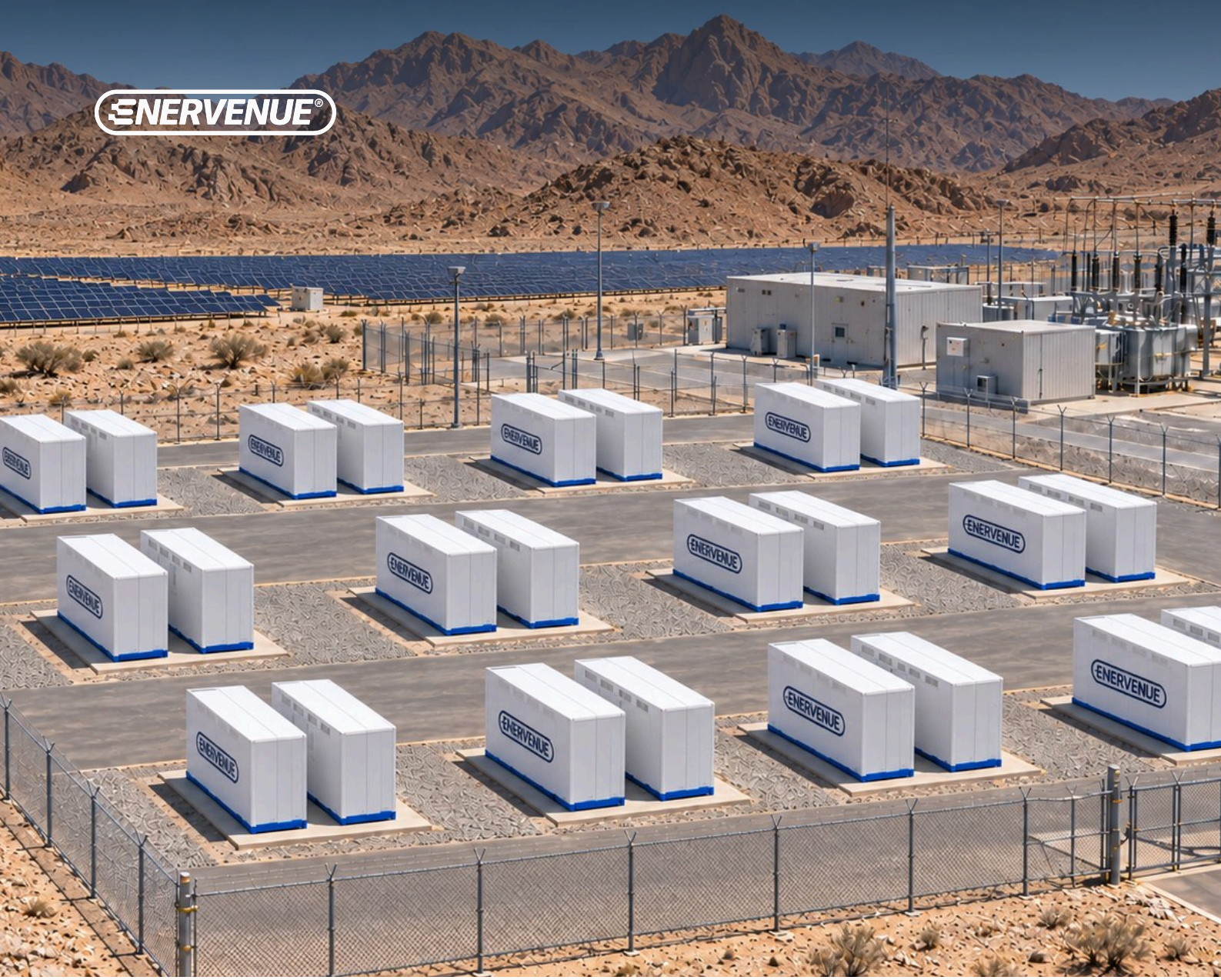


TECHNICAL CASE STUDY

Storage for remote and off-grid power

How a battery lets an off-grid solar and diesel plant use more of the energy its array can produce, install fewer generators and cut its 25-year cost of energy by 10 to 29 percent, and why the battery's chemistry decides whether those savings last.

Executive summary

The plant in this study already has a large solar array, but without storage it can use less than half of the energy that array could produce. The site conditions that make it good for solar are the same conditions that have kept storage off it, and a battery that tolerates them stores the surplus and pays for itself in two to seven years.

PV CURTAILED TODAY	COST OF ENERGY	SIMPLE PAYBACK	GENERATOR FLEET
55%	**−10 to −29%**	**2.0–6.7 yr**	**10 → 6**
of what the array could produce	across the five configurations studied	on the incremental capital only	units installed, same reserve margin

Remote and off-grid sites, among them industrial plants, mines, island communities, resorts, and data and commercial campuses, increasingly pair diesel generators with a large solar array. The array promises cheap daytime energy, but a plant without storage cannot use all of the energy its array could produce. With no main grid to support it, at least one generator must run at all times to form the grid and hold its voltage and frequency steady, and that generator cannot run below its minimum load. Solar can therefore supply only the part of the load above that generator's minimum. Whenever the array could produce more, the plant has to curtail the surplus: the solar inverters hold back their output, and that energy is never produced.

