and Dubai, real-world deployments are proving that 24-hour solar generation is not just possible — it is here.

## 1.1 Why this is a game changer

### 1.1.1 Solar with battery can meet electricity demand any time

Batteries can reshape solar generation to meet electricity demand anytime across the 24 hours of the day. This will unlock benefits far beyond what is possible with solar alone.

When solar is built without batteries, it can only meet electricity demand during daytime hours, leaving the rest of the power system to fill the gap after sunset. As a result, the same fossil-based power plants and grid infrastructure are needed to be maintained to meet the nighttime demand. Shifting some electricity demand from night to day can help reduce this reliance, but the potential is limited.

Other storage technologies such as pumped-hydro or long-duration storage options like compressed air can help, but they are often not readily available, not cost-effective or not ready to scale yet. It is essential to note that solar without batteries still delivers benefits like lowering fossil generation during the day, driving down electricity costs and reducing carbon emissions, but pairing solar with batteries can unlock its full potential.

When solar is built with batteries, it becomes possible to align its generation with electricity demand. It is also worth noting that solar with batteries does not need to deliver the same power every single hour of every day to bring major benefits. Even in less sunny regions battery storage can bring more solar electricity across all hours - meaning fewer power plants and grid infrastructure are needed compared to building solar without batteries.

This shift can significantly ease the high evening prices seen in many countries today, reduce the need for new fossil power plants and defer costly grid upgrades. In California, for example, batteries in 2024 routinely met close to a fifth of daily peak load in the evening hours, displacing gas generation.

### 1.1.2 Pushing solar penetration higher

Solar is the cheapest source of electricity ever, but its generation is limited to sunny hours. This means, without storage, solar can only meet as much of a region's annual electricity demand, as can be realistically squeezed into daytime hours.

Batteries remove this constraint. With storage, solar is no longer limited by the sun — it can scale beyond daytime limits, even nearly 100% of electricity needs in the sunniest regions.

This provides a compelling pathway for solar to become the backbone of a country's electricity system in places with abundant sunlight.

The opportunity may be even greater for electricity users than for the electricity system itself. Bigger consumers like data centres, factories and remote infrastructure require stable, uninterrupted power. For them, 24-hour solar generation can provide a clean, cost-effective alternative to fossil-based grids — available not just as a future ambition, but as a practical solution today.

Depending on grid electricity costs, these users can access cheaper solar power through a range of setups — from partial to near-full coverage, using onsite solar with batteries, or through PPAs with solar-plus-storage systems, especially where land is limited. In the case of PPAs, matching the supply with the consumer's hourly demand level can also bring financial benefits by reducing their exposure to volatile spot market prices.

### 1.1.3 Bringing large savings on grid expansions

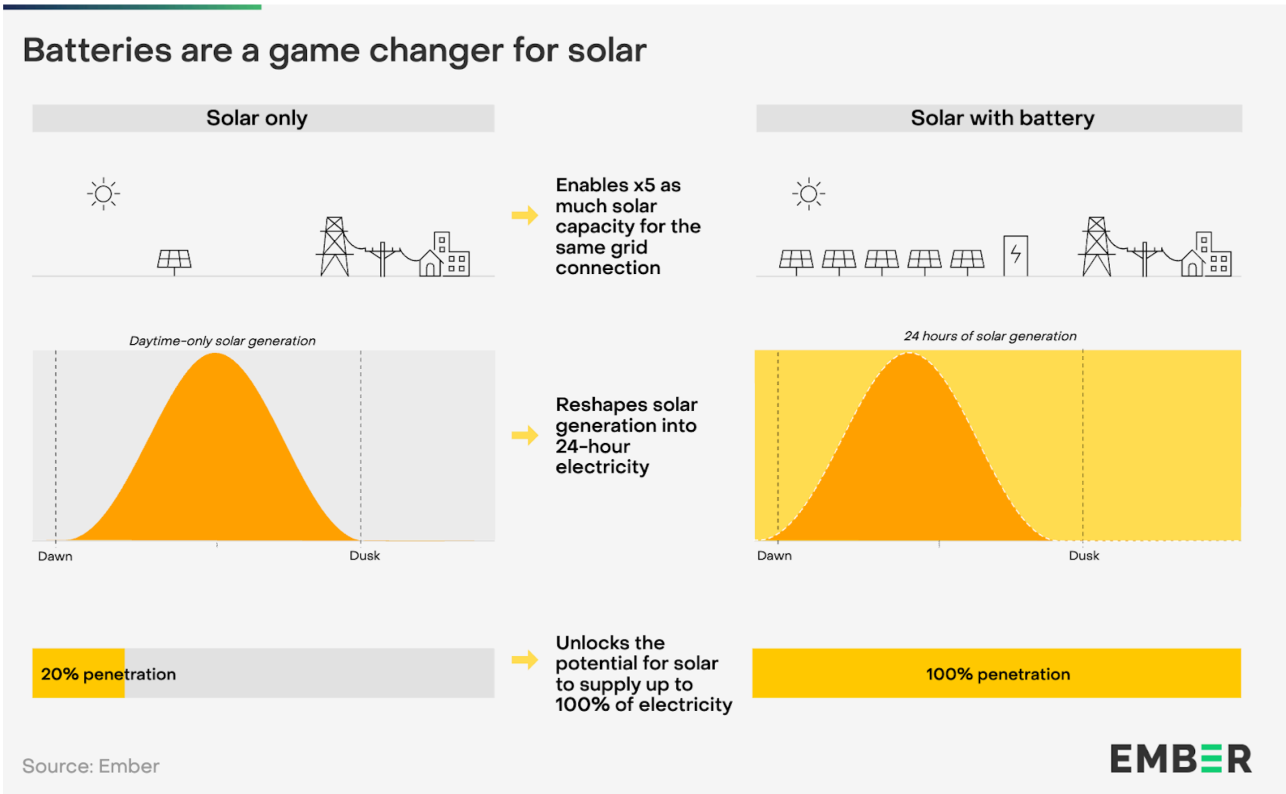
What makes the case for 24-hour solar generation even more compelling is its role in reducing the need for expensive grid expansions — one of the most difficult and expensive challenges in the clean energy transition.

Adding batteries can increase the impact of a single grid connection, meaning up to five times more solar panels can be installed using the same grid capacity as for just one. In sunny regions, a single solar panel has an annual capacity factor of 20%. However, if five times as many solar panels are installed and paired with batteries, solar electricity generated during the day can be stored and released after the sun sets, pushing that 20% towards 100% round-the-clock supply.

Grids are becoming a bottleneck for the deployment of clean power sources, with at least 3,000 GW of renewable projects worldwide stuck in grid connection queues - more than five times the total renewable capacity installed in 2024 (585 GW). Batteries can help reduce the need for grid investments.

Solar and battery systems are emerging as enablers of industrial development. For high-demand electricity consumers like factories and data centres, grid access may be non-existent, delayed for years, or too expensive to justify. Onsite gas power plants, once seen as a quick and affordable solution, no longer offer the same advantages, as lead times for new gas plants can exceed three years and the construction costs to build gas power plants in the US has tripled since 2022 – rising to $2,400/kW. Other markets are also seeing an upward trend, though less extreme, largely driven by material cost inflation.

Fuel price volatility is an additional risk, especially in gas-importing countries. That means solar and battery might often be the only option (or at least the only clean option) to support new industries.




## 1.2 Batteries have suddenly got cheaper and better

Battery technology is advancing at lightning speed, leading to rapid cost reductions.

In 2024 alone, average battery prices fell by 40%, hitting a record low of $165 per kWh for a full battery system (excluding Engineering, Procurement and Construction and grid connection costs). Early 2025 data suggests that the trend is continuing, with two auction results in Saudi Arabia showing prices as low as $72KWh. As production scales and efficiency improves, prices are expected to fall even further.

The rise of Lithium Iron Phosphate (LFP) technology marked a major shift for grid storage. In 2023, LFP made up 80% of all new grid battery installations, leading to lower costs and better performance. LFP batteries use less critical minerals (no nickel or cobalt) and safety improvements have reduced the fire risk by two magnitudes since 2019. These batteries are more long-lasting, with some key manufacturers now providing 20-year warranties. This significantly improves the economics of battery projects, where previously developers often sought a pay back within just ten years.

New developments will enhance battery performance even more. For example, the improved container design allows denser packing with more cells, reducing land requirements, alongside better insulation, which cuts maintenance costs, especially in hot and arid conditions. Easier system integration also lowers the installation costs. The next frontier is sodium ion batteries — the world's first grid-scale sodium ion storage plant has just been commissioned — potentially eliminating the need for lithium, which could drive prices down even further.

