How Often Does a Photovoltaic–Battery System Fall Short of a Continuous 120 kW Load at 3,780 m? A Monte Carlo Study of Shortfall Timing, Size and Economic Array Sizing in Ladakh

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Abstract

The question we ask is narrow and practical: *with only PV and a battery, how often does the system fail to meet the 120 kW power demand, when do these shortfalls occur, and how much PV capacity is worth installing to minimise them.* A design that accepts occasional shortfall is cheaper than one that never fails, but its owner needs the timing and size of the shortfall, not only an annual average, because an outage on a December night is a different event from a lost hour in June. Remote high-altitude sites in Ladakh depend on diesel that is trucked over passes that close in winter. We ask whether photovoltaics (PV) and a battery alone, with no generator, fuel cell or grid, can supply a continuous 120 kW load at 3,780 m (34.3°N, 77.8°E), and, if not, when and by how much the supply falls short. We combine published irradiance data, checked against measured monthly irradiance at Leh (NIWE), with an hourly dispatch model and a stochastic daily-weather model, simulate 6,000 years of operation for each of two irradiance cases, and sweep PV size (1,100–3,500 kWp), battery size (2,400–4,000 kWh) and battery health (12 annual states from 99% to 81% of nominal, with 100, 90 and 80% reported as separate scenarios). Three results stand out. First, the battery has a cliff: below about 2,800 kWh nominal it cannot carry a December night (14.3 h) at the 130 kW winter load (120 kW plus heating) once it has faded to 80%, and short days rise from tens to over a hundred a year. Second, PV has steeply diminishing returns: each further 500 kWp costs about $32,683 (INR 31 lakh) a year and saves less shortfall than the step before. Third, for a working value of lost load of $5.27/kWh (INR 500/kWh) the energy-only cost minimum is 2,000 kWp with 2,800 kWh; we select 2,000 kWp with 3,000 kWh, about $10,543 (INR 10 lakh) a year dearer, because only the larger battery still carries the 130 kW December night at 80% health; on lifetime-average unserved energy alone the 2,800 kWh battery is the cheaper choice, so the larger battery is a reliability margin at end of life, not an economic optimum. The selected design leaves 9.6 MWh a year (0.91% of the 120 kW load; winter heating not served adds 0.7 MWh) unserved in the lower-irradiance case, in about 6.7 events and 13 short days, 64% of it in November–February (8.9 MWh when the yield is derived from the measured NIWE means). Each short day is an overnight outage of about 7 hours. The shortfall triples if the day-to-day spread of cloudiness is 0.45 instead of 0.35, and a one-week December storm or snow burial is not survivable. The weather spread and persistence remain assumptions, because no measured daily series was obtained. We provide the complete simulation and plotting code.

Keywords: off-grid photovoltaics; battery storage; Ladakh; high altitude; Monte Carlo simulation; loss of load; array sizing.

Note on currency. 1 USD = INR 94.85 (Wise, 24 November 2026). Dollar values will drift from rupee values as the exchange rate moves.

1 Introduction

The question we ask is narrow and practical: *with only PV and a battery, how often does the system fail to meet the 120 kW power demand, when do these shortfalls occur, and how much PV capacity is worth installing to minimise them.* A design that accepts occasional shortfall is cheaper than one that never fails, but its owner needs the timing and size of the shortfall, not only an annual average, because an outage on a December night is a different event from a lost hour in June.

Power at remote sites in Ladakh is commonly provided by diesel generators. Fuel is trucked in, and winter road closures are a recognised problem for Leh [5]. Solar resource at the site is excellent, with an annual mean global horizontal irradiance above 255 $\mathrm{W\,m^{-2}}$ over Leh and Kargil [1], but winter is the weak season, and a load that runs 24 hours a day at 120 kW needs storage for the night and for overcast spells.

Related work provides context, not an answer: A solar–hydrogen–battery microgrid at Chushul, Ladakh, at about 4,500 m and −40°C combines 3.7 MW of PV, an electrolyser, hydrogen storage, a battery and a 200 kW fuel-cell system to supply 200 kW day and night all year, which is 18.5 kWp of PV per kW of load [6]. We do not know of published results for a PV–battery system without hydrogen at this altitude.

Contributions. (i) A transparent, reproducible dispatch and weather model for a PV–battery system at 3,780 m, verified for energy conservation, against documented figures for the site (Section 5.1) and against measured monthly irradiance at Leh (Section 5.2). (ii) A map of shortfall by year, month, week and day for one design, with simulated hourly detail of typical and extreme events. (iii) An economic analysis of PV and battery size that includes battery ageing, which moves the answer because of the battery cliff. (iv) Sensitivity and stress tests that show which assumptions matter most.

2 Site and data

2.1 Location, climate and constraints

- **Location and altitude.** Ladakh, 34.3°N, 77.8°E, 3,780 m. Regional context for temperature: the Ladakh-wide mean 2-m temperature (ERA5-Land, 1981–2020) runs from about −22°C in the coldest month to about +5°C in the warmest [1]. This is an average over all of Ladakh, including terrain far higher than the site, not a measurement at the site coordinates; the IMD normals for Leh (3,513 m) are warmer, with the average of the daily maximum and minimum about −6°C in January and +22°C in July [17]. Design extremes are −30°C (fuel) and −35°C (PV string voltage).
- **Fuel logistics.** Diesel is trucked in, and winter road closures are a recognised problem [5].
- **Factors we do not model.** Seismic loading (the site is in the active Karakoram fault region), altitude limits of IT hardware (many servers are rated to about 3,000 m), altitude ratings of power-conversion products (3,000 m for a commonly specified multicluster box), procurement restrictions in border regions, and snow-load structural design.

2.2 Load

The available documentation gives a 120 kW target and a 108 kW stated peak, without saying which governs. We adopt the more demanding reading: 120 kW *continuous* (2,880 kWh/day, 1,051 MWh/yr), plus 10 kW of winter heating from October to March (130 kW, 3,120 kWh/day), giving 1,095 MWh/yr in total. Waste heat from GPUs or other IT equipment is not credited. When supply is short, the 120 kW load is served first and the heating is shed first.

2.3 Initial configuration documented for the site

A draft configuration exists for the site: 350 kWp of PV, 740 kWh of LFP battery, two power-conversion cabinets of about 100 kW each, and one 250 kVA diesel generator derated by 25% to 150 kW. Its documented performance is about 53% of energy from solar, about 190,000 L of diesel a year, a single generator running about 4,100 h a year, and a blackout within about 5 h (4 h in a December storm test) if that generator fails. Documented calculations also state that December needs about 980 kWp of PV for the energy balance and that a 7-day December storm at 20% PV needs about 26 MWh of nominal storage, 35 times the 740 kWh. We could not inspect the design itself, so we use these figures only as external checks on our model (Section 5.1). The same documentation assumes a staged build; we analyse phased deployment in Section 5.7.

2.4 Solar resource

Source data. Verma and Singh [1] give the 40-year mean global horizontal irradiance (GHI) from MERRA-2 ($0.5° \times 0.625°$ grid) as 24-hour mean $\mathrm{W\,m^{-2}}$. Annual mean GHI is above $255\,\mathrm{W\,m^{-2}}$ over Leh and Kargil, i.e. about $6.1\,\mathrm{kWh\,m^{-2}\,day^{-1}}$, and monthly values run from about 115–215 $\mathrm{W\,m^{-2}}$ (December–January) to 295–375 $\mathrm{W\,m^{-2}}$ (June). We digitised their Fig. 6 for south and east Ladakh and scaled it to the annual figure; monthly values carry about $\pm 20\,\mathrm{W\,m^{-2}}$ of reading uncertainty. All inputs of this section are stored, with their sources, in the JSON files documented in Section 3; the cross-checks against independent sunshine and radiation data are in Section 3.5.

Cross-checks. Other published figures differ by about 10% on the annual mean, with winter the weakest (Table 1). The MERRA-2 grid cell is coarse for terrain as rugged as Ladakh, and the interpolation of Verma and Singh to a finer map adds no information on slope, valley or local cloud, so we treat the digitised values as a regional prior and not as a site value. The one set of ground measurements we found, the NIWE monthly means for Leh, is used as a benchmark in Section 5.2.

Source	Figure quoted	Use here
Verma & Singh 2022 [1]	$255\,\mathrm{W\,m^{-2}}$ annual (about $6.1\,\mathrm{kWh\,m^{-2}\,d^{-1}}$)	"Paper" case
Santra (ICAR), Leh [2]	$5.54\,\mathrm{kWh\,m^{-2}\,d^{-1}}$ horizontal; 6.36 on a 35° tilt	"Mid" case (paper $\times 0.91$)
CSE via Down To Earth [3]	$5.29\,\mathrm{kWh\,kWp^{-1}\,d^{-1}}$ average for Ladakh	Check on yield
IISc/CES, Himachal >3500 m [4]	about 2.5–3 $\mathrm{kWh\,m^{-2}\,d^{-1}}$ in winter months	Winter lower bound
NIWE station 1832, Leh [20]	$5.32\,\mathrm{kWh\,m^{-2}\,d^{-1}}$ annual GHI (measured monthly means, 2.85 in January to 7.41 in June)	Measured benchmark (Section 5.2)

Table 1: Irradiance sources.

We define three cases: **Paper** (digitised values), **Mid** (paper $\times 0.91$, anchored to the Leh annual mean) and **Low** (November–February $\times 0.75$, other months $\times 0.88$). We simulate Mid and Low, and use Low as the design basis. Mid gives 5.3–5.9 $\mathrm{kWh\,kWp^{-1}\,d^{-1}}$ from spring to autumn, consistent with the 5.29 average.

Conversion to PV output. Fixed tilt 45°; tilt gain over horizontal 1.45–1.50 in winter and 0.96–1.00 in summer; performance ratio 0.80; snow-loss factors 0.90 (December, January), 0.93 (February), 0.95 (November), 0.97 (March). These are engineering estimates, not measurements.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mid, kWh/kWp/d	3.9	4.5	5.1	5.4	5.7	6.0	5.7	5.5	5.5	5.2	4.2	3.5
Low, kWh/kWp/d	3.2	3.7	4.9	5.2	5.5	5.8	5.5	5.3	5.3	5.0	3.5	2.9
NIWE-derived (check), kWh/kWp/d	3.2	3.5	4.5	4.7	4.7	4.6	4.6	4.8	5.2	5.6	4.5	3.6
350 kWp, Mid, MWh/d	1.4	1.6	1.8	1.9	2.0	2.1	2.0	1.9	1.9	1.8	1.5	1.2
% of daily load	44	50	57	66	69	73	69	67	67	58	47	39
350 kWp, Low, MWh/d	1.1	1.3	1.7	1.8	1.9	2.0	1.9	1.9	1.9	1.8	1.2	1.0
% of daily load	36	42	55	63	67	71	67	65	65	56	39	32
2,000 kWp, Mid, MWh/d	7.8	9.0	10.2	10.8	11.4	12.0	11.4	11.0	11.0	10.4	8.4	7.0
% of daily load	250	288	327	375	396	417	396	382	382	333	269	224
2,000 kWp, Low, MWh/d	6.4	7.4	9.9	10.4	11.0	11.6	11.0	10.6	10.6	10.1	6.9	5.8
% of daily load	206	238	316	363	383	403	383	369	369	322	222	185

Table 2: Monthly PV yield on the tilted plane (data) and the daily energy of two array sizes against the daily load (3.12 MWh/d October–March, 2.88 MWh/d April–September). The Low case in December is about 2.9 kWh/kWp/d. The NIWE-derived row is built from measured irradiance in Section 5.2.

A mean December day at 2,000 kWp exceeds the daily load in energy, but only in daylight hours; the problem is night and overcast spells, not the daily total.

2.5 Cost data

Annualised cost covers PV and battery only. Items common to any design (cabinets, building, civil works, thermal sink, equipment transport) are left out.