On the plant studied here, **55 percent of the energy the array could produce is curtailed**, and diesel still supplies 68 percent of the load. The array was sized for the demand the plant expects in 10 years' time. Until demand grows to that level, more of the array's output is surplus, so curtailment is highest in the early years, when the least of the array's capital cost has been recovered. The generator fleet was sized to meet peak demand, although the average load is only about half of that peak.

A battery removes that constraint. It stores the midday surplus and supplies it after sunset, when the plant would otherwise burn diesel, so the generators run for fewer hours. The battery can also carry the evening peak, and because that peak is what sets the size of the generator fleet, a new plant can be built with fewer generators. In the 12 MWh case, the plant needs seven generators instead of 10. **The battery costs $4.75 million, but the plant costs only $2.9 million more than it would without storage, because the three generators it no longer needs are never bought.** A large part of the battery's cost is therefore covered by the generators it replaces, before a liter of fuel is saved.

Five configurations were modeled for the same plant, using the same 8,760 hours of load and solar data: three battery sizes with the array as designed, and two in which the array is also enlarged. **Every scenario lowers the lifetime cost of energy and pays back its additional capital within seven years.** Across 10,000 randomized runs of each configuration, with 18 uncertain inputs varied together, **not a single run lost money.**

The battery this study assumes

Sites like this one are hot, dusty and far from a service center, and in some seasons they are cold at night. Conventional lithium-ion storage has often been hard to justify on such sites, for three reasons unrelated to its price per kilowatt-hour. First, ambient temperatures fall outside the range in which the cells can work without a refrigerated cooling system. Second, that cooling system needs maintenance, and the nearest technician may be hours away. Third, the fire protection and separation distances required for a flammable electrolyte are hard to provide on a constrained industrial site.

The figures in this paper assume **EnerVenue's Aqueous Metal Cell**, a battery based on nickel-hydrogen chemistry, deployed as the **Energy Prism**, a 600 kWh containerized DC block. The Energy Prism has a wide operating temperature range of −20 °C to +60 °C, held on forced air with a modest cooling load for part of the year in hot climates. The battery has a water-based electrolyte with zero risk of fire from thermal runaway, and it is engineered for up to three cycles a day over a 30-year design life, or roughly 30,000 cycles at full depth of discharge. The 25-year calculations on the following pages rest on these three properties, and page 8 explains why a chemistry without them gives a different answer.

About this paper. This is an engineering study. It takes one representative remote site, models it hour by hour through a full year, and reports what adding storage does to fuel use, the number of generators and the cost of a kilowatt-hour over 25 years. The study is based on a real site, but the figures given here have been scaled, re-costed at a different fuel price, rounded and anonymized, so they describe a class of plant and not a particular project. Proportions that follow from the physics, such as the share of solar curtailed, are carried across unchanged. Equipment and fuel prices are indicative, and storage pricing is available on request.

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Two problems: solar energy the plant cannot use, and storage that has been hard to justify

A remote plant that runs on solar and diesel cannot use much of the energy its array could produce, and the problem has gone unsolved for so long because conventional batteries have been hard to justify on remote sites.

Why remote plants add solar

An industrial site beyond the reach of the grid has to generate its own electricity. Diesel generators are the default choice, because they are well understood, start on demand and can be sized to any load. Their weakness is running cost: every kilowatt-hour is paid for in fuel that must be bought, transported and stored, and on a remote site the delivered price of that fuel includes the cost of getting it there.

Solar photovoltaic (PV) power addresses that cost directly. Once built, a solar array produces energy at close to zero running cost, and its output does not depend on the price or supply of fuel. For a plant that operates through the day, a large array looks like an obvious saving, and many such plants have been built with arrays sized to produce the equivalent of half the annual load or more.

Why so much of the solar energy goes unused

A plant of this kind operates as an isolated grid, with no connection to a wider network. Something on site must therefore form the grid: set the voltage and frequency, absorb sudden changes in load and supply fault current. In a conventional plant that job falls to the generators, so **at least one generator must run at all times**, and a diesel generator cannot run for long periods below roughly a quarter to a third of its rated output without damage to the engine.

The generator's minimum load therefore puts a floor under diesel output through the middle of the day, when solar output is highest. Whenever the array could produce more than the load minus that floor, the surplus has nowhere to go. There is no main grid to export it to and, without storage, no way to keep it, so the plant curtails the array: the solar inverters hold back their output, and the energy is never produced.

> On an isolated grid, the limit on solar is how much energy the plant can absorb at the moment the array can produce it.

Two design decisions that increase curtailment

The array is sized for future demand. A plant that expects its load to grow builds the array once, for the demand it expects in 10 years' time. In every year before then the load is lower, so more of the array's output is surplus and a larger share of it is curtailed. Curtailment is therefore worst in the early years, when the least of the array's capital cost has been recovered.

The generator fleet is sized for the peak. The number of units is set so that the highest half-hour of demand in the year can be met with one unit still in reserve. The average load is typically half the peak, so for most of the year the plant carries generating capacity it does not use, and that capacity was bought and must still be maintained and overhauled on its running hours.

Why storage was not the obvious answer

Storage solves both problems, and in principle it has been available for years. It has often been hard to justify on these sites, because the conditions that make them attractive for solar are the same conditions in which conventional batteries are hardest to keep working.