Deployment of grid batteries, however, is just getting started. There was 169 GWh of capacity installed in 2024. This was an incredible 17 times more than in 2020. However, this is very small compared to the 599 GW of solar installed in 2024.

There is ample manufacturing supply to maintain a high speed of deployment. There is already enough battery manufacturing capacity globally (1450 GWh, including EV batteries) to make over 2 kWh of lithium battery for every 1 kW solar panel added based on 2024 solar capacity additions (585 GW).

Ample supply of low-cost batteries is a game changer for solar.

## 1.3 Solar+battery is already happening

Less than five years ago, solar-plus-battery projects were mostly limited to a few demonstration sites. Today, they are rapidly becoming a mainstream commercial solution for dispatchable solar, with project sizes often exceeding 100 MW. These projects are now being rapidly developed across the world, both by utility solar farms and industrial consumers.

### 1.3.1 Utility solar farms embrace larger batteries

The first gigawatt-scale 24-hour solar project is also already under development in the UAE. The Masdar-led project was announced in January 2025 and will consist of a 5.2 GW PV plant coupled with a 19 GWh battery storage to provide 1 GW uninterrupted electricity supply to the grid.

This project is far from mainstream, but utility-scale solar farms are increasingly adopting large battery systems, either by adding them to existing assets or integrating them in the design of new projects. The US is a prime example of this — in 2023, 75% of all new solar projects awaiting grid connection were paired with battery storage.

In Hawaii, several solar-plus-battery projects are providing electricity through the night after the decommissioning of the last coal power plant in 2022, at a price between 9 and 13 cents per kWh, considerably below the cost of oil generation.

Batteries allow utility solar farms to match the load of industrial offtakers that aim for 24/7 carbon-free electricity - a growing trend among data centre giants such as Google and Microsoft. The 260 MW Sonoran Solar Energy Center in Arizona, the US, will use 1 GWh of storage to match the consumption of Google's forthcoming Mesa data centre. In Australia, the 2.2 GWh of storage of the 500 MW Richmond Valley solar farm, will enable it to supply electricity for green zinc production.

Battery storage can also enable utility solar farms to expand without the need for additional grid connection capacity. In Portugal, the 220 MW Algarve Solara 4 has announced a 400 million euro investment to add 50 MW of solar and 150 MW of wind capacity, along with 320 MWh of battery storage. The project will leverage the complementary generation profiles of solar and wind, supported by a relatively small but effective battery storage solution "to produce electricity 24 hours a day, making the maximum of the 200 MW connection point".

### 1.3.2 It also makes sense for large electricity consumers

Solar-plus-battery solutions are also becoming attractive to commercial and industrial electricity consumers, including behind-the-meter microgrids. These systems help avoid grid-connection queues and reduce exposure to power price volatility and outages – a compelling business case for data centres.

A prime example is the 100 MW Moro Hub in the UAE, world's largest 100% solar-powered data centre, commissioned in 2022 and sitting in the middle of a large solar power plant.

Solar and batteries can also power even the most energy-intensive operations. In West Virginia, US, a 106 MW solar microgrid project with just 261 MWh of storage is set to demonstrate this by powering titanium melting furnaces, once it reaches full capacity in 2027.

At an even larger scale, in late 2023, Saudi Arabia completed a tourism mega project including 16 hotel resorts and supporting facilities, all powered entirely by solar electricity. The project features a large microgrid with 400 MW of solar capacity and 1.3 GWh of storage and has already been operating smoothly for over a year.

Chapter 2

# Getting to 24-hour solar doesn't need a lot of battery

GHI = 4800 W/m²/day

To achieve 24-hour solar electricity in a sunny city like Las Vegas, around 17 kWh of battery storage is needed to cover non-sunny hours and deliver 1 kW of uninterrupted power across 24 hours, on an average day. In sunny cities like Las Vegas, daily battery needs vary only slightly throughout the year – typically ranging from 15.8 to 18.2 kWh — making near-continuous solar electricity supply highly achievable.

In winter

in summer

## 2.1 Around 17 kilowatt hours of battery are enough to flatten solar to 1 kilowatt of 24-hour solar generation

This section looks at how to deliver 24-hour solar electricity by storing day time solar generation in batteries for electricity supply after sunset. It starts by looking at Las Vegas, one of the sunniest cities in the world.

In Las Vegas, to get to 1 kW of continuous 24-hour solar generation on an average day, you need 5 kW of solar panels paired with 17 kWh of batteries. This is because Las Vegas has a solar capacity factor of 20%, meaning that averaged over a day, the 5 kW installation will deliver 1 kW of power per hour (1 kWh), or 24 kWh per day. However, since this generation will happen during the day, battery storage is required to move a part of the daytime solar generation into the night to deliver a flat 1 kilowatt across 24 hours.

The average battery required is 17 kWh. Of the 24 kWh solar electricity generated, 9.6 kWh can be used directly during sunny hours, while approximately 15 kWh needs to be stored for use during non-sunny hours. However, since only 90% of a battery's capacity is usable, to maintain safe operations between 5% and 95% charge levels, a 17 kWh is needed to store those 15 kW. From this, about 14.4 kWh can be released later, taking into account minor efficiency losses.

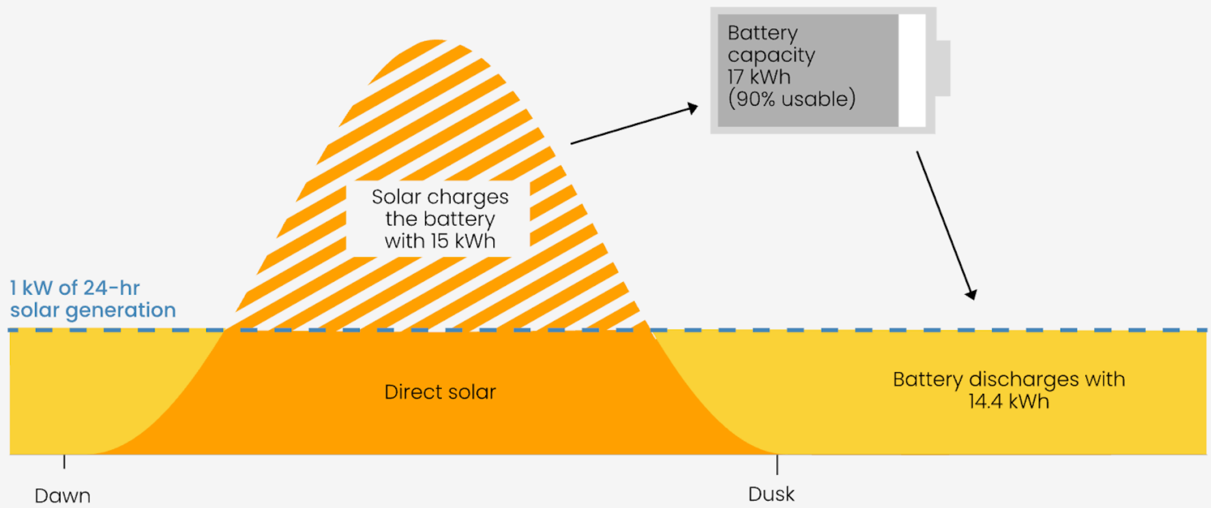
A simple sense-check shows how 17 kWh is about right. Solar panels can deliver power for around nine hours per day, because the day length is 12 hours on average across a year, with lower generation at dawn and dusk. That means the battery needs to operate at 15 hours across the day. At 1 kW, that is 15 GWh. And 15 kWh of usable capacity means 17 kWh of nameplate battery capacity.

A 17 kWh battery is relatively small compared to most electric vehicle (EV) batteries. It is less than half (43%) of the 40 kWh battery of a small city EV like the second generation Nissan Leaf and less than a fifth (17%) of the 100 kWh battery of a long-range EV like Tesla Model S Long Range.

The estimated 17 kWh battery assumes the solar panels are fixed in position. If they track the sun - like so many utility scale ones do - they will generate more electricity, meaning less panels are needed. The savings from needing fewer solar panels need to be weighed against the higher cost of installing them on trackers. However, perhaps surprisingly, tracking barely reduces the amount of battery needed. Although tracking panels deliver more electricity in the early morning and evening hours, anything over 1 kW (from the total 5 kW capacity) - would charge the battery. So the need for battery capacity remains essentially unchanged.