Item	Value used	Anchor / status
PV, installed	\$538/kWp (INR 51,000/kWp) (O&M \$6.33/kWp/yr (INR 600/kWp/yr); 25 yr)	Karnataka commission ground-mount benchmark \$338,956/MW (INR 321.5 lakh/MW) [11], times 1.6 for altitude, snow structure and logistics (our factor)
Battery, installed	\$316/kWh (INR 30,000/kWh) (1.5% O&M; 12 yr)	Indian C&I LFP \$158–264/kWh (INR 15,000–25,000/kWh) at 2 MWh and above, stated without a source in an opinion piece by a solar-company executive [12], not a price survey; remote premium is ours
Diesel (reference only)	\$1.16/L (INR 110/L) delivered	Leh retail \$1.00/L (INR 94.65/L), 7 Sep 2026 [10]; the rest is our trucking allowance
Generator (reference only)	\$0.04/kWh (INR 4/kWh) running; fuel $F = 0.08415\,P_{\text{rated}} + 0.246\,P_{\text{out}}$ L/h, $P_{\text{rated}} = 200$ kW	Documented fuel curve; running cost is our assumption
Finance	10% discount rate	Our assumption

Table 3: Cost inputs. None is a vendor quote. The diesel and generator rows are used only to put a reference cost on firm power (Section 4.7).

At a generator output of 150 kW the fuel curve gives 0.358 L/kWh, so diesel generation would cost about \$0.45/kWh (INR 43/kWh) at the margin.

3 Data catalogue: JSON files and sources

Every number that enters the simulation, and every number used to cross-check the inputs, is stored in a JSON file together with its source. This section documents those files, the sources behind them,

how the code uses them, and what could not be obtained. The files are in the folder `data/json`; the script `ladakh_pv_battery_mc.py` reads them and cites their sources in its console output, in `out/data_sources_used.json` and at the foot of every figure.

3.1 Format and traceability

The data package of the study consists of seventeen CSV files (numbered 00–16). Files 09 and 16 were added after a review that pointed to the NIWE ground measurements at Leh (Section 5.2); the original numbering had no file 09. The script `csv_to_json.py` converts each of them to one JSON file with the same name, and writes a catalogue `_catalogue.json` with the register of sources. A JSON file has the structure in Table 4. Numbers stay numbers, empty cells become `null`, and a per-row `source` column that is the same on every row is moved to the file-level `sources` block, so that no information is lost. Four files keep a source field on each record because their records come from different places (J00, J07, J12 and J14; in J12 the field names the anchor and the status of each row).

Field	Content
`id`, `title`, `description`	Name of the dataset (the file stem) and what it contains.
`data_type`, `role`	Kind of data (astronomical calculation, satellite-derived, station observation, forecast, published quotation, assumption, derived) and its role in the study (found data, model input, derived, verification, documentation).
`sources`	List of sources. Each entry has `name`, `citation`, `url` (null if none is recorded), `retrieved` (date, if recorded), `source_type`, `status` and a `source_id` that points into the register (Table 5).
`provenance`	How the numbers were obtained or computed from the source (transcribed, digitised, scaled, derived with a stated formula).
`caveats`	Known weaknesses of the data.
`used_by_code`	Whether and where the simulation script uses the data.
`columns`, `n_records`, `records`	The data: one object per CSV row.
`numeric_values` (J13, J14 only)	Numeric restatement of values that the CSV holds as text (for example the battery window `0.10-0.95`), so that code need not parse strings.

Table 4: Structure of every JSON data file.

Traceability in the outputs has three layers. First, the script loads data through a small class (`DataStore`) that records each dataset it touches and the purpose; at the start of a run it prints the sources of the datasets loaded, and at the end it prints a report of every dataset used, what it was used for, its sources and its caveats. Second, the same report is written to `out/data_sources_used.json` and into `out/summary.json`. Third, every figure carries a line of small print with the datasets behind it, for example "Input data: [10] Verma & Singh 2022; Santra (ICAR); authors' assumption". The numbers in square brackets are the file numbers of this section (J10 and so on).

3.2 Register of sources

Table 5 lists the sources that appear in the JSON files, what kind of data each is, where it is, and which files it feeds. Sources fall into five groups. (i) *Astronomical calculation*: Tutiempo day length, which depends on date and latitude only. (ii) *Sunshine and radiation products*: CAMS sunshine hours via a secondary site, an older compiled sunshine guide, and a 15-day radiation forecast. (iii) *Station observations*: IMD normals, transcribed from a secondary page, and the monthly means of measured GHI, DNI and DHI at the NIWE station in Leh, transcribed from a secondary copy of the table. (iv) *Published irradiance values*: Verma and Singh, Santra, Down To Earth and the IISc report. (v) *Cost, price and site information*: trade-press and price pages for costs, and site documentation that we could not inspect directly.

Source	Type	Location	Feeds files
Tutiempo Network, daylight hours, Leh [13]	astronomical calculation	https://tutiempo.net/daylight-hours/leh.html; retrieved 2026-11-23	J01, J02, J15
Tutiempo Network, solar radiation forecast, Leh [14]	weather forecast model	https://tutiempo.net/solar-radiation/leh; retrieved 2026-11-23	J06
NomadSeason, climate of Leh [15]	satellite-derived (secondary site)	https://nomadseason.com/climate/india/ladakh/leh	J03, J08
P. J. Tyson, Sunshine Guide to Leh [16]	compiled climatology	https://climates.com/ASIA/PDF/IND11ASA.pdf	J04, J08
India Meteorological Department normals for Leh, as shown on Wikipedia [17]	station observations (secondary transcription)	https://en.wikipedia.org/wiki/Leh	J05
NIWE, Solar Radiation Resource Assessment [20]	station observation (ground-measured, secondary transcription)	https://niwe.res.in/static/pdf/Ladakh_Presentation_06.12.2019.pdf	J09, J16
P. Santra, Scope of Solar Energy in Cold Arid Region of India at Leh Ladakh, Annals of Arid Zone [2]	published (secondary snippets)	https://doi.org/10.56093/aaz.v54i3-4.63046	J07, J10, J11
ResearchGate figure pages	published (secondary quote)	no URL recorded	J07
Verma & Singh (2022) [1]	reanalysis (MERRA-2)	https://doi.org/10.5194/isprs-archives-XLIII-B4-2022-183-2022	J07, J10, J11, J14
Down To Earth, Solar power in cold desert [3]	news article quoting CSE	https://www.downtoearth.org.in/climate-change/solar-power-in-cold-desert-ladakhs-abundant-sun-can-be-harnessed-for-renewable-electricity-generation-and-heating	J07
IISc Centre for Ecological Sciences, Technical Report 131, Solar potential of the Himalayan landscape [4]	technical report	https://wgbis.ces.iisc.ac.in/biodiversity/pubs/ces_tr/TR131/section8.htm	J07
FAO-56 default Angstrom-Prescott coefficients [18, 19]	standard method	no URL recorded	J08, J16
SolarQuarter, Karnataka sets new solar tariffs [11]	trade press	https://solarquarter.com/2025/07/10/karnataka-sets-new-solar-tariffs-and-eases-rules-to-boost-distributed-solar-adoption-in-fy26/	J12
Y. Tarwadi, opinion piece in pv magazine India, 14 Sep 2026 [12]	industry commentary (opinion piece)	https://www.pv-magazine-india.com/?p=16741	J12
Diesel price in Leh, 7 September 2026 [10]	price listing	https://energy.thecore.in/fuel/petrol-price/leh; retrieved 2026-09-07	J12
Site documentation for the Ladakh installation	private site documentation	no URL recorded	J13, J14

Source	Type	Location	Feeds files
Authors' study assumption / engineering estimate	assumption	no URL recorded	J10, J11, J12, J13
Authors' own calculation	derived	no URL recorded	J00, J15, J16
MNRE, Decentralised RE and green hydrogen for Leh [5]	government document	https://nghm.mnre.gov.in/admin/uploads/resources/172710454691863Decentralised_RE_GH2_waste_water_compressed.pdf	J14
pv magazine India, NTPC inaugurates solar-hydrogen-based microgrid at Chushul [6]	trade press	https://www.pv-magazine-india.com/2025/11/28/ntpc-inaugurates-solar-hydrogen-based-microgrid-at-chushul	J14
O. P. Madan et al., Surface wind at Leh, MAUSAM 43, 155, 1992 [7]	journal article	https://doi.org/10.54302/mausam.v43i2.3365	J14
B. Ravindra et al., Wind pattern near Merak village, Pangong Tso, Exp. Astron. 59, 4, 2025 [8]	journal article	https://doi.org/10.1007/s10686-024-09972-6	J14
P. K. Sharma et al., Wind-solar hybrid potential in Jammu and Kashmir, Int. J. Ambient Energy 41, 1026, 2020 [9]	journal article	https://doi.org/10.1080/01430750.2018.1501743	J14

Table 5: Register of sources cited inside the JSON files (field `sources`). Every JSON file lists the entries from this register that apply to it. "No URL recorded" means that the data package does not record a locator for that source, and none was invented.

3.3 The datasets

Each paragraph below documents one JSON file. "Found data" is data we retrieved for Leh or Ladakh and did not produce with the simulator; "derived" marks values computed from other files with the formula stated; "model input" marks the data that drive the simulation.

J00 `00_data_sources_index.json`. One row per source: what it offers, what was retrieved and what was not. Documents the search, not a data series. *Type:* index (documentation; 14 records). *Sources:* authors' calculation. *Provenance:* Compiled by the study authors in compile_data.py (part A9). *Caveats:* 'status' says RETRIEVED / SNIPPET ONLY / NOT RETRIEVED; only retrieved sources feed other files. *Use in the code:* no (documentation only; printed in the data-source report).

J01 `01_leh_daylight_by_day_2026.json`. Sunrise-to-sunset duration (hh:mm, minutes, hours) for the 365 days of 2026. *Type:* astronomical calculation (no weather) (found data; 365 records). *Sources:* Tutiempo daylight 2026 [13]. *Provenance:* Transcribed by hand from the web page into compile_data.py; monthly sums reproduce the page's monthly totals with 0 min difference (file 02). *Caveats:* Astronomical day length only; says nothing about cloud. Page location is the town of Leh (34.15 N), not the 34.3 N site. *Use in the code:* yes: verification V9 (model day length vs astronomical day length) and fig_inputs panel (b).

J02 `02_leh_daylight_monthly_2026.json`. Published monthly day/night totals and the sum of the 365 transcribed daily values. *Type:* astronomical calculation (found data; 12 records). *Sources:*

Tutiempo daylight 2026 [13]. *Provenance:* Published totals from the page; the daily sums are computed in compile_data.py. *Caveats:* difference_minutes is 0 for all months, i.e. the transcription is consistent with the page. *Use in the code:* yes: transcription check printed with the data report.

J03 `03_leh_sunshine_hours_cams_2017_2022.json.` Monthly sunshine hours, mean daily daylight, derived sunshine fraction, UV index. *Type:* satellite-derived (Copernicus CAMS) via a secondary site (found data; 12 records). *Sources:* CAMS via NomadSeason [15]. *Provenance:* Transcribed from the site; sunshine_hours_per_day and sunshine_fraction_derived are computed by the authors. *Caveats:* Grid-cell values, secondary site. The site's ERA5 temperature and precipitation columns were not used because they do not match IMD station values. *Use in the code:* yes: fig_inputs panel (c).

J04 `04_leh_sunshine_guide_climates_com_2003.json.` Sunshine hours per day, blue-sky area, dry, snowy, thunder and frosty-morning percentages. *Type:* compiled climatology (found data; 12 records). *Sources:* Tyson 2003 (climates.com) [16]. *Provenance:* Transcribed; decimal hours and sunshine fraction derived by the authors. *Caveats:* Method undocumented. Disagrees strongly with CAMS in winter (Jan 3.8 vs 7.4 h/day). *Use in the code:* yes: fig_inputs panel (c).