The first obstacle is ambient temperature. Desert and high-altitude sites swing from below freezing at night to well above 40 °C in the afternoon, and lithium-ion cells can be charged and discharged at their rated power without faster degradation only within a narrow temperature range. Keeping them in that range takes a refrigerated HVAC system sized for the worst hour of the year, with the parasitic load, capital cost and risk of failure that come with it.

The second obstacle is maintenance. A cooling circuit has pumps, filters and refrigerant, and a fault in it can take the battery offline. On a site several hours from the nearest service center, the number of components that need maintenance is a design consideration in its own right, and it does not show up in a price per kilowatt-hour.

The third obstacle is fire safety. A flammable organic electrolyte brings requirements for fire suppression, separation distances and explosion control, which are expensive to meet on a constrained plot next to process equipment and fuel storage.

A battery answers all three objections if it stays within its operating range on forced air with a modest cooling load, needs far less thermal management than a lithium-ion installation, has no liquid cooling circuit to maintain and carries zero risk of fire from thermal runaway. This study assumes a battery of that kind, so the result that follows is a commercial calculation of what storage is worth on this plant.

Where this applies

The plant modeled here is industrial, but the same mechanism applies wherever an isolated grid pairs solar with engine generators: mining and processing sites, oil and gas facilities, the grids of island and remote communities, telecom and data sites, resorts and commercial campuses, and construction and military camps. What changes between them is the shape of the load, and therefore how much storage is needed to reach a given solar share, not whether storage pays.

The reference plant, and how it runs today

The study models one representative site hour by hour, using 8,760 hourly values of load and irradiance.

Parameter	As designed	What the study varies
Load	25,000 MWh/yr · 5.6 MW peak · around the clock	Unchanged in every case
PV array	10 MWp fixed tilt · 17,500 MWh/yr (P90), 70% of annual load on paper	Cases 1–3 keep 10 MWp; Scenarios 4 and 5 grow it to 15 and 20 MWp
Generators	10 × 1,250 kW, loaded 25–85%, sized on peak with reserve; the units the net load requires are online, never fewer than one	How many units the battery allows the plant to omit at the same reserve. One unit stays online for grid forming in every case
Storage	None	6 / 12 / 25 MWh at 10 MWp; 28 MWh at 15 MWp; 44 MWh at 20 MWp
Fuel	Diesel at $0.85/L delivered, escalating 2%/yr	$0.65 and $1.05 tested separately
Result today	**32% of load from solar · 55% of solar curtailed · 4,628 kL of diesel a year**	**Solar share, fuel, fleet size, cost of energy, breakeven, cash**

Table 1. The reference plant and the variables of the study. Figures are scaled and re-costed, and describe a class of plant, not a particular installation.

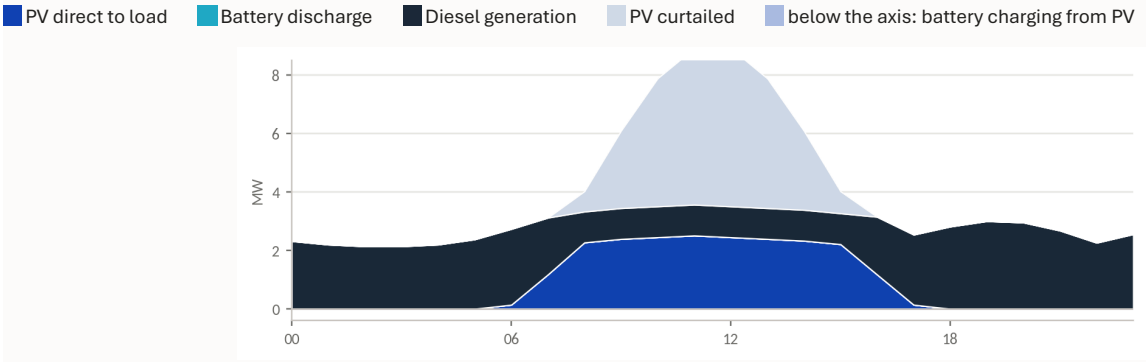


Figure 1. An average day without storage, built from all 8,760 hours. Diesel output never falls to zero; the pale dome above the served load is curtailed solar.

The chart shows three things. Diesel runs through the middle of the day, held at minimum load to keep the grid stable. Solar is curtailed in a broad dome across those same hours. After sunset the evening peak is met entirely by diesel, and that peak is what keeps the fleet large.

The plant needs 10 units of 1,250 kW to cover its 5.6 MW peak with reserve. Eight are installed for duty, and the rest cover the peak and maintenance. Each unit is costed at $500/kW in the first year, and the overhaul reserve is based on running hours, not calendar time, so a fleet that runs fewer hours costs less to own as well as less to fuel.

The resulting cost of energy is **$0.239/kWh**, against a **marginal cost of diesel energy of $0.265/kWh**. The second figure is the benchmark for everything that follows: it is what the plant pays for the next kilowatt-hour it generates from fuel, and so it is the cost a battery has to undercut to be worth building.

Table 2. The plant without storage. Fuel dominates: nine dollars in ten of the annual operating cost is diesel, which is why the fleet's running hours have the largest effect on cost.