**17 kilowatt hours of battery are enough to flatten solar to 1 kilowatt of 24-hour solar generation**

Modelled operation of 5kW solar and 17 kWh battery on an average day in Las Vegas, kW per hour




Source: Ember analysis of JRC hourly solar radiation data
Assumptions: Solar PV (fixed system), DC-coupled with battery; Losses: 3.8% PV to grid; 5.6% PV to grid via battery; 90% usable battery capacity
Solar output profile based on the average generation per hour across 2022

However, no day is an average day. The amount of battery needed varies by day of the year and location. Sunny days have more solar at midday to capture and can deliver more than 1 kW per hour on average. Cloudier, short days may have very little solar output, delivering less than 1 kW per hour but also needing much less battery to flatten it. The next section examines the variability of this.

## 2.2 17 kWh is close to optimal for most sunny places

While Las Vegas would need a 17 kWh battery on an average day to deliver a constant 1 kW solar generation, no day is truly average and no other city is exactly as sunny as Las Vegas. The optimal size of the installed battery capacity will vary depending on location and the intended use case, especially if the goal is to capture all the solar electricity generated on the sunniest days, leading to underutilisation of the battery most of the time. However, our analysis shows that this relatively is limited. A 17 kWh battery is close to optimal for capturing most days in most sunny regions. Optimal size to Avoid underutilization

### 2.2.1 What is the variability throughout the year in Las Vegas?

For half of the days of the year, daily battery needs are steady — between 15.8–18.2 kWh. The lowest needs occur on cloudy days with less solar to store. On these days less battery is needed, but also solar generation is lower and will not get to 1 kW per hour on average.

¿Cloudy?

The highest needs come on sunny but short winter-spring days (Feb–Apr), when energy must be spread over longer evenings. These peaks are rare and likely low-value, so building for them may not be worth it.

### 2.2.2 What is the variability throughout different cities?

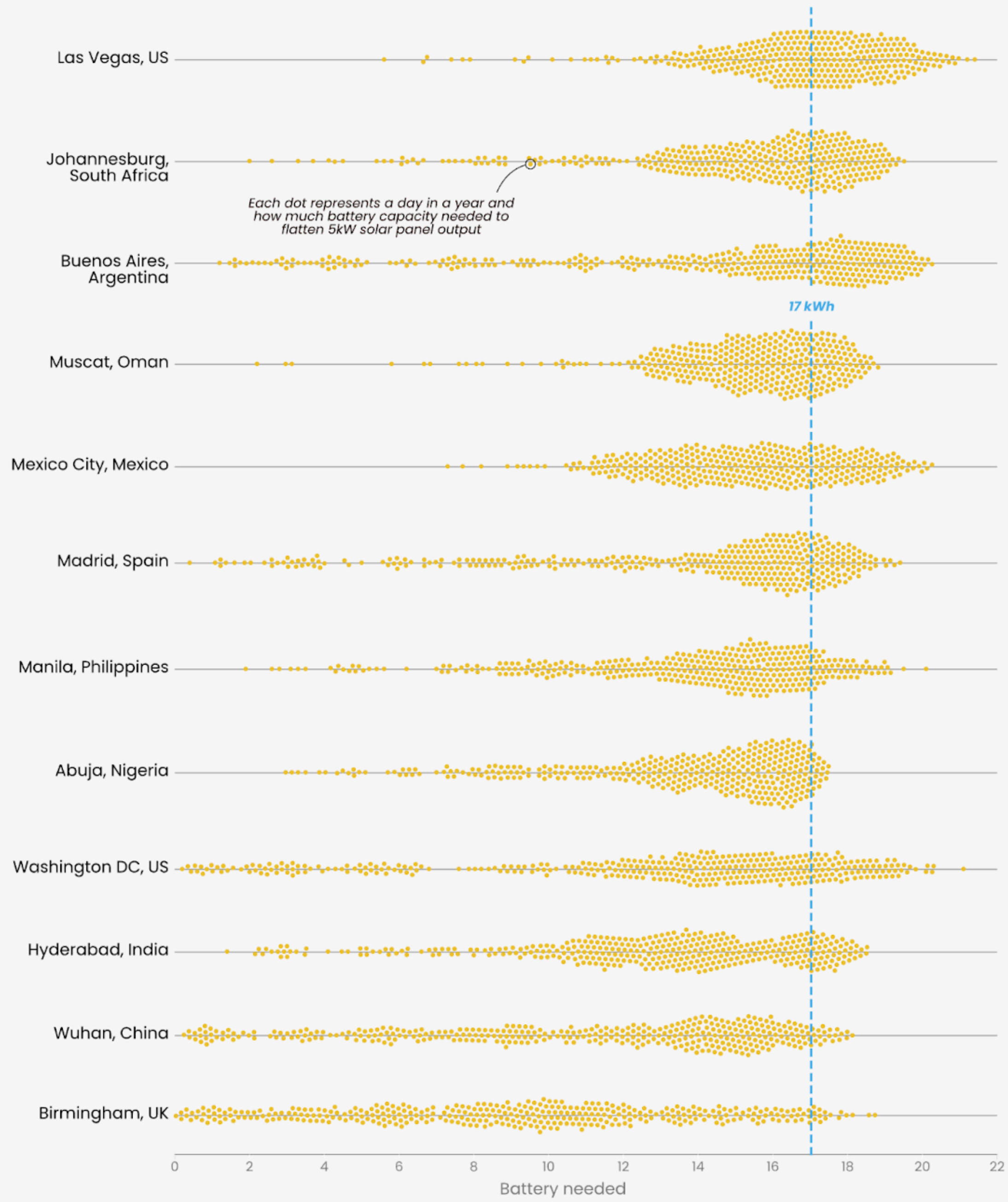
Las Vegas is the sunniest city analysed in this study, and all other cities require less battery storage than Las Vegas - both on an annual average level and on the sunniest days.

In other sunny cities like Johannesburg, Mexico City and Madrid, the average battery requirement falls slightly to 16 kWh. For less sunny cities, the fall is much steeper — for example, Birmingham requires just 9 kWh on average across the year.

The variation in battery needs on peak days is even smaller than for the average. Birmingham, for example, needs up to 19 kWh of battery to flatten the solar generation profile - almost as much as Las Vegas's peak day requirement of 21 kWh. That is because even in less sunny locations, some days can be very clear, providing a lot of solar generation to flatten the curve. In Birmingham's case, it just does not happen that often.

## Around 17 kWh of battery flattens the electricity output of 5 kW of solar panels almost anytime, anywhere

Battery capacity (kWh) needed to flatten the output of 5 kW solar panels on any specific day across 12 cities




Source: Ember analysis of JRC hourly solar radiation data
Assumptions: Solar PV (fixed system), DC-coupled with battery; Losses: 3.8% PV to grid; 5.6% PV to grid via battery; 90% usable battery capacity
Solar output profile based on the average generation per hour across 2022

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Designing a battery system to cover every outlier day would be prohibitively expensive, as that excess capacity would be underused for most of the year. In most cases, sizing systems for average or "most days" performance offers a more cost-effective solution. While the actual optimal capacity will vary by location and use case, this analysis finds that 17 kWh is close to optimal for most sunny places. The next chapter explores the economics of delivering 24-hour solar electricity not just on a single day, but across every hour of every day of the year - 24/365 solar generation.

# Getting close to 24/365 solar generation is cost-competitive in sunny regions

**While achieving 24-hour solar generation is easy in sunny regions, maintaining the same output every single day of the year remains a challenge due to clouds. With the right mix of solar capacity and battery storage, sunny cities can get as close as 97% of the way to full 24/365 solar coverage for just $104/ MWh.**

We used hourly solar radiation data from 12 cities across the world with diverse geographical conditions to evaluate how close they can get to 24/365 solar generation with the same solar-plus-battery configuration.

## 3.1 Sunny cities can get very close to 24/365 solar generation

In sunny cities like Las Vegas or Muscat, 24/365 solar generation is within reach, with cloudy days only occasionally providing small shortfalls. The analysis explores the limits of what solar and batteries can do, independent of the grid or other back-up power.

### 3.1.1 Las Vegas can get 97% of the way to 24/365 solar generation

Ember's modelling shows 24/365 solar generation is possible in a sunny city like Las Vegas: 6 GW of solar panels paired with 17 GWh of battery capacity can deliver 1GW of continuous solar electricity for 97% of the year. This model assumes a utility-scale project, moving from the kW scale explored until now to GW scale. It also assumes more solar capacity to reach higher reliability (6 GW for 1 GW target supply vs 5 kW for 1 kW average supply previously).