J05 `05_leh_imd_climate_normals_via_wikipedia.json.` Monthly record/mean temperatures, precipitation, rain days, relative humidity at 17:30 IST. *Type:* station observations (secondary transcription) (found data; 13 records). *Sources:* IMD via Wikipedia [17]. *Provenance:* Transcribed from the Wikipedia table that cites IMD. *Caveats:* No sunshine or radiation rows. The two precipitation rows and the printed annual totals are internally inconsistent; use temperatures only. *Use in the code:* no (context for the paper's temperature statements).

J06 `06_leh_radiation_forecast_15day_2026-11-23.json.` Hourly W/m^2 (07-16 h) and daily Wh/m^2 totals, with ratio to the clearest day. *Type:* FORECAST model output (not observation) (found data; 15 records). *Sources:* Tutiempo radiation forecast [14]. *Provenance:* Transcribed from the page on 2026-11-23; ratio_to_clearest_day computed by the authors. *Caveats:* Forecast, only 15 days. Used only to illustrate the day-to-day spread of clear and overcast days, not to calibrate the weather model. *Use in the code:* yes: fig_inputs panel (d) (illustration of daily variability).

J07 `07_published_irradiance_figures_leh_ladakh.json.` Annual and monthly irradiance figures quoted from papers and secondary pages. *Type:* quoted from publications (found data; 12 records). *Sources:* Santra (ICAR) [2]; ResearchGate Leh review; Verma & Singh 2022 [1]; CSE/Down To Earth [3]; IISc CES TR131 [4]. *Provenance:* Each row names its own source in the 'source' field; most are secondary quotations. *Caveats:* Several figures are not reconciled with one another (e.g. 5.54 annual mean vs a 7-7.5 'maximum'). *Use in the code:* yes: cross-checks printed in the data-source report; Table 'irr' of the paper.

J08 `08_indirect_estimate_ghi_from_sunshine.json.` Monthly extraterrestrial radiation H0 and GHI estimated from the CAMS and climates.com sunshine fractions. *Type:* derived estimate (derived; 12 records). *Sources:* FAO-56 / Klein 1977 [18, 19]; CAMS via NomadSeason [15]; Tyson 2003 (climates.com) [16]. *Provenance:* H0 from Klein (1977) representative days at 34.15 N; H = H0 (a + b S/S0), a=0.25, b=0.50. *Caveats:* Default FAO-56 coefficients, not site-calibrated; high-altitude coefficients are typically larger, so these estimates are likely low. *Use in the code:* yes: fig_inputs panel (a) (plausibility check of the yield inputs).

J09 `09_niwe_leh_srra_monthly_ghi_dni_dhi.json.` Monthly long-term mean irradiance (W/m^2, 24-h mean) of global horizontal, direct normal and diffuse horizontal radiation at the

NIWE station in Leh, and the same values as daily irradiation (kWh/m^2/day). *Type:* station observation (ground-measured monthly means; secondary transcription) (found data; 12 records). *Sources:* NIWE SRRA Leh [20]. *Provenance:* Table 'Data_for_Monthly_Long_Term_Aver' of the NIWE 2019 Ladakh presentation, transcribed and then checked in review against page 14 of the original presentation (all 36 values agree; largest difference 5e-7 W/m^2); kWh/m^2/day = W/m^2 × 24/1000 (largest difference to the CSV columns 5e-5). The file carries the station-register coordinates and elevation, which agree with the NIWE register page retrieved on 24 November 2026; the presentation prints 34.1288986°N, 77.4600983°E. The presentation gives no averaging period or data completeness. *Caveats:* Station is 34.3 km from the study site with the register coordinates (36.6 km with those printed in the presentation) and 528 m lower (3,252 m against 3,780 m). Monthly means only: no daily or hourly values, so the day-to-day spread and persistence of the weather model cannot be estimated from it. *Use in the code:* yes: niwe_crosscheck.py (benchmark of the Mid and Low cases and the NIWE-derived yield case); not read by ladakh_pv_battery_mc.py.

J10 `10_pv_yield_monthly_mid_low.json`**.** Mid yield (kWh/kWp/day, 45° tilt, PR 0.80, snow loss included), Low scale factors, daily load, array energy at 2000 kWp. *Type:* model input (derived from published irradiance) (model input; 12 records). *Sources:* Verma & Singh 2022 [1]; Santra (ICAR) [2]; authors' assumption. *Provenance:* Paper case = digitised Verma & Singh monthly GHI scaled to the annual figure; Mid = Paper × 0.91, anchored to the Santra Leh annual mean (5.54 kWh/m^2/day); Low = Nov-Feb × 0.75, other months × 0.88. Conversion to the tilted plane and snow factors are engineering estimates. *Caveats:* Monthly digitised values carry about ±20 W/m^2 reading uncertainty. Tilt gain, performance ratio and snow-loss factors are estimates, not measurements. *Use in the code:* yes: MID, LOW_FACTOR, monthly load, Oct-Mar winter flag.

J11 `11_irradiance_case_definitions.json`**.** Text definitions of Paper, Mid, Low, the irradiance-to-PV conversion and snow-loss factors. *Type:* model definition (model input; 5 records). *Sources:* Verma & Singh 2022 [1]; Santra (ICAR) [2]; authors' assumption. *Provenance:* Authors' definitions; numbers are implemented through file 10. *Caveats:* Conversion and snow factors are engineering estimates. *Use in the code:* yes: definitions are printed in the data-source report.

J12 `12_cost_assumptions.json`**.** PV and battery capex, O&M, lives, discount rate, diesel price, generator curve, value of lost load. *Type:* assumptions anchored to published prices (model input; 11 records). *Sources:* SolarQuarter 2025 [11]; pv magazine India (opinion) [12]; energy.thecore.in 2026 [10]; authors' assumption. *Provenance:* Each row's 'source_or_status' states the anchor and which part is the authors' own factor. None is a vendor quote. *Caveats:* PV x1.6 and battery remote premium, trucking allowance, O&M, lives and discount rate are the authors' assumptions. *Use in the code:* yes: COST dictionary; diesel and generator rows used only for the reference cost of firm power.

J13 `13_simulation_parameters.json`**.** Site coordinates, load, battery window, efficiency, C-rate, health levels, weather-model parameters, sample sizes. *Type:* model input (site facts and assumptions) (model input; 15 records). *Sources:* site documentation; authors' assumption. *Provenance:* Site, load and selected design come from the site documentation; battery window, round trip, weather parameters are assumptions. *Caveats:* The clearness-factor spread (0.35) and lag-1 correlation (0.6) are assumptions; fetch_nasa_power_leh.py would estimate them from NASA POWER data. *Use in the code:* yes: LAT, CORE_KW, HEAT_KW, battery limits, SOH levels, SIGMA, RHO, clip, default design, sample sizes.

J14 `14_site_documentation_facts.json`**.** Initial configuration and its documented performance, December requirement, storm storage, temperatures, wind and Chushul references. *Type:* docu-

mented facts (model input / context; 13 records). *Sources:* site documentation; Verma & Singh 2022 [1]; MNRE [5]; Madan et al. 1992 [7]; Exp. Astron. 59 (2025) [8]; Sharma et al. 2020 [9]; pv magazine India 2025 [6]. *Provenance:* Each row names its source in the 'source' field. *Caveats:* 'documented for the site' facts could not be independently verified. *Use in the code:* yes: initial configuration (350 kWp / 740 kWh, 53 % solar share) used in verification V6-V8.

J15 `15_model_vs_astronomical_daylength.json`**.** Day length from the simulator's declination formula at 34.3 N and 34.15 N against the Tutiempo astronomical value, per day. *Type:* derived comparison (verification; 365 records). *Sources:* authors' calculation; Tutiempo daylight 2026 [13]. *Provenance:* Model: Cooper declination, no refraction. Reference: file 01. *Caveats:* The simulator's declination formula ignores refraction and the solar disc and is 5-19 min shorter than the astronomical day (about 8 min in January, 16-19 min in Sep-Nov, 11 min on annual average); the error is on the conservative side for PV. *Use in the code:* yes: recomputed in verification V9 and compared with this file.

J16 `16_niwe_transposed_yield_vs_cases.json`**.** Monthly clearness index, closure (GHI-DHI)/DNI, Klein Rb, tilted-plane irradiation and PV yield derived from the NIWE means, with the Mid and Low yields and their ratios. *Type:* derived comparison (verification; 12 records). *Sources:* NIWE SRRA Leh [20]; authors' calculation; FAO-56 / Klein 1977 [18, 19]. *Provenance:* Direct part (GHI-DHI) × Klein (1977) monthly Rb for 45° tilt at 34.14 N; isotropic diffuse; ground albedo 0.20 (0.50 in the snow-albedo column for Nov-Feb); PR 0.80; the snow-loss factors of file 11. *Caveats:* Isotropic-sky transposition, no temperature or soiling model; NIWE site is 528 m lower than the study site; averaging period of the NIWE table unknown. *Use in the code:* yes: written by niwe_crosscheck.py, which also runs the selected design with this yield as a third case.

3.4 Where each model parameter comes from

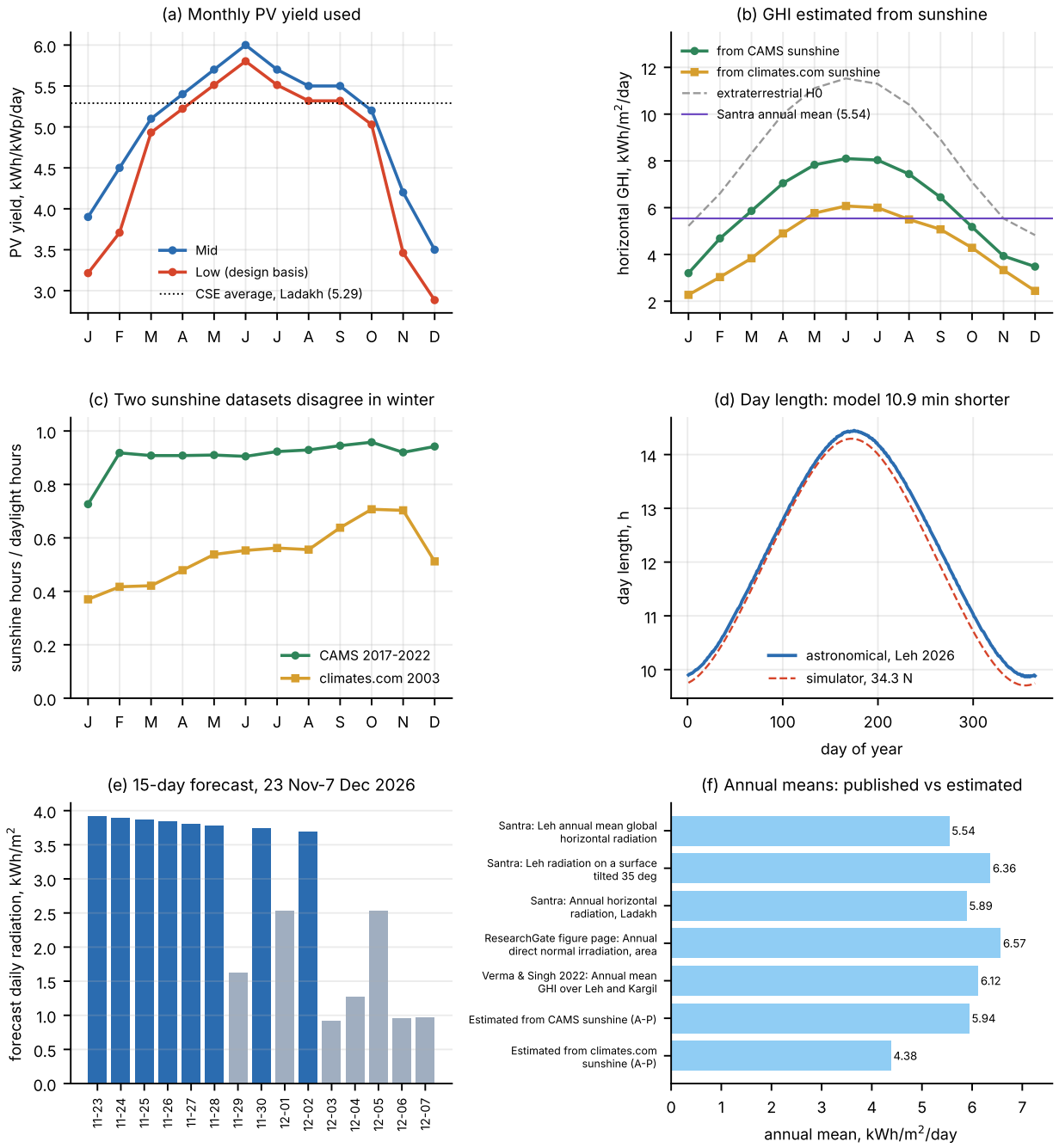
Table 6 links the parameters of the simulator to JSON records. Nothing in the numerical part of the script is typed in, except the scenario settings of the experiments themselves (grid values, the storm start date and the PV fraction during the storm tests) and the astronomical constants of the day-length formula.