Annual energy and cost, plant without storage	Value
Load served	25,000 MWh
Solar used directly	7,870 MWh (31.5% of load)
Solar curtailed	**9,630 MWh (55.0% of potential output)**
Diesel generation	17,130 MWh (68.5% of load)
of which produced during daylight hours	3,670 MWh
Diesel fuel	4,628 kL
Generator fleet running hours	22,150 unit-h/yr
ANNUAL COST, YEAR 1	
Fuel	$3,934k
Generator O&M	$332k
Overhaul reserve	$277k
Total operating cost	**$4,541k**
Generator capital, year 0	$6.25M
Levelized cost of energy, 25 years	**$0.239/kWh**

What storage changes, and how big it should be

Storage has four separate effects, which arrive at different times and are worth different amounts.

1. It turns curtailed solar into diesel savings

The surplus that had nowhere to go is stored and returned after sunset. Every kilowatt-hour returned is one a generator does not have to produce, and the fuel is saved at the margin, where it costs most. Storing that surplus is the largest single effect, and it starts on the first day.

2. It allows a smaller generator fleet

Because the battery carries the evening peak, the plant can meet the same demand with fewer installed units. On this site a unit can be left out only if the battery matches its power *and* can hold that power for the length of the peak. Where it can, the capital for that unit is never spent.

3. It reduces running hours on the units that remain

Fewer generators running for fewer hours means less servicing, fewer overhauls and fewer call-outs. On a remote site a service visit is a long and costly trip, so the saving is worth more than its line in the cost model shows.

4. It responds faster than an engine

A battery responds to a sudden change in load in milliseconds, where a generator takes seconds. Sudden load changes that previously required an extra generator to run as spinning reserve can be met from the battery instead.

What storage does not do

Storage does not remove the need for grid forming. One generator stays online at all times in every configuration in this study, and its minimum load keeps a floor under diesel output through the day. That floor alone accounts for roughly 3.7 GWh of diesel generation a year. Grid forming can be transferred to a grid-forming inverter, which would remove that floor entirely, and that is the natural next step for plants of this kind. This study does not assume it, so the savings reported here are the conservative case.

Sizing the battery

Every battery size from 0.25 to 30 MWh was run through the hourly model, with the array held at 10 MWp and the inverter sized for four hours. The resulting cost curve is not smooth, and its shape determines a sensible choice.

From 0 to 3 MWh the cost falls steeply with the fleet unchanged at 10, because each additional megawatt-hour shifts more solar into the night. **At about 3 MWh the curve steps down**, because the battery can now cover the evening peak well enough for two units to be left out of the build; at 9 MWh a third is left out.

Three sizes were carried forward. The **6 MWh** battery is the smallest that lifts solar from 32 to 40 percent of load and still releases two units. The **12 MWh** battery sits at the knee of the curve. The **25 MWh** battery is within a tenth of a cent of the curve's minimum and brings curtailment down to single figures.

Beyond 25 MWh the curve flattens and then rises gently. Additional capacity then buys autonomy and resilience more than fuel savings, and would have to be justified on those grounds.

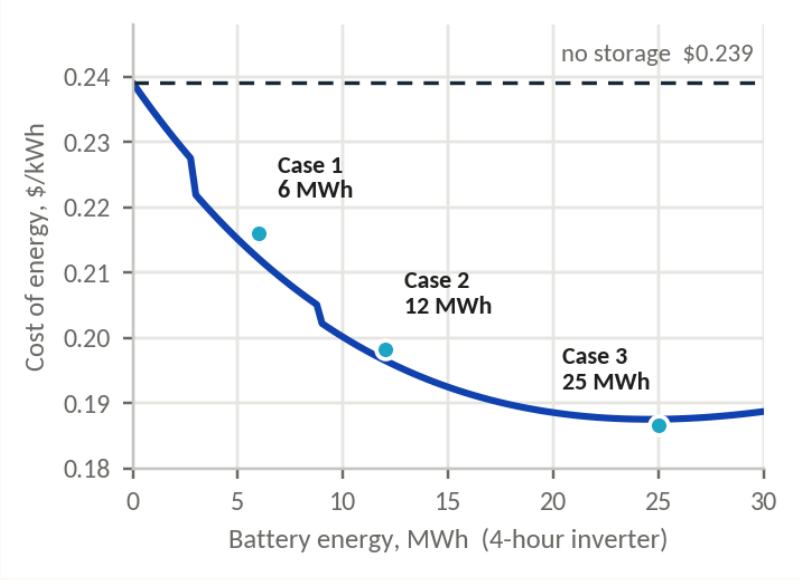


Figure 2. Cost of energy against battery size, with the array fixed at 10 MWp. The steps mark the points where generators leave the build.

Results with the array as designed

The load, the hours and the cost basis are the same in every case; only the battery and the generator fleet change.