Some years are sunnier than others, leading to varying reliability. The average reliability across 2005-2023 was 97%, with the lowest year (2010) reaching 95% and the best year (2007) achieving 99%. The graphic below shows the days of 2023 which had an average of 96%.

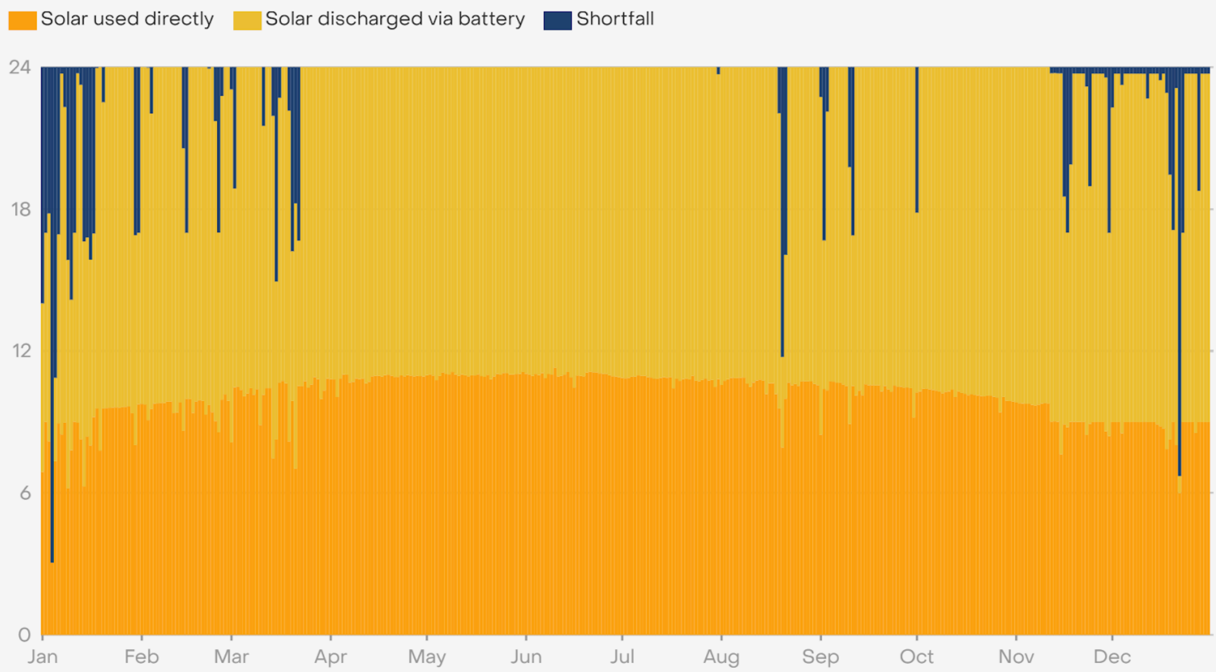
In 2023, there were 301 days when the system delivered a full 1 GW every hour; only four days had a shortfall of more than 12 hours. The lowest performing day, January 4, saw just 0.13 GW of electricity delivered across the entire day - equivalent to three hours of full 1 GW power over a 24-hour period.

Batteries help by carrying excess electricity from the previous day. However, this buffer can help bridge only small gaps, usually a couple of cloudy days, before the battery reaches its minimum state of charge. Once that point is reached, a shortfall for several hours can occur. To maintain 100% reliability during extended cloudy periods, additional long-duration storage, a back-up generator or grid electricity is needed, without building more solar and battery.

## How close is 24/365 solar?

Modelled electricity supply from solar with battery, targeting constant 1 GW supply every hour (0-24) of every day (1-365)

Las Vegas, US




Source: Ember analysis of JRC hourly solar radiation data (2023 values) · Assumptions: 6 GW solar PV (fixed system), DC-coupled with 17 GWh battery and constant 1 GW target supply (24 GWh per day); Losses: 3.8% PV to grid; 5.6% PV to grid via battery; 90% usable battery capacity

### 3.1.2 The sunniest cities can get more than 90% of the way to 24/365 solar generation

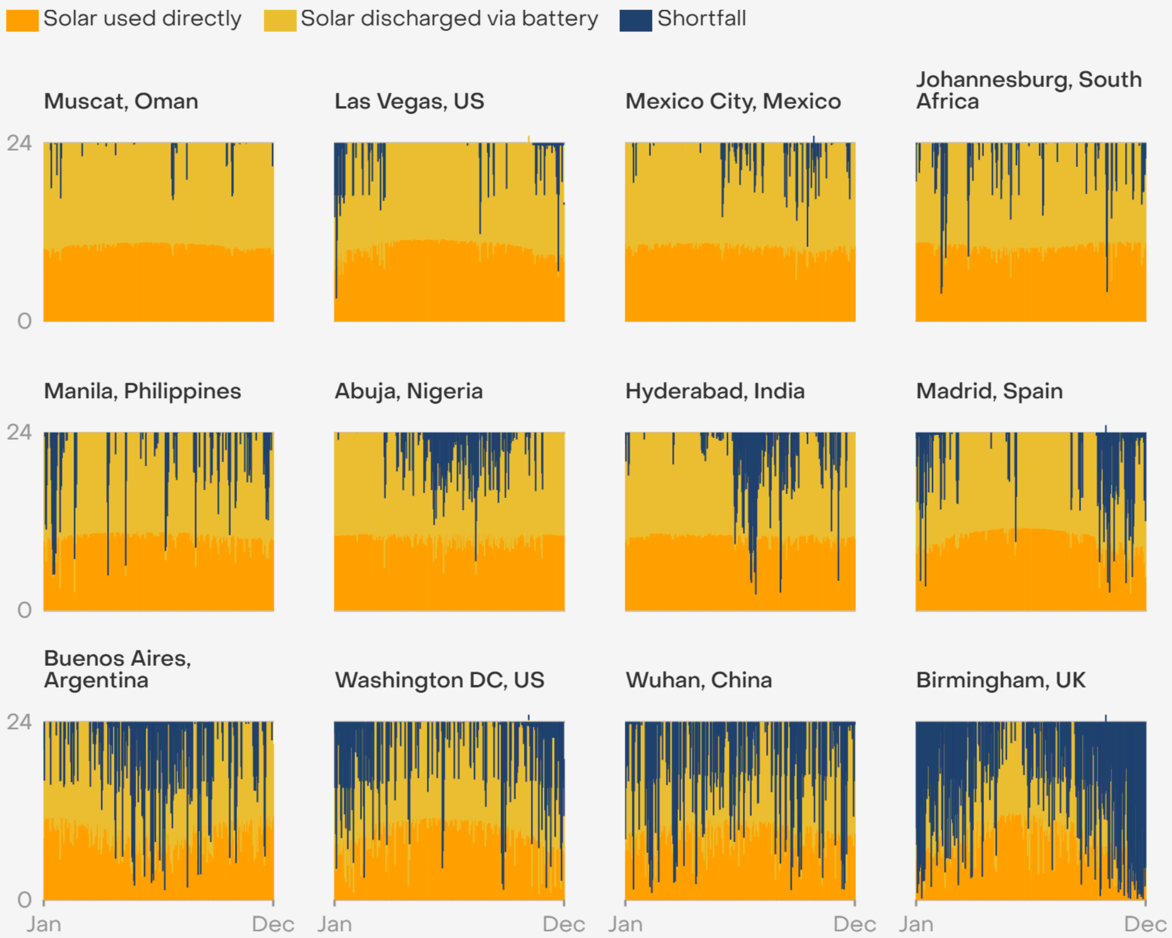
We tested the same solar and battery configuration of 6 GW solar and 17 GWh battery in 12 cities across the world.

Most cities analysed showed some seasonality with the biggest shortfalls happening during stretches of consecutive cloudy days in winter. Even Las Vegas, located just 4000 km north of the equator, gets only 9 hours and 21 minutes of daylight on its shortest day of the year - 2 hours 39 minutes less than the average 12-hour day.

In Hyderabad, supply shortfalls were driven not by winter, but by cloudy monsoon days. Madrid struggled in November and December, due to shorter, cloudier days in winter. Meanwhile in Wuhan, cloud cover was evenly scattered throughout the year - but on many days, it was dense enough to cut solar generation to very low levels. Birmingham barely had two good months of reliable sunshine. Even near the equator, like in Abuja, solar is not guaranteed year-round. Extended cloudy periods still push 100% reliability just out of reach.