Parameter	File	Record or field	Code name
Latitude, altitude	J13	latitude, altitude	`LAT`, `ALT`
Month lengths, winter flag (Oct–Mar), daily load	J10	days, winter_month_oct_mar, daily_load_kwh	`MONTH_DAYS`, `WINTER`
Mid yield, kWh/kWp/day	J10	mid_kwh_per_kwp_day	`MID`
Low case scale (0.75 / 0.88 over 0.91)	J10	low_scale_vs_paper, mid_scale_vs_paper	`LOW_FACTOR`, `LOW`
Continuous load, winter heating	J13	core_load, winter_heating	`CORE_KW`, `HEAT_KW`
Battery window, round trip, C-rate, health levels	J13	battery_soc_window, ...	`BAT_EMIN/EMAX/RT/CPOW`, `SOH_LEVELS`, `SOH_SCEN`
Weather model σ, ρ, clip	J13	clearness_sd, clearness_ar1_correlation, clearness_clip	`SIGMA`, `RHO`, `FMIN/FMAX`
Selected design, sample sizes	J13	selected_design_*, monte_carlo_years	`DEFAULT_PV/BATT`, `-years`
PV and battery cost, O&M, life, discount rate	J12	pv_installed_cost, ..., discount_rate	`COST`
Initial configuration and documented solar share	J14	numeric_values	`INITIAL_CONFIG`
Astronomical day length (verification V9)	J01, J02, J15	daylight_hours, difference_minutes	`verify_daylength()`
Measured benchmark and NIWE-derived yield case	J09, J16	all fields (niwe_crosscheck.py)	`niwe_crosscheck.py`
Cross-checks and Fig. 1	J03, J04, J06, J07, J08	sunshine, forecast, published figures	`make_input_figure()`

Table 6: Parameters of the simulator and the JSON records they are read from.

3.5 What the found data say about the inputs

Figure 1 puts the input data and the independent datasets side by side. Six points follow, and the last one limits how far the results can be trusted.



Input data: [10] Verma & Singh 2022; Santra (ICAR); authors' assumption | [08] FAO-56 / Klein 1977; CAMS via NomadSeason; Tyson 2003 (climates.com) | [03] CAMS via NomadSeason | [04] Tyson 2003 (climates.com) | [01] Tutiempo daylight 2026 | [06] Tutiempo radiation forecast | [07] Santra (ICAR); ResearchGate Leh review; Verma & Singh 2022; CSE/Down To Earth; IISc CES TR131

Figure 1: Input data and cross-checks, all read from the JSON files. (a) Monthly PV yield used (J10). (b) GHI estimated from sunshine fraction with default Angström–Prescott coefficients (J08) against the published annual mean (J07). (c) Sunshine fraction from two datasets (J03, J04). (d) Simulator day length against Tutiempo's astronomical day length (J01). (e) Daily radiation in the 15-day forecast (J06). (f) Annual means published or estimated (J07, J08). The source of each dataset is printed at the foot of the figure.

1. **The day length of the model is conservative.** The simulator's declination formula gives day lengths 5–19 min shorter than the astronomical day length of Leh for 2026 (mean −10.9 min; about 8 min in January and 16–19 min from September to November). This is check V9 in Table 8. The transcription of the 365 daily values reproduces the monthly totals of the source page exactly (J02: difference 0 min in every month).

2. **The two sunshine datasets disagree in winter.** The CAMS-based figures give 4034 h of sunshine a year, 91% of the 4446 h of daylight, with a winter sunshine fraction of 0.73 in January. The older compiled guide gives 2403 h, with 0.37 in January. Angström–Prescott estimates of annual mean GHI are therefore 5.94 $\mathrm{kWh\,m^{-2}\,d^{-1}}$ from CAMS and 4.38 from the older guide, against 5.54 (Santra) and about 6.1 (Verma and Singh). The CAMS-based estimate lies between those two published values; the older guide implies far less sun than any of the published figures. The default coefficients are not calibrated for this altitude and are likely to underestimate.

3. **The yield inputs are plausible but not independently confirmed.** The day-weighted annual mean of the Mid yield is 5.02 $\mathrm{kWh\,kWp^{-1}\,d^{-1}}$ and of the Low yield 4.66. The Mid value is below the 5.29 average quoted for Ladakh [3], which is consistent with our choice to include snow losses and to anchor Mid below the digitised values. The Low case, which we use as the design basis, is 7% below Mid on the annual mean and 18% below it in November to February.

4. **A measured monthly benchmark from NIWE lies between the Mid and Low winter cases.** The NIWE station in Leh (J09) gives an annual GHI of 5.32 $\mathrm{kWh\,m^{-2}\,d^{-1}}$, 4% below the Mid anchor and 13% below the digitised MERRA-2 mean. Converted to a 45° plane (J16), the November–February yield is 3.69 $\mathrm{kWh\,kWp^{-1}\,d^{-1}}$, between Low (3.32) and Mid (4.03). The comparison, and its limits, are in Section 5.2.

5. **The forecast shows how variable winter days are, and is used for illustration only.** In the 15-day radiation forecast for 23 November to 7 December 2026 (J06) the daily totals range from 0.92 to 3.92 $\mathrm{kWh\,m^{-2}}$ (mean 2.75), and 5 of 15 days are below half of the clearest day. This is a model forecast, not an observation, and 15 days are too few to estimate σ or ρ; we do not use it to calibrate the weather model.

6. **No measured daily or hourly irradiance for Leh was obtained.** Only the NIWE monthly means above are measured, and monthly means say nothing about day-to-day spread. The clearness-factor spread $\sigma = 0.35$ and correlation $\rho = 0.6$ remain assumptions, tested in Section 5.6. This is the main gap in the data.

3.6 Data not obtained

Table 7 lists sources that we tried or identified and did not use, taken from the index file J00 and from a later review. They are listed because they are the natural next step: any of the first four would replace the synthetic weather model by measured or modelled daily data.

Source	What it would add	Status
NIWE station 1832, one-minute and hourly records [20]	Measured GHI, DNI and DHI at Leh, by minute and hour; would give the daily spread and persistence of clearness directly	Not obtained: only the monthly means (J09) were available; the time series have to be requested from NIWE
ERA5-Land and AgERA5 (Copernicus) [24]	Hourly or daily surface solar radiation, cloud cover and snow at the site coordinates, decades long (reanalysis, not measurement)	Not retrieved
NASA POWER [25]	Daily GHI, clear-sky GHI and clearness index since 1981 (satellite and reanalysis)	Not retrieved: no network access from the analysis environment. The helper script `fetch_nasa_power_leh.py` computes σ and ρ by month; it is untested here
PVGIS [26]	Monthly and hourly irradiation	Not retrieved (interactive tool)
Global Solar Atlas [27]	Long-term GHI, DNI and PV output (Solargis)	Not retrieved (downloadable reports)
IMD climatological tables 1991–2020 [28]	Observed bright sunshine and cloud normals for Leh; the best direct observed source	Not retrievable (the direct address was refused)
IMD extreme-weather page for Leh	Monthly extremes of temperature and 24-h rainfall	Found, not transcribed; no sunshine data
Santra (ICAR), full text [2]	Monthly radiation at Leh (given in a figure)	Only text snippets retrieved; full text not read

Table 7: Sources tried or identified but not used (from J00).

4 Methods

4.1 Experimental design

We simulate a PV array, an AC-coupled battery and a 120 kW load, with no firm source, over many random years. For each design we measure the *shortfall*: the energy not delivered to the 120 kW load, the hours and days in which that happens, and when in the year it happens. We run five experiments: (E1) a sizing grid; (E2) a large Monte Carlo of the selected design; (E3) sensitivity tests; (E4) phased deployment; and (E5) deterministic storm and snow-burial tests. The selected design is 2,000 kWp and 3,000 kWh; the reasoning is in Section 5.3.

4.2 PV model

Daily PV energy equals the monthly mean yield (Table 2) times that day's clearness factor times the array size. Hourly PV follows a half sine between sunrise and sunset, which we compute from latitude 34.3°N and day of year; the December solstice has about 9.7 h of daylight and 14.3 h of night. This formula gives day lengths 5–19 min shorter than the astronomical day length of Leh in 2026 (check V9 and Section 3.5). All tilted-plane yields, including the NIWE transposition in Section 5.2, are for a 45° plane that faces the equator (due south); neither the yield data nor the scripts have an azimuth parameter.

4.3 Weather model

The clearness factor of day d is $k_d = 1 + \sigma z_d$, where z_d is a Gaussian AR(1) series with lag-1 correlation ρ. We use $\sigma = 0.35$ and $\rho = 0.6$ as base values. The factor is limited to 0.05–1.30 and rescaled so that its long-run mean is 1, so the monthly mean yield is preserved. The value of σ is the same in every month and ρ is our choice; neither is measured at the site, and Section 5.6 tests both. In this model about 0.7% of days have a clearness factor below 0.15, in every month.

4.4 Dispatch

We simulate hourly. The battery has a 10–95% state-of-charge window, a 90% round-trip efficiency (split equally between charge and discharge) and a power limit of 0.5 C unless stated. In each hour the load is served from PV first and then from the battery down to the 10% floor; surplus PV charges the battery up to the 95% ceiling and the rest is curtailed. Within each hour the 120 kW load has priority over the 10 kW heating, but the dispatch has no look-ahead: heating is served whenever energy is available and is shed only in an hour in which supply falls short. It therefore draws on the battery overnight, and the shortfall of the 120 kW load in October–March is the shortfall of a 130 kW winter load (Section 5.3). Each trajectory is two years long and the first year is discarded as spin-up.

4.5 Shortfall metrics

An hour is *short* if the power delivered to the 120 kW load is below 120 kW. A *short day* is a calendar day with at least one short hour (an overnight outage that crosses midnight touches two calendar days). *Unserved energy* is $\sum(120\,\text{kW} - P_{\text{delivered}})$ over short hours. An *event* is a run of consecutive short days. We never throttle the load in advance, so a shortfall is typically an outage, not a brownout.

4.6 Battery health

A battery fades during its 12-year life. We assume a linear fade from 100% to 80% of nominal capacity and simulate 12 annual health states, one per year of life, each with equal weight. State k has the capacity at the middle of year k, $1 - 0.2\,(k - 0.5)/12$, i.e. 99.2% in year 1 down to 80.8% in year 12, so the 12 states average exactly 90%. "Lifetime" figures are the equal-weight average over these 12 states. Fixed health levels of 100, 90 and 80% are simulated separately and reported as scenarios (new battery, mid-life, end of life); they are *not* pooled into the lifetime figures, because giving each of three levels one third of the lifetime is not a linear fade. The battery model has no calendar or cold-temperature ageing and no augmentation.