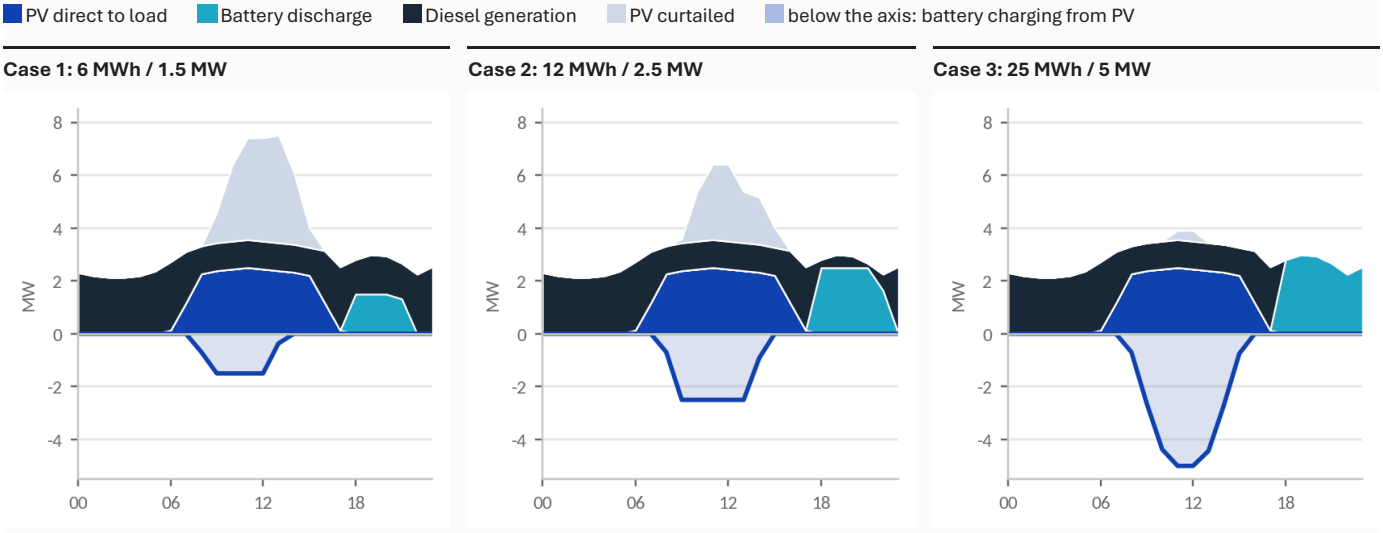


Figure 3. The same average day with each battery, drawn to one scale. The pale band of curtailed solar shrinks from a broad dome to a thin residue, and the dark diesel band shrinks in the middle of the day and in the evening. On an average day Case 3 absorbs almost all of the surplus; the 9 percent curtailment reported below is an annual figure, and it comes from the brightest days of the year, which produce more surplus than any battery in this study can hold.

	Without storage	Case 1 6 MWh / 1.5 MW	Case 2 12 MWh / 2.5 MW	Case 3 25 MWh / 5 MW
Generators installed	10	8	7	7
Solar share of load	32%	40%	48%	59%
Solar curtailed	55%	40%	27%	9%
Diesel fuel	4,628 kL	4,038 kL	3,507 kL	2,780 kL
Fuel saving	–	**13%**	**24%**	**40%**
Energy through the battery	–	2,120 MWh/yr	4,250 MWh/yr	5,920 MWh/yr
Full equivalent cycles	–	355 /yr	355 /yr	240 /yr
Capital, year 0	$6.25M	$7.40M	$9.12M	$14.25M
Operating cost, year 1	$4,541k	$3,960k	$3,449k	$2,793k
Levelized cost of energy	**$0.239**	**$0.216**	**$0.198**	**$0.187**
Change versus no storage	–	**−10%**	**−17%**	**−22%**
Breakeven	–	**2.0 yr**	**2.6 yr**	**4.6 yr**
Net cash saved, 25 years	–	**$17.3M**	**$31.9M**	**$47.5M**

Table 3. Three battery sizes against the plant without storage, with the array fixed at 10 MWp. Capital includes the generators each configuration installs.

The pattern is consistent. The smallest battery breaks even fastest, because the first megawatt-hours of storage displace the most expensive diesel and release two generators for a modest outlay. The largest delivers the lowest cost of energy and almost three times the cash saving, but needs twice the capital and takes twice as long to pay back.

The capital row shows what the battery is doing. Case 2 costs $2.9 million more than the plant without storage, although the battery itself costs $4.75 million. The difference is the three generators the plant no longer needs, because the battery carries the evening peak that would otherwise set the size of the fleet. On a new-build plant, a large part of the storage is paid for by the equipment it replaces, before a liter of fuel is saved.

The cycle counts in the table set the requirement for the battery. At 240 to 355 full equivalent cycles a year, each a deep cycle in a hot climate, this is a far harder duty than the few hundred shallow cycles a grid-connected battery sees. Whether the economics above last 25 years depends on a chemistry that can sustain that duty, which is the subject of page 8.

If the array can grow

Once a battery removes the constraint, a larger solar array becomes worth building.

Where land and connection capacity allow, a larger array is the next question. Solar is the cheapest source of energy on the site, and now that the plant can keep what the array generates, the question is how far that goes. **Three array sizes were modeled (10, 15 and 20 MWp)**, with the battery re-sized at each, and the additional panels costed at $600/kWp.

From 10 to 15 MWp, each additional megawatt-peak saves more than it costs. Solar rises from 59 to 70 percent of load, fuel use falls by 56 percent against the plant as built, and the cost of energy is lowest at **$0.169/kWh** of the array sizes modeled. That is 29 percent below the plant without storage and the lowest figure in this study.