## How close is 24/365 solar?

Modelled electricity supply from solar with battery, targeting constant 1 GW supply every hour (0-24) of every day (1-365)




Source: Ember analysis of JRC hourly solar radiation data (2023 values) · Assumptions: 6 GW solar PV (fixed system), DC-coupled with 17 GWh battery and constant 1 GW target supply (24 GWh per day); Losses: 3.8% PV to grid; 5.6% PV to grid via battery; 90% usable battery capacity

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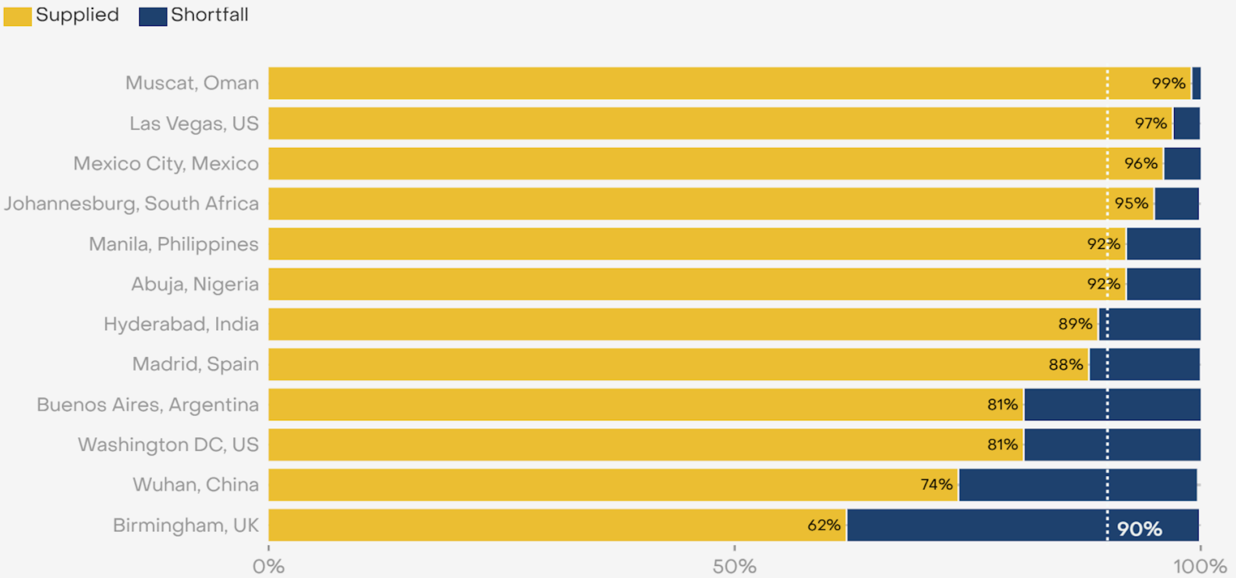
Overall across the year, Muscat in Oman comes closest to 24/365 solar generation, at 99% of the way - beating Las Vegas's 97%. Six out of the 12 cities we analysed achieved over 90%: Mexico City in Mexico (96%), Johannesburg in South Africa (95%), Manila in the Philippines (92%) and Abuja in Nigeria (92%). Four other cities achieved between 80-90% reliability: Hyderabad in India (89%), Madrid in Spain (88%), Buenos Aires in Argentina (81%) and Washington D.C in the US (81%). Only two cities fell short — Wuhan in China with persistent, dense cloud cover (74%) and Birmingham with short, dark winter days (62%).

**Many sunny places can get at least 90% of the way to constant 24/365 solar generation**

Share of electricity supplied from solar with battery, targeting constant 1 GW electricity, % (2005-2023 average)




Source: Ember analysis of JRC hourly solar radiation data · Assumptions: 6 GW solar PV (fixed system), DC-coupled with 17 GWh battery and constant 1 GW target supply every hour of every day of the year in full off-grid mode; Losses: 3.8% PV to grid; 5.6% PV to grid via battery; 90% usable battery capacity

The level of reliability achieved in the sunniest cities, like 97% in Las Vegas, is remarkably high and it is possible to imagine industrial users taking 97% without even needing a grid connection - relying just on solar and batteries and managing electricity use during the few cloudy days, or supplementing with small back-up generators.

Even Birmingham in the United Kingdom reached 62% of the way to 24/365 solar generation. While it is not imaginable for solar and batteries alone to power users in this city independently, it is high enough to play a substantive role in local generation alongside wind and other electricity sources.

## 3.2 How close to 24/365 solar generation is optimal?

If solar and battery capacity is sufficiently oversized, then it is of course possible to reach 100% of the way to 24/365 solar generation. But doing so is likely to be uneconomic — especially due to the high cost of batteries needed to store electricity across multiple days. The cheapest solar electricity comes without any battery at all, but that only provides daytime electricity - a long way from 24/365 solar generation.

In this section, we explore the trade-offs between different levels of solar and battery capacity and how these impact the Levelised Cost of Electricity (LCOE). We used global average prices (see Methodology) to reflect a typical international case and compare what price different cities can achieve based on their local solar resources.

In a sunny city like Las Vegas, standalone solar electricity costs $41/MWh (see mark 1 on graphic). While that is a very low price, it only delivers electricity for only 21% of the hours needed for full 24/365 solar generation. If low cost is the goal, and grid electricity is available for the rest of the time, then a battery is not optimal.

However, by adding some batteries and some more solar panels, it is possible to quickly get to 60% of the way to 1 GW of 24/365 electricity. This set-up based on 3 GW solar and 7 GWh of storage can generate enough electricity to cover much of the high value evening and morning hours and will increase the LCOE cost to $75 /MWh.

To reach 97% of the way to 24/365 solar generation in Las Vegas (as detailed in the previous chapter), 6 GW of solar panels and 17 GWh of battery capacity is needed. This takes solar generation way past high-value hours only, providing the same 1 GW power every hour of every day. The LCOE cost rises to $104 per MWh — $63/MWh more than standalone solar — but delivers nearly five times more reliability, moving from 21% to 97%.

Taken to the extreme, it is possible to get even further — reaching 99.4% of the way to 24/365 solar generation by continuing to overbuild solar and battery capacity (see mark 3 on graphic). This would need 7 GW of solar and 35 GWh of battery storage, raising the LCOE to $167/MWh. Compared to 97% configuration, the additional 2.4% of the year's electricity would cost $2700/MWh more — making it clear why 97% is likely to be more optimal than 99.4%.