4.7 Economic criterion

Annualised cost uses a capital recovery factor at 10% over 25 years (PV) and 12 years (battery), plus O&M. We minimise annualised cost plus lifetime-average unserved energy times a value of lost load (VoLL). The data contain no VoLL for the site. We therefore report the optimum over a range from \$1.05 to \$21.09/kWh (INR 100 to INR 2,000/kWh), and use \$5.27/kWh (INR 500/kWh) as a working value: more than ten times the marginal cost of diesel generation above, because an outage of a continuous computing or communications load costs more than its energy.

4.8 Sample sizes and seeds

E1: for each of six PV sizes, six battery sizes and two irradiance cases, 75 simulated years for each of the 12 annual health states (900 years per cell, used for all lifetime averages), plus 300 years for

each of the fixed 100, 90 and 80% scenarios (reported separately), with common random numbers across designs. E2: 500 years for each of the 12 annual states and case (6,000 years per case), plus 2,000 years for each fixed-health scenario. E3, E4 and E6: 1,500 years. E5 is deterministic. Seeds are fixed in the code (Appendix B).

5 Results

5.1 Verification

Table 8 lists the checks. The simulator conserves energy to machine precision, reproduces the input monthly yields within sampling error, and, with mean weather every day, serves the full load in both cases. Independent calculations for the documented initial configuration land close to the documented figures: PV and battery alone would meet about 53% (Mid) and 50% (Low) of the load against a documented solar share of about 53%, and the storage calculation gives a figure near the documented 26 MWh. The December PV requirement brackets the documented 980 kWp. The model day length is shorter than the astronomical day length on every day of the year, by 11 min on average, which is conservative for PV output.

Check	Result	Criterion
V1. PV energy balance (PV = direct use + charge + curtailment), 60 years	max. relative error 3e-16	$< 10^{-9}$
V2. Battery energy balance, 60 years	max. error 5e-10 kWh	$< 10^{-6}$ kWh
V3. Delivered energy = direct PV use + battery discharge	max. relative error 2e-16	$< 10^{-9}$
V4. Mean weather every day (2,000 kWp, 3,000 kWh)	unserved energy 0 kWh (Mid), 0 kWh (Low)	zero
V5. Simulated monthly mean yield against input yield	max. deviation 0.8% (clearness mean 1.000)	within sampling error
V6. Initial configuration (350 kWp, 740 kWh) share of load met by PV and battery	52.9% (Mid), 50.3% (Low)	documented about 53%
V7. Storage for 7 December days at 20% PV, 350 kWp array	24.9 MWh nominal	documented about 26 MWh
V8. PV needed to balance December energy (3.12 MWh/d)	891 kWp (Mid), 1,082 kWp (Low)	documented about 980 kWp
V9. Simulator day length against the astronomical day length of Leh for the 365 days of 2026 (J01)	shorter by 10.9 min on average; largest difference 19.7 min	all days within 20 min
V10. NIWE monthly table (J09): $\mathrm{W\,m^{-2}} \times 0.024$ against the $\mathrm{kWh\,m^{-2}\,d^{-1}}$ columns; closure (GHI − DHI)/DNI in every month	arithmetic within 5×10^{-5}; closure 0.43–0.76, highest in summer, lowest in December (as the mean cosine of the zenith angle should be)	arithmetic $< 10^{-3}$; closure between 0 and 1

Table 8: Verification of the simulator. V1–V5 test internal consistency; V6–V8 compare independent calculations with figures documented for the site; V9 compares the model day length with an astronomical calculation (J01); V10 tests the internal consistency of the NIWE table (J09), which is found data for Leh (`niwe_crosscheck.py`). Neither check validates the weather model. V6 is a comparison of different quantities (the documented figure is the solar share with a diesel generator filling gaps) and is read as a plausibility check, not a calibration.

5.2 Check against measured irradiance (NIWE)

Data. The only ground measurement of irradiance near the site that we found is the table of monthly long-term mean GHI, DNI and DHI of the NIWE Solar Radiation Resource Assessment station 1832 at the Energy Park of the Ladakh Renewable Energy Development Agency in Leh [20]. We use the coordinates and elevation of station 1832 in the NIWE station register (34.140°N, 77.481°E, 3,252 m; commissioned 23 August 2011), which we retrieved on 24 November 2026 [20] and which agree with the values used here; the 3,252 m elevation rests on that entry alone. The original presentation prints slightly different coordinates (34.1288986°N, 77.4600983°E). The station lies 34.3 km from the study site (34.3°N, 77.8°E) with the register coordinates, which is the distance used here (about 34 km), or 36.6 km with the coordinates printed in the presentation, and 528 m lower. The table is in $\mathrm{W\,m^{-2}}$ (24-hour means); we convert to daily irradiation by $\times 0.024$ (J09). The source gives no averaging period or completeness, and our copy is a transcription that was checked in review against the table on page 14 of the original presentation: all 36 GHI, DNI and DHI values agree (largest difference $5 \times 10^{-7}\,\mathrm{W\,m^{-2}}$). We also checked its arithmetic and physical consistency (V10). We use it as a benchmark of the monthly means, not as a calibration.

Monthly means. The day-weighted annual means are $5.32\,\mathrm{kWh\,m^{-2}\,d^{-1}}$ for GHI (1,942 $\mathrm{kWh\,m^{-2}}$ a year), 5.63 for DNI and 1.70 for DHI; DNI and DHI are different components and are not added to GHI. The GHI is 4% below the Mid anchor (5.54, Santra), 10% below the Angström–Prescott value from CAMS sunshine (5.94) and 13% below the digitised MERRA-2 mean (about 6.1). It is lowest in December–January (2.92 and 2.85) and highest in June (7.41). This is independent, measured support for winter being the weak season (Table 9, Figure 2a).

Yield. On the 45° plane the NIWE-derived yield is $3.60\,\mathrm{kWh\,kWp^{-1}\,d^{-1}}$ in December, 4.53 in November, 3.17 in January and 3.47 in February. The November–February mean is 3.69, between Low (3.32) and Mid (4.03). In November and December the NIWE-derived yield is above Low by 31 and 25%, in January it matches Low, and in February it is 6% below Low. In April to September it is 6–23% below Mid and 2–21% below Low, which does not matter for the energy balance (the 2,000 kWp array still yields more than three times the daily load) but does matter for the small summer shortfall below. The annual mean is 4.46, below both Mid (5.02) and Low (4.66).

Reliability. Running the selected design with the NIWE-derived yield and the same weather draws gives a lifetime-average shortfall of 8.9 MWh a year (0.84% of the 120 kW load), about 12.2 short days and 88 short hours (Table 10). That is 7% below the Low case (9.6 MWh) and 21% above Mid (7.3 MWh). With a snow albedo of 0.5 in November–February it is 8.6 MWh. At a clearness spread of 0.45 it is 24.0 MWh against 24.6 for Low (1,000 years each). The winter share is lower than in Low: November–February is 56% of the unserved energy, against 64% for Low, and the summer months (April–September) add about 2.7 MWh instead of 2.2. The conclusions of Section 5.5 therefore do not change: the Low case is mildly conservative in November and December and mildly optimistic in February.

Limits of the check. (i) Monthly means do not test the day-to-day spread σ or persistence ρ, which drive the shortfall (Section 5.6); the NIWE one-minute and hourly records, which we did not obtain, would. (ii) The station is lower than the site, where the thinner atmosphere would normally give somewhat more irradiance, and the terrain and snow cover differ. (iii) The transposition assumes a south-facing (equator-facing) 45° plane, because Klein's monthly R_b is the equator-facing formula, and it is a transposition of monthly means, not a series of measured plane-of-array irradiation: the NIWE-derived result is an independent resource-level scenario, not proof that the daily weather sequence is right. It is isotropic, with no temperature or soiling model; the snow-loss factors and performance ratio are unchanged and are still estimates. (iv) The averaging period of the NIWE table is not stated.

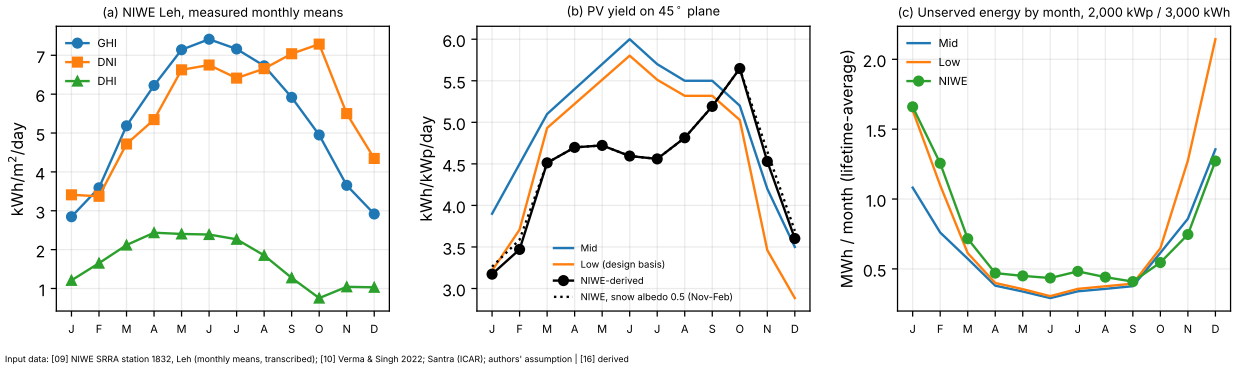


Figure 2: Check against measured irradiance. (a) NIWE monthly mean GHI, DNI and DHI at Leh (J09). (b) PV yield on the 45° plane: Mid, Low (design basis) and derived from the NIWE means (J16), the dotted line with snow albedo 0.5 in November–February. (c) Lifetime-average unserved energy by month for 2,000 kWp and 3,000 kWh under Mid, Low and the NIWE-derived yield.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
GHI, kWh m^{-2} d^{-1}	2.8	3.6	5.2	6.2	7.1	7.4	7.2	6.7	5.9	5.0	3.7	2.9
DNI, kWh m^{-2} d^{-1}	3.4	3.4	4.7	5.3	6.6	6.8	6.4	6.7	7.0	7.3	5.5	4.3
DHI, kWh m^{-2} d^{-1}	1.2	1.7	2.1	2.4	2.4	2.4	2.3	1.9	1.3	0.8	1.0	1.0
Clearness index K_T	0.55	0.54	0.62	0.62	0.64	0.64	0.63	0.65	0.66	0.70	0.66	0.60
Closure (GHI−DHI)/DNI	0.48	0.57	0.65	0.71	0.71	0.74	0.76	0.73	0.66	0.58	0.47	0.43
NIWE-derived yield, kWh/kWp/d	3.17	3.47	4.51	4.70	4.72	4.59	4.56	4.81	5.19	5.65	4.53	3.60
Mid yield	3.90	4.50	5.10	5.40	5.70	6.00	5.70	5.50	5.50	5.20	4.20	3.50
Low yield	3.21	3.71	4.93	5.22	5.51	5.80	5.51	5.32	5.32	5.03	3.46	2.88
NIWE / Mid	0.81	0.77	0.89	0.87	0.83	0.77	0.80	0.88	0.94	1.09	1.08	1.03
NIWE / Low	0.99	0.94	0.92	0.90	0.86	0.79	0.83	0.91	0.98	1.12	1.31	1.25

Table 9: NIWE measured monthly mean irradiation at Leh (J09) and the PV yield derived from it (J16): Klein monthly R_b for a 45° plane facing due south at 34.14°N, isotropic diffuse sky, ground albedo 0.20, performance ratio 0.80 and the snow-loss factors of Section 2. The closure column is the direct horizontal part divided by DNI, which should equal the DNI-weighted mean cosine of the zenith angle.