Beyond 15 MWp the right battery is already large, and growing the array further adds panels that spend more of the year curtailed. At 20 MWp the plant saves the most cash in absolute terms and removes a fourth generator, but the cost per kilowatt-hour has begun to rise and the payback has stretched to nearly seven years. **Cost of energy and cash saved do not peak at the same configuration**; which of the two to favor depends on how the plant is judged, which is the subject of page 9.

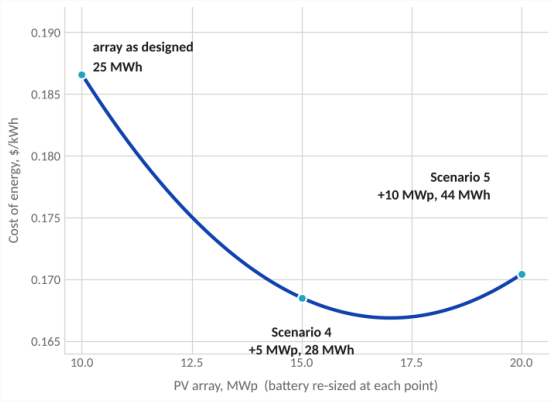


Figure 4. Cost of energy against array size, with the battery re-sized at each point. Three array sizes were modeled (10, 15 and 20 MWp), and the line between them is interpolated.

	Without storage	Case 1	Case 2	Case 3	Scenario 4	Scenario 5
CONFIGURATION						
PV array · battery	10 MWp	10 MWp 6 MWh	10 MWp 12 MWh	10 MWp 25 MWh	15 MWp 28 MWh	20 MWp 44 MWh
Battery inverter	–	1.5 MW	2.5 MW	5 MW	5.5 MW	9 MW
Generators installed	10	8	7	7	7	6
ENERGY, ANNUAL						
Solar share of load	32%	40%	48%	59%	70%	81%
Solar curtailed	55%	40%	27%	9%	27%	36%
Diesel fuel	4,628 kL	4,038 kL	3,507 kL	2,780 kL	2,029 kL	1,262 kL
Fuel saving	–	**13%**	**24%**	**40%**	**56%**	**73%**
COMMERCIAL						
Capital, year 0	$6.25M	$7.40M	$9.12M	$14.25M	$18.43M	$27.15M
Operating cost, year 1	$4,541k	$3,960k	$3,449k	$2,793k	$2,082k	$1,424k
Breakeven	–	**2.0 yr**	**2.6 yr**	**4.6 yr**	**5.0 yr**	**6.7 yr**
Net cash saved, 25 yr	–	$17.3M	$31.9M	$47.5M	$66.1M	$78.0M
Total cost of ownership, 25 yr	$151.7M	$134.4M (−11%)	$119.8M (−21%)	$104.2M (−31%)	$85.7M (−44%)	$73.7M (−51%)
NPV of savings at 8%	–	$6.2M	$10.9M	$14.0M	$18.8M	$18.3M
Levelized cost of energy	**$0.239**	**$0.216**	**$0.198**	**$0.187**	**$0.169**	**$0.170**
Change versus no storage	–	**−10%**	**−17%**	**−22%**	**−29%**	**−29%**

Table 4. All five configurations against the plant without storage. Each pays only for the generators it installs, and one generator remains online at all times in every case.

Why the Aqueous Metal Cell suits this duty

Every result above assumes the battery is bought once and is still within its rating after 25 years. This page sets out what that assumption rests on.

Parameter	Published value	Relevance to this duty
Chemistry	Aqueous Metal Cell, a nickel-hydrogen chemistry with a water-based electrolyte; in NASA service for over 30 years	Zero risk of fire from thermal runaway; no fire-suppression package; long unattended duty
Cycle envelope	Up to 3 cycles a day over a 30-year design life, or about 30,000 cycles at 100% depth of discharge	The duty here is about 1 cycle a day: under a third of the rated life, with headroom for the second and third daily cycles that load growth brings. Usable energy equals nameplate.
Temperature and cooling	Wide operating temperature of −20 °C to +60 °C, on forced air with a modest cooling load; natural air on indoor products	Far less thermal management than a lithium-ion installation needs
Rate and efficiency	C/24 to 0.55C (container), C/24 to 1.4C (cell); round-trip >87% at rack level, 25 °C, with 85% AC-to-AC assumed here	The 4-hour duty here is 0.2 to 0.25C; losses are paid for in solar that would otherwise be curtailed
Augmentation	No augmentation requirement over the design life	No mid-life capital
Building block	Energy Prism, 600 kWh containerized DC block, IP54; Energy Rack, 150 kWh indoor	25 MWh ≈ 42 containers on this site
Standards	Cell and vessel: UL 1973 held, UL 9540A tested. System: engineered to UL 9540 and IEC 62933-5-2, certification in progress	Confirm current status for your jurisdiction before a permitting submission

Table 5. Published Aqueous Metal Cell characteristics (V8 data sheets, August 2026) against the requirements of a remote solar and diesel plant. Confirm against the current data sheet before use in a specific proposal.

The duty is demanding, and it grows with the load

A grid-connected battery makes a few hundred shallow cycles a year. The battery here fills every morning and empties every evening, outdoors in a hot climate, for the life of the plant: **240 to 355 full equivalent cycles a year**, or 6,000 to 8,900 deep cycles over 25 years. A good lithium iron phosphate product is rated at around 8,000 to 10,000 cycles, so at today's load of roughly one cycle a day the two chemistries are closer than their headline ratings suggest.