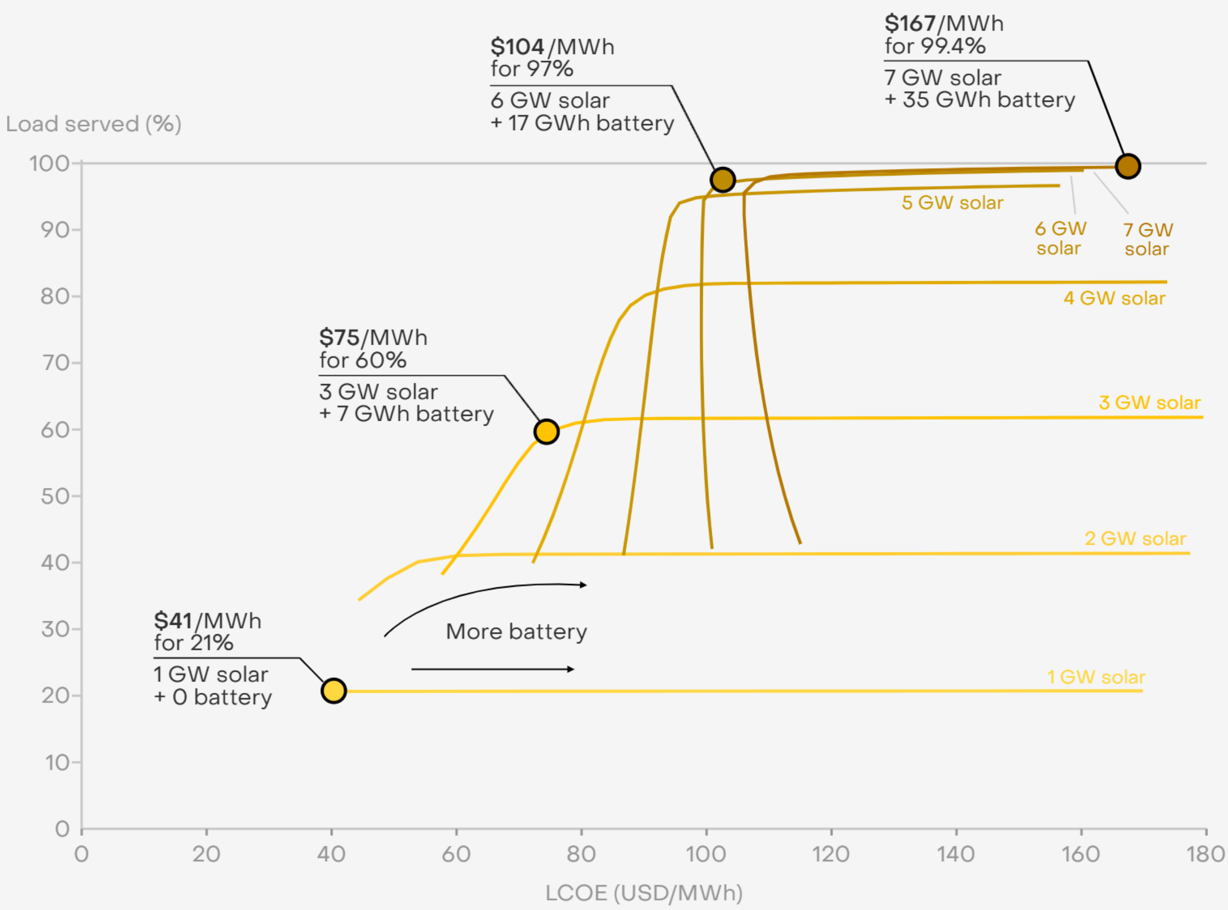
This shows that ultra-sunny places can economically come very close to 24/365 solar electricity. While the LCOE costs above are based on solar radiation in Las Vegas, the results are very similar for cities like Muscat, Mexico City and Johannesburg.

In moderately sunny places, solar and batteries can economically deliver 60-90% of the way to constant electricity every hour of every day. In sunny cities like Madrid and Abuja, extended cloudy periods mean storing electricity across multiple days becomes necessary to go above 90% of the way to 24/365 solar generation, something which isn't currently cost-effective.

The answer to "what is optimal" depends on the location and value of the shortfall generation and the cost of the alternative solution to fill this shortfall. This could come from load shifting or load curtailment, grid electricity or onsite generation. For off-grid use cases, it could be gas generation - which may be grid or onsite, and maybe from existing gas power plants or new ones. While aiming for nearly 100% 24/365 solar generation may be feasible and desirable in the sunniest regions, in most sunny areas, the optimal and practical role for solar-plus-battery is to likely deliver 60-90% of the way to 24/365 electricity.

## It is now cost-effective to get close to 100% constant solar generation in the sunniest cities like Las Vegas

Load served* and LCOE of different solar (GW) and battery (GWh) configurations




Source: Ember LCOE calculations, Full methodology · Key assumptions: CAPEX - $388/kW solar, $165/kWh battery; Other costs: $76/kW grid connection; $48/kW inverter; 10% total cost markup for soft costs; 7.7% discount rate over 20 years lifetime
* Load served refers to the system ability to supply 1 GW constant power supply every hour over the whole year

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## 3.3 The LCOE of near 24/365 solar generation are falling fast - 22% in the last year alone

It has not always been economical to get close to 100% of the way to 24/365 generation. But that has changed rapidly. In the last year alone, LCOE prices have fallen by 22%, driven by a 40% fall in battery prices.

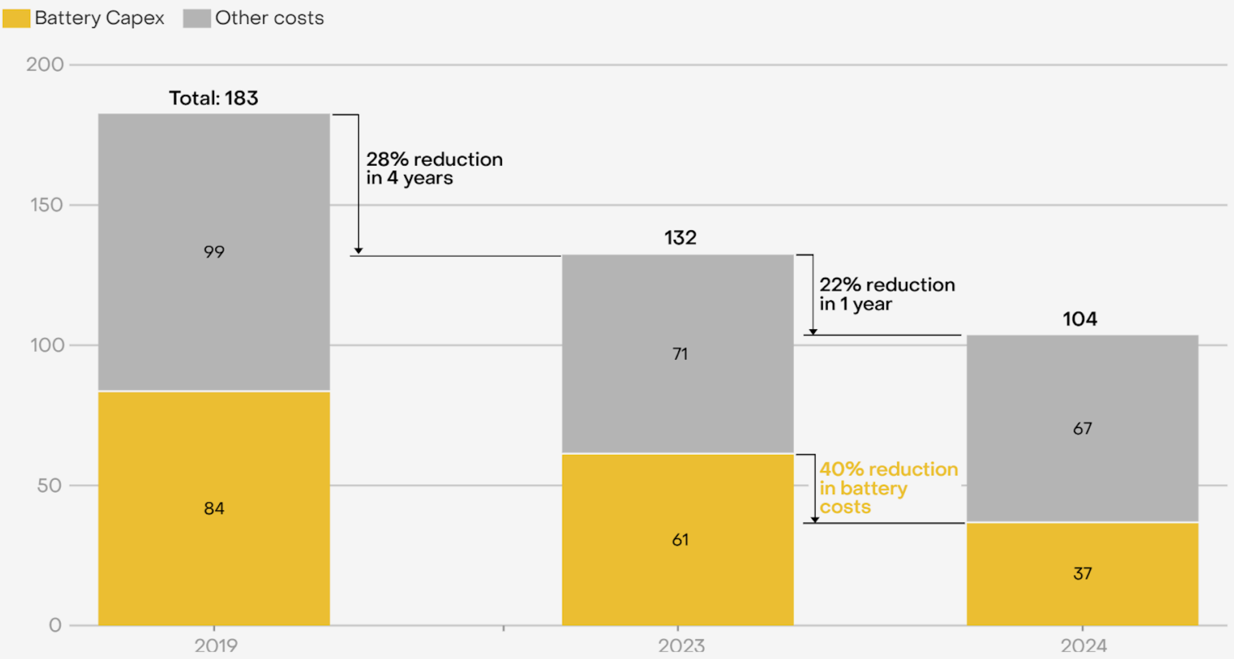
Getting 97% of the way at $104/MWh in Las Vegas is based on 2024 global average solar module and battery prices, a 22% fall from 2023.

In 2024, average global battery prices dropped to $165/MWh, down 40% from $275/MWh in 2023. The impact on overall system costs is striking: in 2023, battery capex accounted for $61/MWh, almost half (46%) of the total LCOE. Just a year later, in 2024, that contribution dropped to $37/MWh or 36% of the total.

While $165/MWh reflects the 2024 global average, actual battery prices can be far lower. In early 2025, tenders for large-scale battery storage projects in Tabuk and Hail, Saudi Arabia, reported prices as low as $72/kWh — less than half the global average. These record-low prices highlight the growing potential for even more affordable clean electricity.

In the past year alone, cheaper batteries led to 22% overall LCOE reduction

LCOE by component of 6 GW solar paired with 17 GWh battery, delivering 97% uptime in Las Vegas, US




Source: Ember LCOE calculations, Full methodology
Key assumptions: CAPEX - $388/kW solar, $165/kWh battery; Other costs: $76/kW grid connection; $48/kW inverter; 10% total cost markup for soft costs; 7.7% discount rate over 20 years lifetime