Irradiance case	Yield	Unserved, MWh/yr	Short days/yr	Short h/yr	P90, MWh
Mid	5.02	7.3	10.0	72	13.8
NIWE-derived	4.46	8.9	12.2	88	16.1
NIWE-derived, snow albedo 0.5 in Nov–Feb	4.50	8.6	11.7	85	15.7
Low (design basis)	4.66	9.6	13.3	94	17.1

Table 10: Selected design (2,000 kWp, 3,000 kWh) under the irradiance cases, lifetime average over the 12 annual battery-health states (6,000 simulated years per row, same weather draws). Yield is the day-weighted annual mean, kWh kWp^{-1} d^{-1}; P90 is the 90th percentile of annual unserved energy.

5.3 Sizing: PV, battery and the battery cliff

Figure 3 and Tables 14–11 show the sizing experiment.

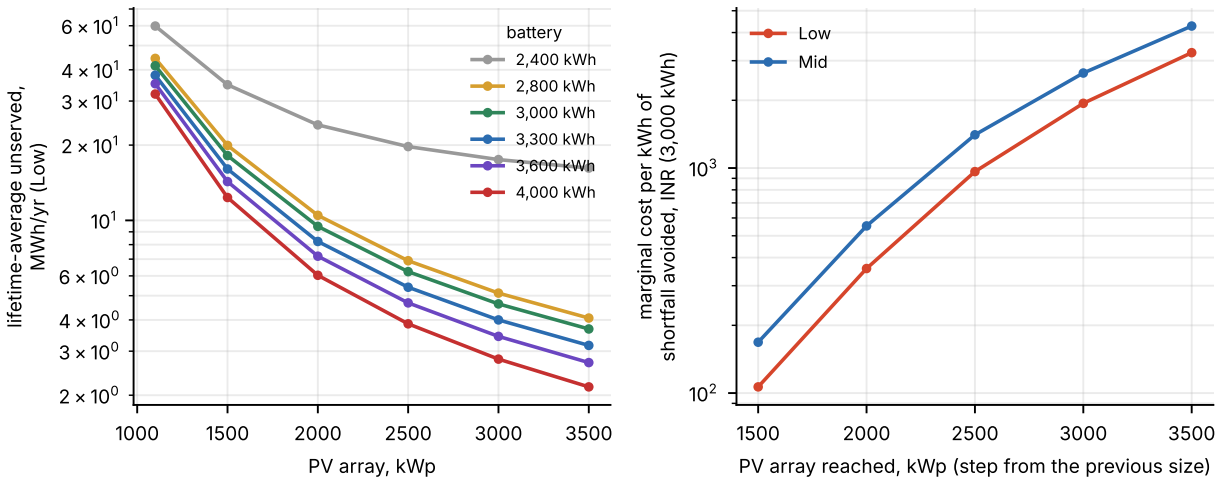


Figure 3: Left: lifetime-average unserved energy against PV size, one line per battery size (Low case, log scale). Right: cost of each additional kWh of shortfall avoided as the array grows from the previous size, at 3,000 kWh.

Battery cliff. A December night is about 14.3 h long, so a 130 kW load (120 kW plus heating) draws about 1.9 MWh from the battery before sunrise. With the 10–95% window and 90% round trip, a battery needs roughly 2,305 kWh of nominal capacity to carry that night when new and 2,881 kWh at 80% health, assuming it starts full (Table 12). In the simulations, 2,400 kWh fails on about 111 days a year on a lifetime average (186 days at 80% health), and 2,800 kWh, which is adequate until about 90% health, fails on about 18 days a year on a lifetime average, almost all of them in the last year or so of its life, and on 133 days at 80% health (Table 11). A larger battery moves the cliff beyond the battery's life.

Battery, kWh	Cost, USD/yr (INR lakh/yr)	Short days/yr, fixed health 100%	90%	80%	Lifetime avg. (12 states) short days	unserved, MWh
2,400	$254,085 (241)	15	144	186	111	24.1
2,800	$274,117 (260)	12	15	133	18	10.5
3,000	$284,660 (270)	11	13	16	13	9.5
3,300	$300,474 (285)	9	12	14	11	8.2
3,600	$315,235 (299)	8	10	12	10	7.2
4,000	$335,266 (318)	6	8	10	8	6.0

Table 11: The battery cliff (Low case, 2,000 kWp). The fixed-health columns are scenarios (300 simulated years each); the last two columns average the 12 annual health states (75 years each). The simulated winter load is 130 kW (120 kW plus heating, Section 5.3). Below about 2,800 kWh nominal the battery cannot carry a December night at that load once it has faded to 80% of nominal, and short days jump from tens to over a hundred a year.

What the cliff measures: a 130 kW load, not a 120 kW load. The simulator dispatches hour by hour with no look-ahead. Heating is therefore served whenever energy is available, and is shed first only in an hour that is already short, which in practice means the last partial hour of a night. Heating thus drains the battery all night, and the core-load shortfalls in this paper in October–March are those of a 130 kW load whose heating share is dropped at the end. Table 12 gives the nominal capacity needed to carry a fully charged December night at each load, and Table 13 runs the simulation with heating served and with heating switched off. At 2,800 kWh and 80% health the nominal capacity needed is 2,659 kWh for 120 kW and 2,881 kWh for 130 kW: the battery passes the first and fails the second, and its 133 short days at 80% health fall to 14 when the heating is

switched off. Those 133 days are evidence of the 130 kW endurance limit and should not be read as the reliability of a 120 kW core load.

Winter load	Night energy, kWh (14.3 h)	Nominal battery needed, kWh, at health 100%	90%	80%
120 kW (core load only)	1,715	2,127	2,364	2,659
130 kW (core load plus heating)	1,858	2,305	2,561	2,881

Table 12: Nominal capacity needed to carry a fully charged December night of 14.3 h: $C_{\text{nom}} = Pt/\left[(0.95-0.10)\sqrt{0.90}\,\text{SOH}\right]$. It assumes the battery starts the night full and that no other restriction applies, so it is a lower bound on the capacity a stochastic simulation needs.

Battery, kWh nominal	Health	Short days per year served	off	Core-load unserved, MWh/yr served	off	Heating unserved, MWh/yr
2,400	100%	16	13	11.3	9.3	0.9
2,400	90%	144	20	21.9	10.7	2.5
2,400	80%	186	153	47.8	29.8	5.7
2,800	100%	13	10	9.1	7.4	0.7
2,800	90%	15	12	10.6	8.6	0.8
2,800	80%	133	14	13.7	10.2	2.4
3,000	100%	11	9	8.2	6.6	0.6
3,000	90%	13	11	9.6	7.8	0.7
3,000	80%	16	13	11.3	9.3	0.9

Table 13: Core-load shortfall with the winter heating served (130 kW, the base case) and with the heating switched off (120 kW only), Low case, 2,000 kWp, fixed battery health, 1,500 simulated years each. The last column is the heating energy that goes unserved in the base case.

The 120 kW and 130 kW results should therefore be kept apart. The sizing grid, the value-of-lost-load optima and the lifetime statistics treat the heating as discretionary but served when possible, which is a defensible reading if the heating really is discretionary. If the heating is a firm requirement, the design should be re-sized with the 130 kW load protected throughout. We ran this only for the selected design (the protected-heating row of Table 20, 8% more unserved energy), not as a full optimisation, so we do not claim an optimum for that case.

Diminishing returns in PV. With a 3,000 kWh battery, each step of 500 kWp costs about $32,789 (INR 31 lakh) a year, but the shortfall it removes falls from about 23 MWh a year for the first step to about 1 MWh at the last (Table 14). Moving from 1,500 to 2,000 kWp costs about $3.77/kWh (INR 358/kWh) of shortfall avoided (Low case); the next step costs about $10.16/kWh (INR 964/kWh).

PV step kWp	Added cost, USD/yr (INR lakh/yr)	Unserved energy saved, MWh/yr Low	Mid	Cost per kWh saved, USD (INR Low	Mi
1,100 → 1,500	$26,252 (24.9)	23.3	14.8	$1.13 (107)	$1.77 (168
1,500 → 2,000 (selected)	$32,789 (31.1)	8.7	5.6	$3.77 (358)	$5.83 (553
2,000 → 2,500	$32,789 (31.1)	3.2	2.2	$10.16 (964)	$14.81 (1,405
2,500 → 3,000	$32,789 (31.1)	1.6	1.2	$20.44 (1,939)	$27.87 (2,643
3,000 → 3,500	$32,789 (31.1)	1.0	0.7	$34.33 (3,256)	$45.07 (4,275

Table 14: Marginal economics of PV with a 3,000 kWh battery (lifetime-average unserved energy). Each 500 kWp step costs about $32,789 (INR 31 lakh) a year and saves less than the step before.

Economic optimum. Table 15 gives the cost-minimising design for VoLL from $1.05 to $21.09/kWh (INR 100 to 2,000/kWh). At the working value of $5.27/kWh (INR 500/kWh) the grid optimum is 2,000 kWp. If an unserved kWh is worth less than about $3.48 (INR 330), a smaller array (1,500 kWp) pays; if it is worth more than about $9.17 (INR 870), a larger one (2,500 kWp) does.

Value of lost load USD/kWh (INR/kWh)	Optimum, Low kWp / kWh	Optimum, Mid kWp / kWh	Low unserved MWh/yr	Low short days/yr	Cost, USD/yr (INR lakh/yr)
$1.05 (100)	1,500 / 2,400	1,100 / 2,400	34.9	126	$221,402 (210)
$2.11 (200)	1,500 / 2,800	1,500 / 2,800	19.9	35	$241,434 (229)
$5.27 (500)	2,000 / 2,800	1,500 / 2,800	10.5	18	$274,117 (260)
$10.54 (1,000)	2,500 / 2,800	2,000 / 2,800	6.9	11	$306,800 (291)
$21.09 (2,000)	2,500 / 3,300	2,500 / 3,000	5.4	7	$333,158 (316)

Table 15: Cost-minimising design for different values of lost load, from a grid of PV 1,100–3,500 kWp and battery 2,400–4,000 kWh. Unserved energy is the lifetime average over the 12 annual battery-health states. The optimum minimises annualised cost plus unserved energy times the value of lost load.

The energy-only optimum at $5.27/kWh (INR 500/kWh) pairs 2,000 kWp with a 2,800 kWh battery. Over a 12-year fade the 2,800 kWh battery is short on about 18 days a year on average (Low), against 13 for 3,000 kWh; the extra 200 kWh saves 1.0 MWh a year, worth about $5,271 (INR 5 lakh) at $5.27/kWh (INR 500/kWh), and costs about $10,543 (INR 10 lakh) a year. The lifetime-average argument therefore does not favour 3,000 kWh. We select it for end-of-life margin: at 80% health the 2,800 kWh battery cannot carry the 130 kW December night (133 short days a year, Table 11), and it fails in the last year or so of its life. The selected design is a reliability-constrained choice and not an economic optimum: **2,000 kWp of PV and 3,000 kWh of battery**.

5.4 Selected design

Item	Value
PV	2,000 kWp: about 3,650 modules of 550 W in 146 strings of 25 (2,007 kWp). About 3.6 ha at 1.8 ha/MWp (our estimate). Bifacial, 45° or steeper, AC-coupled. That is 15.4–16.7 kWp per kW of load.
Battery	3,000 kWh nominal LFP, liquid cooled, in a heated, seismically anchored building, split into at least three strings.
Curtailed PV	about 2,260–2,515 MWh/yr (66–69% of the array's output).
Capital	$2,024,249 (INR 19.2 crore): PV $1,075,382 (10.2 crore), battery $948,867 (9.0 crore).
Annualised cost	$284,660 (INR 270 lakh) (PV $130,733 (124 lakh), battery $153,927 (146 lakh)), about $0.26 (INR 25) per kWh of load (1,095 MWh/yr).