The gap opens with load growth, which these plants are designed for. As demand rises, the evening peak lengthens, the array is enlarged, and the battery is asked for a second cycle a day. At two cycles a day an 8,000-cycle product lasts 11 years and a 10,000-cycle product 14 years, so augmentation or replacement falls within the 25 years. Neither appears in the cash flows reported here, because the Aqueous Metal Cell needs neither: even at three cycles a day its published rating lasts 27 years.

High ambient temperature adds to this. A cycle rating is quoted at a controlled cell temperature, so on a hot site it depends on a cooling plant holding that temperature for 25 years, hours from a technician, and if the cooling degrades, the rating degrades with it. The Aqueous Metal Cell holds its operating range on forced air with a modest cooling load, so its rating does not depend on keeping the cells at a narrow controlled temperature.

Temperature and cooling

The operating temperature runs from **−20 °C to +60 °C**, held on forced air with a modest cooling load of the order of 5 kW on a 600 kWh container for part of the year in hot climates. A chemistry with a narrow operating range needs a refrigerated enclosure sized for the worst hour of the year, with the parasitic load and the risk of failure that come with it. The installation is simpler, but it still needs conditioning: the power conversion equipment needs its own, whatever the battery. What can be claimed is a large reduction in cooling load; the plant still needs some cooling.

Safety, siting and maintenance

The electrolyte is water-based, with **zero risk of fire from thermal runaway**. Under abnormal conditions the cell's integrated pressure-relief device vents water vapor. That removes the need for a fire-suppression system and for the separation distances that dominate the siting of a lithium-ion installation. The cell and vessel hold UL 1973, and the containerized system is engineered to UL 9540 and IEC 62933-5-2, the mandatory standards for this class of installation, with certification in progress.

Where the chemistry is already working

The study above is modeled, but the chemistry is already in service. Host names are withheld, and operating data is available under a non-disclosure agreement.

Hot and humid, eastern China. An outdoor Energy Rack at an industrial site with on-site renewables and electric-bus charging, which has run a fixed charge and discharge schedule since November 2025, through a subtropical summer.

Cold climate, northern China. A project that has operated in a continental winter.

Oilfield solar shifting, northern China. An Energy Prism order for the duty modeled here: charged from the array by day and discharged into the site's peak operating hours. The first units ship in December 2026.

Remote grid, Western Australia. A project in commissioning on a remote off-grid network.

How reliable the result is, and which configuration to build

Each configuration was run 10,000 times with 18 uncertain inputs varied together.

A single result hides how much it depends on its inputs. Varying one input at a time helps, but in practice inputs move together. Each of the 18 uncertain inputs (among them fuel price and escalation, irradiance, battery and power-conversion prices, generator capital and loading, round-trip efficiency, availability, discount rate, and O&M and overhaul intervals) was given a realistic range and drawn at random, 10,000 times for each configuration.

Not one of the 50,000 runs lost money. In nine runs out of ten the smallest configuration still returns at least $1.9 million in present value, and the largest at least $9 million. The spread widens with configuration size because the larger capital commitment is exposed for longer, but the result is positive in every run.

Fuel price has the largest effect on every result. It is varied in the simulation along with the other 17 inputs, and it was also tested separately at fixed values so that its effect can be seen on its own: at $0.65/L the smallest case still breaks even in 2.8 years and the largest in 9.3 years; at $1.05/L they break even in 1.6 and 5.3 years. A higher fuel price favors the larger batteries and the larger array. Anyone applying this study to their own site should start by substituting their own delivered fuel cost.

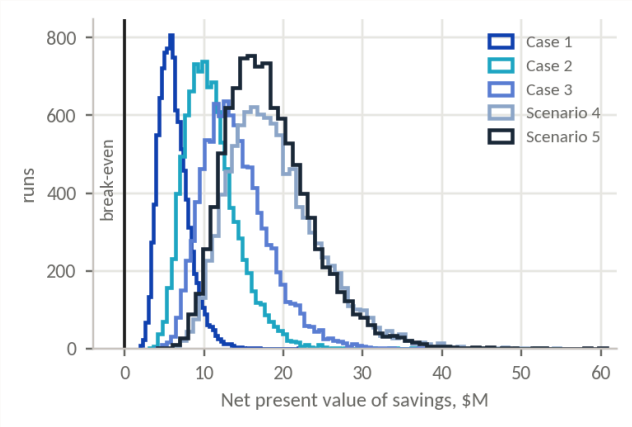


Figure 5. Net present value of savings across 10,000 runs per configuration.

Choosing a configuration

All five configurations lower the cost of energy and all five pay back. The choice between them is a question of which constraint applies: available capital, available land, or a fuel or emissions target.