## 3.4 And now 97% of the way to 24/365 solar generation is cheaper coal and nuclear in sunny places

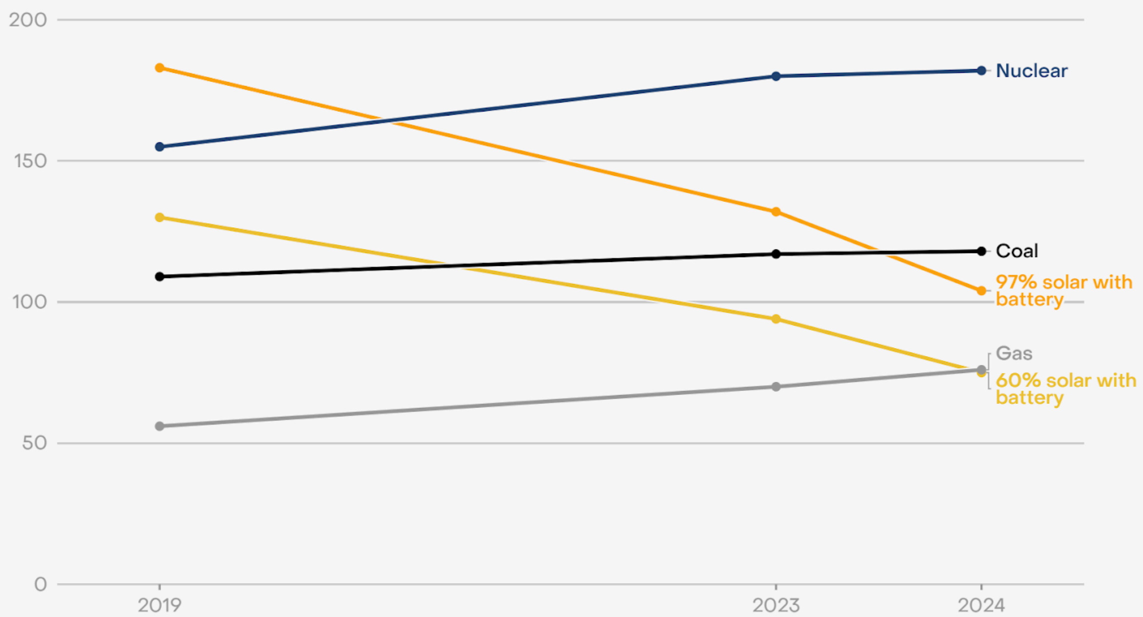
The most recent cost declines and longer battery lifetimes have dramatically shifted the economics of solar generation with batteries compared to other sources of electricity.

As of 2024, combining solar and battery storage to meet 97% of round-the-clock electricity demand in sunny places ($104/MWh) is cheaper than new coal ($118/MWh) and nuclear ($182/MWh), according to Lazard's latest LCOE data. This marks a dramatic reversal from 2019, when 97% uninterrupted solar was still more expensive than fossil and nuclear alternatives. In some countries - notably China and India - new coal can be significantly cheaper than the US-focused price of Lazard.

Even natural gas is being challenged. While the LCOE of new combined cycle gas stands at $76/MWh in 2024, 60% of the way to 24/365 solar electricity (using 3GW of solar and 7GWh of battery) costs $75 - a whisker less than new-build gas. This gas LCOE assumes relatively cheap fuel price, as Lazard's figures are based on US-focused data. In other regions dependent on imported gas, the LCOE of gas could be more than [double](#) the US level.

**97% uninterrupted solar generation with battery every hour of every day is now cheaper than coal and nuclear**

Evolution of the LCOE of generation technologies since (2019-2024), USD/MWh




Source: Ember LCOE calculations, Full methodology · Key assumptions: CAPEX - $388/kW solar, $165/kWh battery; Other costs: $76/kW grid connection; $48/kW inverter; 10% total cost markup for soft costs; 7.7% discount rate over 20 years lifetime
LCOE for Coal, Gas and Nuclear from Lazard's Levelized Cost of Energy Analysis—Version 17.0 (2024)

# Unlocking 24-hour solar is the new frontier for energy policy

For years, the role of solar in electricity systems has been confined to the hours when the sun shines. But recent advancement in battery storage has expanded the scope of what solar can deliver. Solar is no longer just a daytime solution — it can now be a round-the-clock resource.

This shift opens a critical new policy frontier: how to support, integrate and scale 24-hour solar as part of a broader power system strategy. Some good practices are already emerging, with governments integrating storage into renewable energy tenders, like in India. In 2025, India's SECI concluded its first-ever tender for 100% renewable "Round-the-Clock (RTC)" electricity with stricter financial and performance guarantees.

### The off-grid opportunity: from power gap to industrial growth

Solar-plus-storage can deliver reliable electricity without waiting for costly grid expansion. This offers a new pathway for electrification and economic growth, particularly across emerging economies in sunny regions like Africa and Latin America.

New industrial use cases are emerging: solar-powered manufacturing, desalination and data centres. These facilities can be located where the solar resource is strongest, not just where the grid currently reaches. The concept of "solar industrial zones" or "desert megabases" powered by standalone microgrids is becoming viable, and deserves serious policy attention.

### Technology and economics are ready, first-movers need to lead the way

While the solar and batteries are already mature, affordable and ready, the biggest barrier to scaling up 24-hour solar is a business-as-usual mindset. Power system planners, financiers and regulators are still mostly unfamiliar with the concept or remain sceptical of its reliability.

Even fossil-fuel-based off-grid solutions — such as gas turbines — require redundancy to meet reliability standards. Properly sized and managed solar and batteries can compete with or outperform these in reliability, especially when redundancy is designed in (e.g. in the form of oversizing the system, some grid-based electricity or back-up generators that are used only 3-5% of the time annually). After all, gas facilities need regular maintenance, while weather forecasting makes cloudy days more predictable than unexpected gas turbine failures.

The barrier is no longer technical feasibility, but regulatory conservatism and risk aversion.

### At the national level, 24-hour solar helps reduce grid expansion costs

At the grid level, solar with batteries will be a growing asset — though not a silver bullet. Demand varies hourly and seasonally, and no single resource can meet that variability alone. Batteries play a crucial role in balancing, but must work alongside other renewables like wind, hydro, geothermal, as well as interconnectors and flexible demand.

Crucially, 24-hour solar can dramatically reduce grid expansion costs. By flattening the curve, batteries allow up to five times more solar capacity to connect behind the same grid connection — maximizing existing assets and deferring costly upgrades.

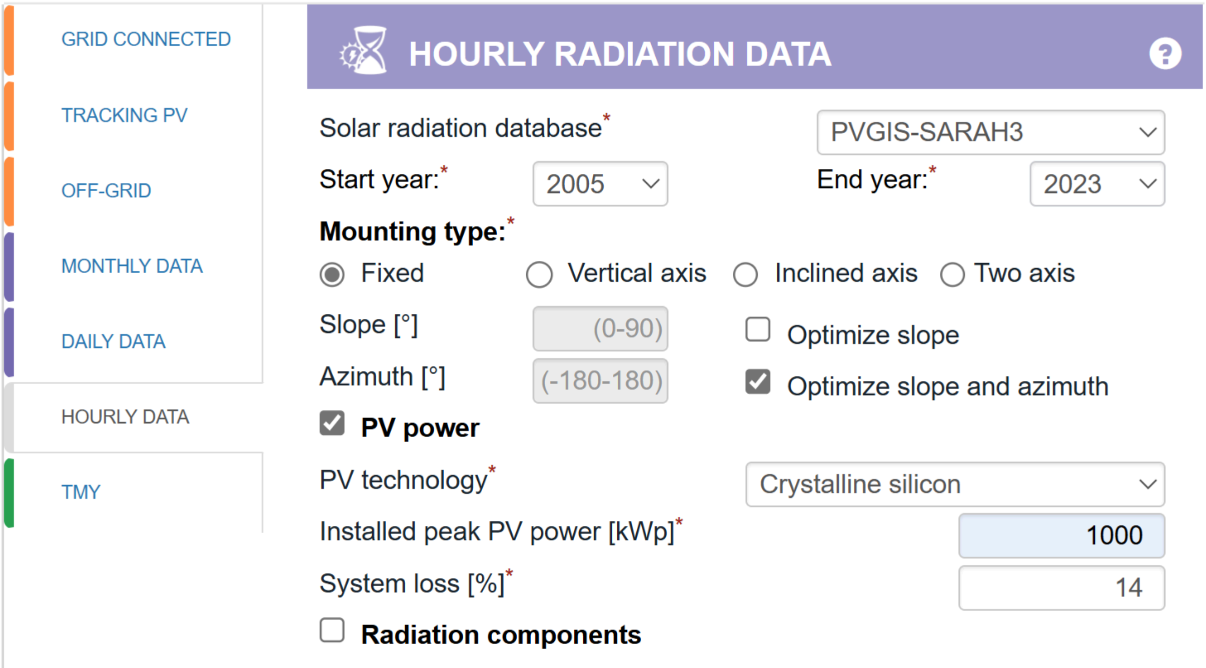
# Methodology

This methodology outlines the modelling approach used to simulate hourly performance and estimate the Levelized Cost of Electricity (LCOE) for solar photovoltaic (PV) systems integrated with battery energy storage (BESS). The model evaluates energy flows over a full-year period using hourly solar irradiance data. Financial calculations extended over a 20-year project life. It supports batch analysis of multiple capacity configurations to assess system performance and economics under various design scenarios.