Table 16: The selected design.

5.5 Shortfall statistics

All results in this subsection are for the selected design, 6,000 simulated years per irradiance case, averaged over the 12 annual battery-health states (500 simulated years each). A simulated year is a random draw of weather, not a forecast of a particular calendar year. The maps therefore give how likely each day and week is to fall short and how large the shortfall tends to be.

5.5.1 The year

	Mid case			Low case		
Battery health	New 100%	Fixed 80%	Lifetime	New 100%	Fixed 80%	Lifetime
Mean unserved energy, MWh/yr	6.2	8.4	7.3	8.2	10.9	9.6
Median year, MWh	5.3	7.5	6.5	7.2	10.1	8.7
90th-percentile year, MWh	12.4	15.1	13.8	15.3	18.9	17.1
99th-percentile year, MWh	19.4	23.1	21.5	23.2	27.7	26.0
Worst year simulated, MWh	30.1	30.8	31.5	33.6	37.0	38.5
Load served, %	99.41	99.20	99.30	99.22	98.96	99.09
Short days per year (mean)	8.5	11.5	10.0	11.3	15.7	13.3
Short days, 90th-percentile year	15	19	17	19	25	21
Short days, 99th-percentile year	21	26	24	26	33	29
Short hours per year (mean)	61	84	72	80	110	94
Longest run of short days (mean)	3.0	3.3	3.2	3.5	4.0	3.7
Longest run, 99th percentile (days)	8	8	7	8	9	9
Longest run, worst year (days)	12	13	11	12	15	18
Years with no shortfall at all, %	1.9	0.4	0.7	0.5	0.1	0.1

Table 17: Annual shortfall for 2,000 kWp and 3,000 kWh nominal. "New 100%" and "Fixed 80%" are fixed-health scenarios (2,000 simulated years each). "Lifetime" is the equal-weight average over 12 annual battery-health states, 99.2% in year 1 to 80.8% in year 12 (500 simulated years each, 6,000 years), a linear fade over the 12-year battery life. Within each hour the 120 kW load is served before the 10 kW winter heating, but the heating is served whenever energy is available and so draws on the battery overnight (Section 5.3); heating energy that cannot be served is counted separately.

- **Typical year (Low, lifetime).** The median year loses 8.7 MWh, with about 13 short days and 94 short hours; the mean is 9.6 MWh (0.91% of the 120 kW load; 7.3 MWh, 0.70%, in Mid). As the battery fades from 100% to 80% the mean rises from 8.2 to 10.9 MWh.
- **Bad year.** One year in ten loses more than 17 MWh and has more than 21 short days; one in a hundred loses more than 26 MWh and has more than 29. The worst of 6,000 simulated years loses 39 MWh, with a longest run of 18 short days.
- **Events.** Short days come in about 6.7 separate events a year (Low; 5.2 in Mid). An event touches about 2.0 calendar days on average and loses about 1.4 MWh. 42% of events touch one calendar day, 23% three or more and 4% five or more; the longest simulated event is 18 days and 17 MWh.
- **Seasons.** 64% of unserved energy falls in November–February (55% in Mid) and 77% in October–March. Heating that cannot be served adds about 0.7 MWh a year (Low).

5.5.2 Month by month

Month	P(any shortfall), %		Short days		Hours short	Unserved, MWh		Low 95th	kWh per	Hours per
	Mid	Low	Mid	Low	Low	Mid	Low	pct. MWh	short day	short day
Jan	54	71	1.5	2.3	16	1.08	1.63	6.2	716	7.0
Feb	41	54	1.0	1.5	11	0.76	1.10	4.9	735	7.1
Mar	33	36	0.8	0.8	6	0.57	0.61	3.4	733	7.3
Apr	24	25	0.5	0.5	4	0.38	0.40	2.4	728	7.1
May	21	22	0.5	0.5	4	0.34	0.36	2.2	721	7.3
Jun	19	19	0.4	0.4	3	0.29	0.30	1.9	713	7.2
Jul	22	22	0.5	0.5	4	0.34	0.36	2.2	719	7.3
Aug	23	24	0.5	0.5	4	0.36	0.38	2.2	720	7.1
Sep	23	24	0.5	0.5	4	0.38	0.39	2.5	748	7.4
Oct	34	35	0.8	0.8	6	0.61	0.65	3.6	777	7.5
Nov	47	60	1.2	1.8	12	0.86	1.28	5.5	712	6.9
Dec	63	80	1.9	3.1	21	1.36	2.14	7.4	700	6.9
Year			10.0	13.3	94	7.33	9.60			

Table 18: Expected shortfall by month, pooled over the 12 annual battery-health states (500 simulated years each, 6,000 years). "P(any shortfall)" is the share of simulated years with at least one short hour in the month. A "short day" is a calendar day with at least one hour below 120 kW; an overnight outage that crosses midnight touches two calendar days. The percentile column is the month's unserved energy exceeded in 5% of years (Low case).

December is the worst month, with about 3.1 short days and 2.1 MWh in a Low-case December and a 80% chance of at least one short hour; June is the best, at 19%. When a day does fall short it loses about 700–777 kWh in about 7 hours in every month. The *size* of a shortfall barely changes through the year; its *frequency* changes by a factor of about four.

5.5.3 Week by week

Figure 4 and Table 19 summarise the weekly map; Appendix A lists all 52 weeks. The shortfall rises as the weekly mean PV output approaches the load.

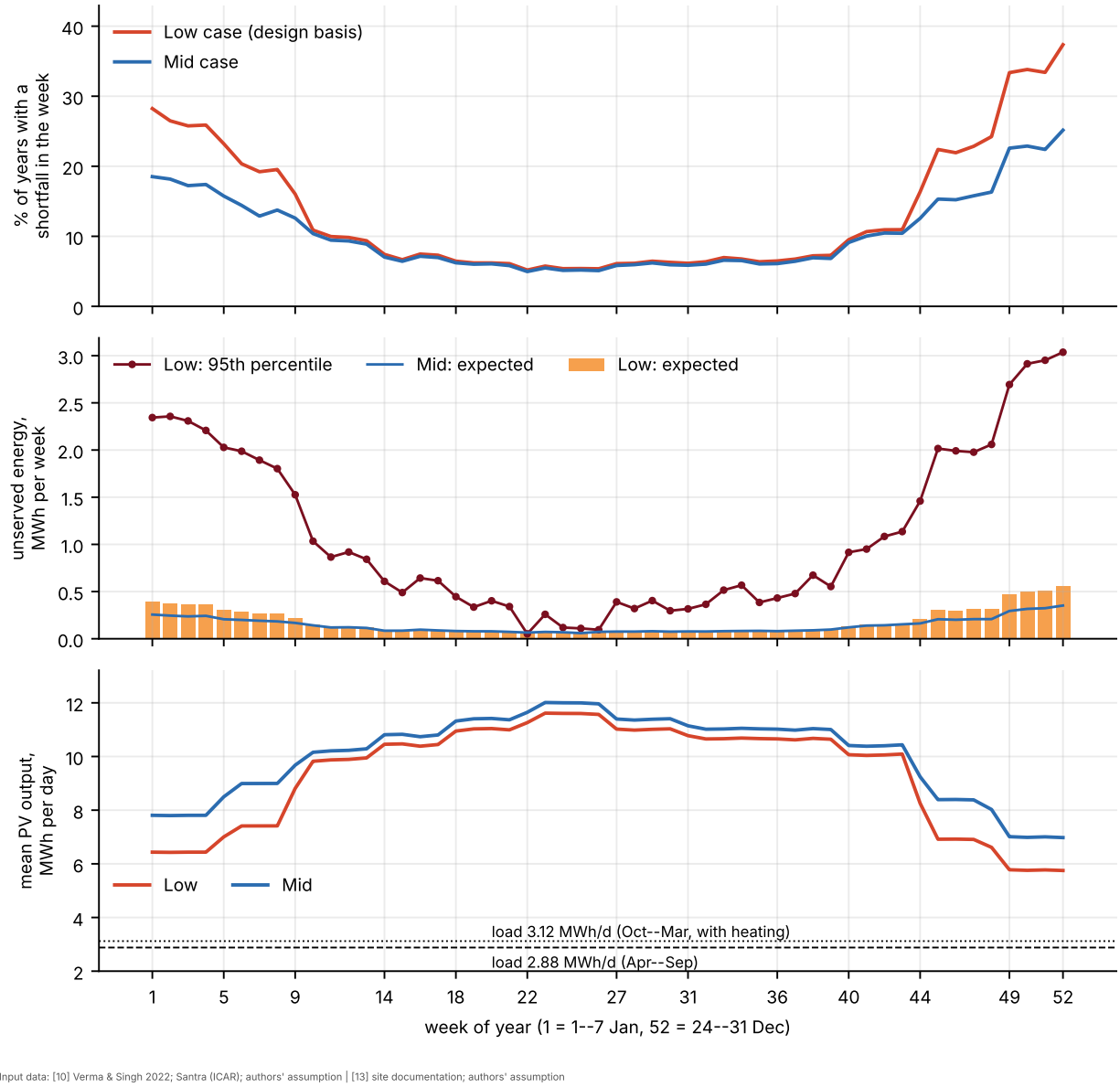


Figure 4: Weekly map. Top: chance that a week has any hour below 120 kW. Middle: expected unserved energy per week (bars, Low) and its 95th percentile. Bottom: mean PV output against the load.

Band	Weeks	P(short), Low, %	P(short), Mid, %	Expected MWh/wk, Low	Avg. deficit kW, Low
Deep winter	49–52 and 1–4 (24 Dec–28 Jan)	26–37	17–25	0.36–0.56	2.1–3.0
Winter shoulders	44–48 and 5–9 (29 Oct–4 Dec; 29 Jan–4 Mar)	16–24	13–16	0.21–0.32	1.3–1.9
Spring and autumn edge	10–13 and 40–43 (5 Mar–1 Apr; 1–28 Oct)	9–11	9–10	0.12–0.16	0.7–1.0
Summer and early autumn	14–39 (2 Apr–30 Sep)	5–7	5–7	0.06–0.10	0.4–0.6

Table 19: Weekly shortfall bands, from Table 23. The “average deficit” spreads the week’s unserved energy over all 168 hours, so it is small even when the outage, when it occurs, is about 100 kW for several hours.

Weeks 49–52 and 1–4 (24 December to 28 January) have a 26–37% chance of a shortfall in any one week (Low). Summer weeks carry a residual risk of about 5–7% per week. This floor comes from the symmetric weather model, which allows near-zero-PV days in every month; with lower summer variability the total shortfall falls by about 21% (Table 20). We keep the symmetric model so as not to flatter the design.