Main constraint	The configuration that fits	Why
Capital	**Case 1: 6 MWh**	The smallest commitment, at $1.15M above the plant without storage; two generators are not bought, breakeven comes in two years, and solar still rises from 32 to 40 percent of load.
Generator count	**Case 2: 12 MWh**	Removes three generators from the build, the same reduction as Case 3 at two-thirds of the capital, and sits at the knee of the cost curve.
Cost per kWh with the array as built	**Case 3: 25 MWh**	The lowest cost of energy and the most cash without changing the array; curtailment falls to single figures.
Cost per kWh, with land available	**Scenario 4: 15 MWp + 28 MWh**	The lowest cost of energy in the study at $0.169/kWh. Requires a further 5 MWp of array and the connection to carry it.
Fuel displaced or emissions	**Scenario 5: 20 MWp + 44 MWh**	Fuel down 73%, solar at 81% of load, a fourth generator removed and the largest cash saving, with a longer payback.

Table 6. Matching the configuration to the main constraint.

Start with the delivered fuel price. Every saving here scales with it, and on a remote site the delivered cost, including logistics, differs substantially from the pump price. It is the first number to replace when applying this study elsewhere. **Solar targets translate into battery sizes:** on this plant, 40 percent of load from solar needs roughly 6 MWh, 50 percent needs 12 MWh and 60 percent needs 25 MWh; beyond that the array has to grow as well.

The grid-forming arrangement should also be reviewed. The floor under diesel output is the largest remaining constraint in every configuration. Moving grid forming to a grid-forming inverter raises the ceiling on solar share considerably, and it is the first thing to examine on any site where the numbers here do not go far enough.

Method, limits and conclusion

How the model works

Load and solar are supplied as 8,760 hourly values. In each hour, solar serves the load first, subject to the minimum load of the generators that must remain online. Surplus solar charges the battery within its power, energy and state-of-charge limits, and stored energy is discharged into the evening and night load. Generators meet the remainder, dispatched by rule between 25 and 85 percent of rating, with the number online following the net load and never falling below one.

The fleet required by each configuration is set by the worst evening of the year at the loading cap, plus one unit in reserve. Costs are assembled year by year in nominal terms with explicit escalation over 25 years and discounted at 8 percent.

What is included and excluded

The comparison covers the dispatchable plant and the storage. The existing 10 MWp array is excluded on both sides because it is identical in every case; where the array is enlarged, only the additional capacity is costed. Each configuration is charged for the generators it installs, which is appropriate for a new-build plant. Generator replacement, emissions or carbon value, battery auxiliary consumption, financing, tax and salvage are not included, and most of these would improve the result reported here.

Limits a reader should keep in view

Results are specific to this load shape and this solar resource. A site whose demand peaks at midday will gain less from shifting energy and more from using solar directly; a site with a flatter load will need proportionally more storage to reach the same solar share.

Generator, solar and O&M prices are indicative and should be replaced with project values. The model assumes the plant is dispatched to the rules described here: a real plant operated more conservatively (more units online, higher minimum loading) will show a smaller benefit, and one that moves grid forming off the diesel fleet will show a larger one.

The figures in this paper have been scaled and rounded from the modeled study and do not correspond to any single installation. They show the shape of the result and the scale of the potential saving, and they are not a quotation.

Conclusion

A remote plant that pairs diesel generation with a large solar array has a structural problem. It cannot keep its grid stable without a generator running at minimum load, so solar can supply only the part of the load above that floor. More than half of the array's potential output goes unused in the hours it was built for, and the generator fleet is sized for a peak that occurs for only a few hours a year.

Storage removes that limit. Modeled hour by hour across a full year, every configuration tested displaces diesel, allows a smaller generator fleet and lowers the lifetime cost of energy, by 10 to 29 percent, with payback in two to seven years and no configuration losing money in 50,000 randomized runs.

Two conclusions apply beyond this plant. **First, most of the battery's value comes from removing a constraint**: much of the energy it stores would otherwise have been curtailed, and a large part of its capital is returned in generators that are never bought ($1.9 million of the 12 MWh case's $4.75 million battery). **Second, the site conditions that make these plants attractive for solar are the same conditions that made storage hard.** High ambient temperatures, remoteness and fire separation have made conventional batteries hard to justify at the sites with the most to gain, and a chemistry that is unaffected by all three changes what can be built. The analysis can be repeated for any site with a year of hourly load and irradiance data.

LOWEST COST OF ENERGY ACHIEVED
−29%
15 MWp array with 28 MWh of storage

FASTEST BREAKEVEN
2.0 yr
6 MWh, array as designed

FUEL REDUCTION, LARGEST CASE
−73%
4,628 kL/yr down to 1,262 kL/yr

RUNS LOSING MONEY
0 of 50,000
Monte Carlo, five configurations

Talk to EnerVenue about applying this to your site.

Send a year of hourly load and irradiance data, your delivered fuel price and your generator schedule, and EnerVenue can reproduce the analysis in this paper for your plant. The Aqueous Metal Cell is designed for this duty: deep daily cycling outdoors, on air cooling with a modest conditioning load, for 30 years, with no augmentation requirement and zero risk of fire from thermal runaway.

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Definitions. *Levelized cost of energy*: the net present cost of all costs over the study period divided by the net present value of energy served. *Curtailed solar*: energy the array could have produced but did not, because the plant could not absorb it at that moment. *Grid-forming unit*: the generator held online at all times to set voltage and frequency on an isolated grid. *Full equivalent cycles*: energy discharged in a year divided by the battery's rated energy. *Breakeven*: the year in which cumulative savings equal the additional capital, undiscounted.