**Data sources**

Hourly solar generation data is sourced from the European Commission's JRC PVGIS tool. Simulations use:

- Fixed-tilt PV systems (crystalline silicon technology), with optimised slope and azimuth per location
- Installed DC PV capacity set to 1000 for baseline scaling
- SARAH3 solar irradiance database where available, otherwise ERA5 is used
    - To improve the accuracy of modelled solar PV performance in Manila, a manual correction was applied to the ERA5-derived solar irradiance data to increase the annual solar capacity factor from around 15% in ERA5 to 18%, ensuring alignment with realistic regional expectations while preserving the original variability in the data.




## Inputs

Each simulation scenario is defined by the following inputs:

- Solar Capacity (GW): Total installed PV capacity
- Battery Storage Duration (GWh): Battery capacity expressed in energy terms - GWh
- Solar CSV File: Hourly PV output data (DC) from PVGIS
- Time Zone: Local time zone used to convert UTC timestamps from the original PVGIS dataset

## Technical assumption

- System architecture: A DC-coupled solar + storage configuration is assumed. This enables shared inverter use and improved round-trip efficiency. The battery is not charged from the grid.

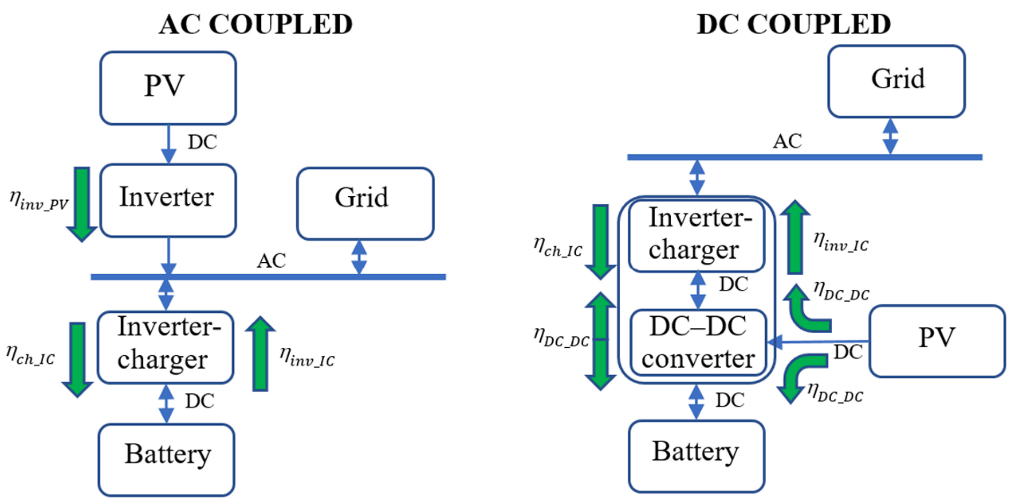



*Figure source: Dufo-López et al*

- Grid interaction:
    - Maximum grid export limited to 1 GW hourly, referred to as "Demand Cap" later in this document
    - No grid import is permitted, the battery can charge only from solar
- Efficiency losses:

| **Process** | **Efficiency** | **Loss** |
|---|---|---|
| PV to Grid | 96.24% | 3.76% |
| PV to Battery | 98.2% | 1.8% |
| Battery to Grid | 96.24% | 3.76% |
| PV → Battery → Grid (full path/round trip) | 94.4% | 5.6% |

- PV to battery loss is based on DC-DC conversion losses, Dufo-López et al (see references)
- PV to Grid and Battery to grid loss is based on DC-DC (98.2%) and DC-AC (98%): 98.2% * 98% = 96.24%
    - DC-AC loss based on Sungrow Power (see references)

- Battery operational constraints:
  - Total usable battery: 90% of nameplate capacity
    - Minimum state-of-charge (SoC): 5%
    - Maximum SoC: 95%

### Hourly Energy Flow Logic

For each hour in 2023, the model performs the following steps:

1. Solar Output Limiting
   a. PV Output (MWdc) is scaled by installed capacity
   b. Limited Solar Output (MWac):
      Limited = min(PV Output × (1 - PV to Grid Loss), Demand Cap)
   c. Excess PV generation beyond 1 GW is classified as surplus solar, which may be stored or curtailed.

2. Battery Charging
   a. Battery only charges from surplus solar beyond the grid demand cap
   b. Charge energy is adjusted for PV-to-battery efficiency losses
   c. Battery does not charge when solar is below the cap
   d. Initialisation: The model starts on 1 January with the battery fully charged. This avoids undefined behaviour during the first discharging event.

3. Battery Discharging
   a. When solar output is below demand, the battery discharges to meet shortfalls
   b. Discharge is constrained by:
      i. Available state-of-charge
      ii. Battery-to-grid losses
      iii. Remaining capacity above the minimum SoC

4. State-of-Charge Tracking

   Battery state is updated hour by hour, ensuring:

   i. No overcharging beyond 95% capacity
   ii. No discharging below 5% capacity
   iii. All charging/discharging honours respective efficiency losses

5. Residual Load: Residual Load = Discharge Needed - Actual Battery Discharge

### Annual Aggregation

For each scenario, the following annual energy metrics are calculated:

- Total Solar Supplied (MWh): PV output delivered directly to grid
- Total Battery Supplied (MWh): Discharged energy from BESS
- Total Supplied Energy = Solar + Battery
- Total Residual Load: Unmet demand
- Total Excess Solar: Curtailment due to full battery

### Cost and Financial Assumptions

1. Capital Expenditure (CAPEX)

| Component | Unit cost (USD) | Source |
|---|---|---|
| Solar PV | \$388M / GW | (a) |
| Battery Storage | \$165M / GWh | (b) |

| | | |
|---|---|---|
| Grid Connection | $76M / GW | (c) |
| Inverter | $48M/ GW | (d) |
| Soft Costs | 10% markup | (e) |

a. Solar PV cost is based on the following assumptions on subcomponents:
    i. Module price: $110M/ GW, based on the August-December 2024 price range of TOPCon modules in EU and China (90-120).
        1. 2023 module cost: $130M/GW
        2. 2019 module cost: $427M/GW
    ii. Balance of system hardware (cabling, mounting and raking, safety and monitoring): $143M/GW based on the average across countries in Renewable Power Generation Costs in 2023, IRENA.
    iii. Installation (electrical and mechanical installation, inspection): $135M/GW based on the average across countries in Renewable Power Generation Costs in 2023, IRENA.

b. Battery storage cost is based on the 2024 global average, estimated at $165/GWh (2024 Annual Battery Report, Volta Foundation) and more recent cost reports $72M/ GWh (the reported results from the tenders for battery storage systems in Tabuk and Hail, Saudi Arabia, see Dr. Marek Kibik).
    i. 2023 battery cost: $275M/GWh
    ii. 2019 battery cost: $375M/GWh

c. Grid connection cost is based on the average across countries in Renewable Power Generation Costs in 2023, IRENA. It is scaled based on the Demand Cap.

d. Inverter cost is based on the average across countries in Renewable Power Generation Costs in 2023, IRENA. It is scaled based on the Demand Cap.

e. Soft costs (e.g. System design, permitting) are applied to total capital costs (a-d).

2. Operating Expenditure (OPEX)

| **Component** | **Unit cost (USD)** | **Source** |
|---|---|---|
| Solar PV | $12.5M / GW/ year | Lazard, midpoint between low and high case |
| Battery | $5.9M / GWh / year | Lazard, midpoint between low and high case |

a. Escalation rate: 2.5% annually
b. Project life: 20 years

3. Degradation Rates
    a. PV degradation: 0.5% per year
    b. Battery degradation: 2.6% per year

4. Discounting
    a. Discount rate: 7.7% (Lazard LCOE+)
    b. Discounting applied annually to both costs and energy output

### LCOE Calculation

The LCOE is calculated as:

LCOE [$/MWh] = Total Discounted Energy Supplied / Total Discounted Costs

Where:

- Total Costs include CAPEX, discounted OPEX
- Total Energy Supplied includes discounted energy from PV and battery

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Ember: Rashmi Mishra, Reynaldo Dizon, Richard Black, Neshwin Rodrigues, Beatrice Petrovich, Kingsmill Bond, Hannah Broadbent, Matt Ewen, Wilmar Suarez, Sam Hawkins, Daan Walter, Kavya Sharma.

Cover Photo

Multiple exposure of the midnight sun moving across the horizon over the Arctic Coast.

Credit: Image Source Limited / Alamy Stock Photo