5.5.4 Day by day

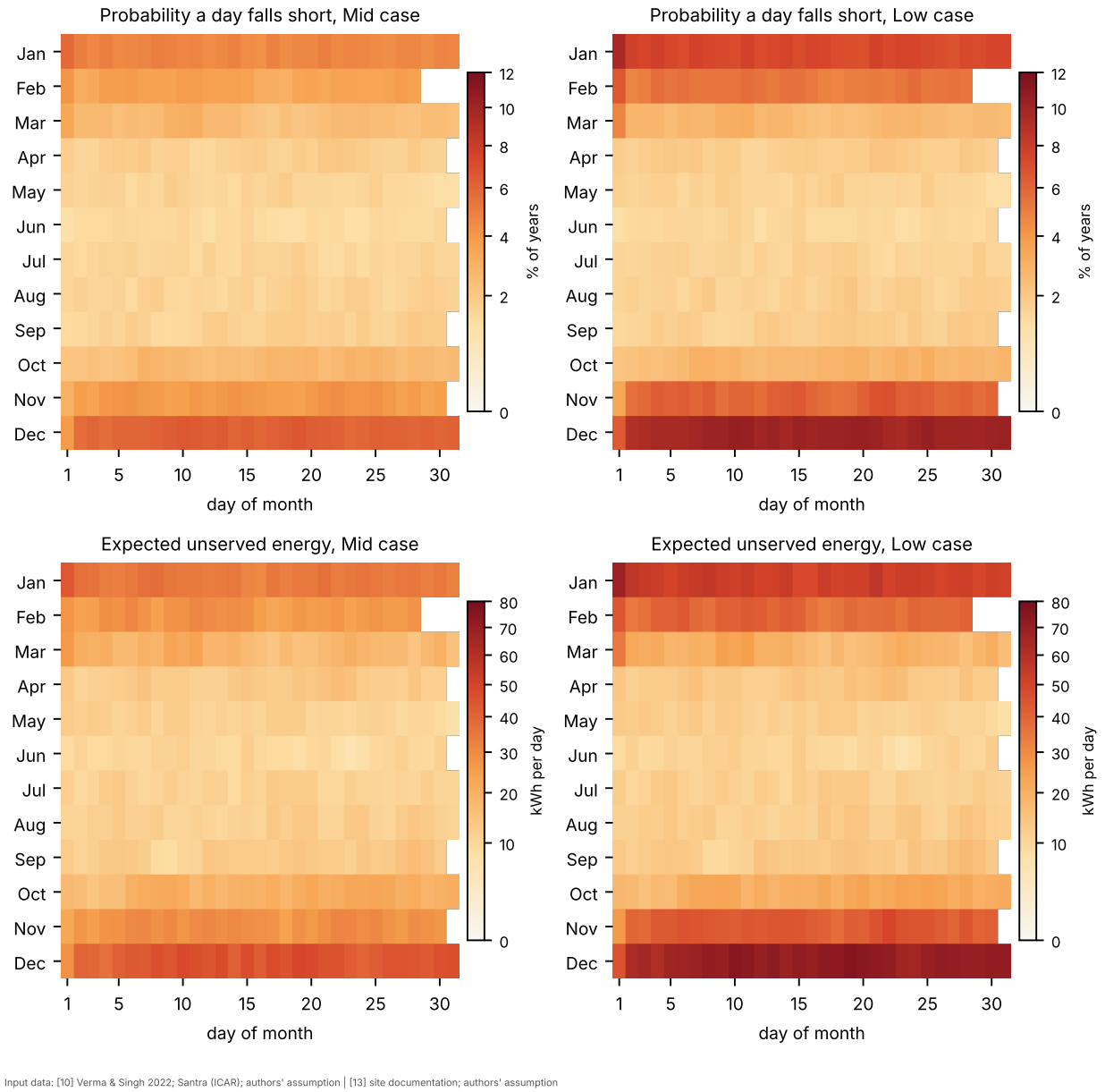


Figure 5: Calendar maps. Top: probability that each day has at least one hour below 120 kW. Bottom: expected unserved energy on each day. Mid case left, Low case right; both averaged over the 12 annual battery-health states. The darkest days (late December and early January, Low) fall short in about 10% of years and lose about 75 kWh on average.

The map is smooth because it averages thousands of random years. No single date is special: the risk follows the season, and the same date is bad in some years and fine in most.

5.5.5 Individual years

Figure 6 shows three simulated Low-case years with a new battery: the median year (7.2 MWh, 11 short days), the 90th-percentile year (15.3 MWh, 19 days) and the worst of 2,000 (33.6 MWh, 35 days). Short days cluster in the winter months and appear in runs.

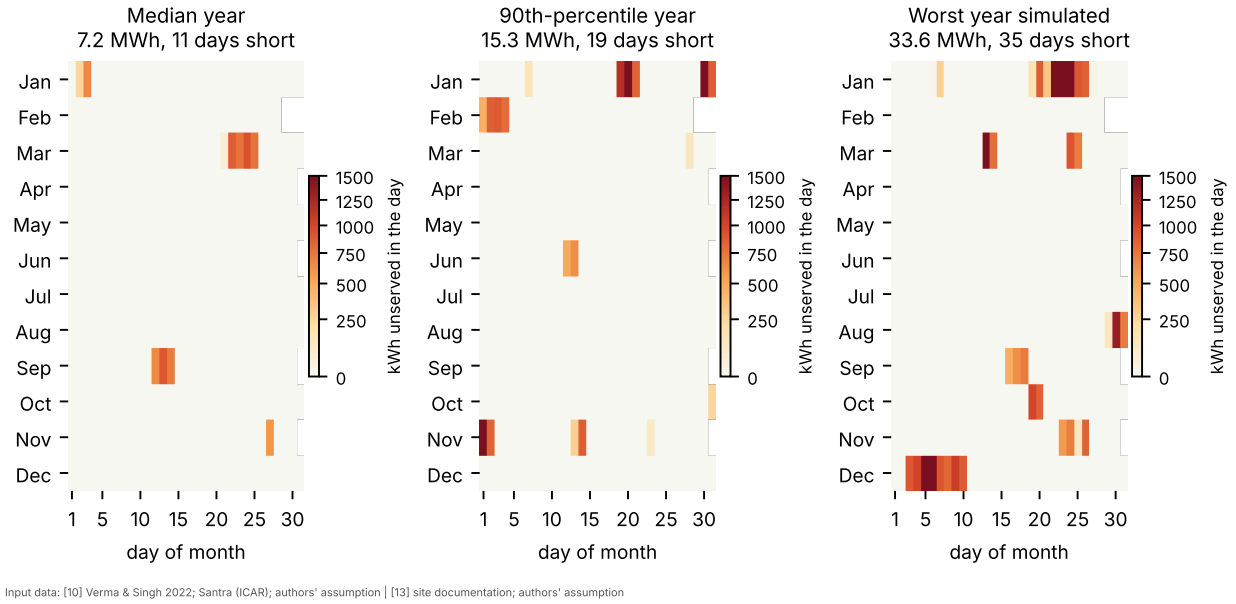


Figure 6: Three simulated years, Low case, new battery. Each cell is one day; colour shows kWh unserved that day (dark red is about 1.5 MWh, close to a total loss of the night).

5.5.6 Hourly simulation of short days

Figure 7 shows two events simulated hour by hour. In the typical event (from day 326) one dark day at a clearness factor of 0.18 leaves the battery only about 33% charged; the following night runs it to its 10% floor and the load drops out for about 9 hours before the sun returns (1.2 MWh). In the worst event among the new-battery years (12 days from day 1, 19.0 MWh), eleven consecutive days at 5–35% of normal PV hold the battery near its floor, and the site delivers full power only for a few midday hours on the brighter days.

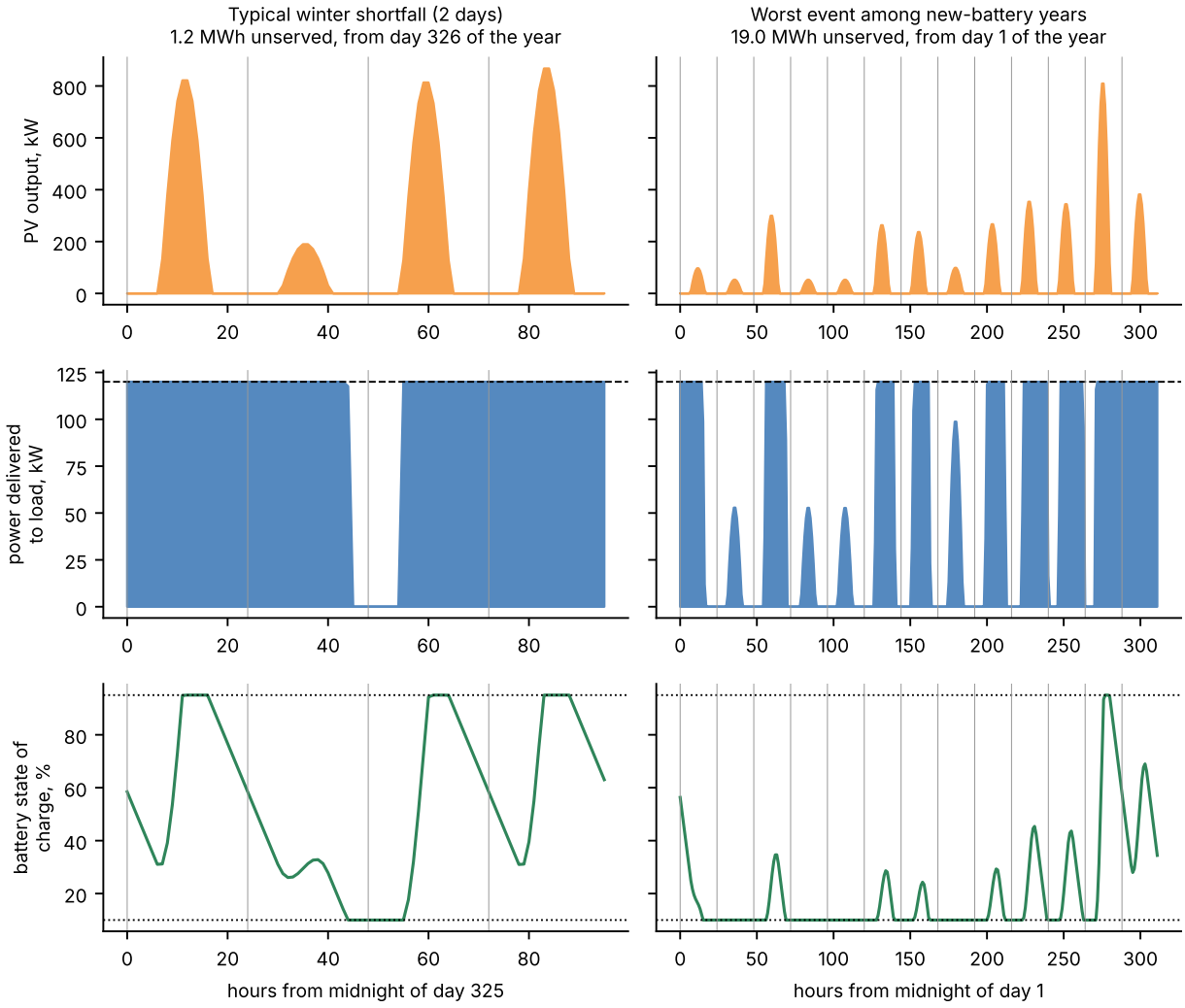


Figure 7: Hourly simulation of a typical winter shortfall (left) and the worst simulated event (right). Top: PV output. Middle: power delivered to the load (dashed: 120 kW). Bottom: battery state of charge (dotted: 10% and 95% limits). Vertical lines mark midnights.

5.6 Sensitivity

Change from base	Mid case MWh/yr	Mid case days/yr	Low case MWh/yr	Low case days/yr	Low case 90th pct. MWh
Base: sd 0.35, corr 0.6, new battery	6.1	8	8.1	11	14.7
Clearness sd 0.45	21.2	24	24.7	28	37.3
Clearness sd 0.55	42.7	43	47.3	47	66.9
Day-to-day correlation 0.3	5.2	8	6.9	11	11.5
Day-to-day correlation 0.85	7.7	8	10.0	11	22.6
Lower summer variability (sd 0.25 Apr–Sep)	4.5	6	6.4	9	12.4
Battery power limited to 0.15C	6.1	8	8.1	11	14.7
Winter heating protected (130 kW core)	6.6	8	8.7	11	15.9
Winter heating off (120 kW only)	5.1	7	6.5	9	12.5
Battery at 90% health	7.2	10	9.4	13	16.4
Battery at 80% health	8.4	12	11.1	16	18.6
Battery at 70% health	25.2	150	28.1	150	35.6
One of three battery strings out (2/3)	35.8	161	38.7	163	46.2

Table 20: Sensitivity of the shortfall for 2,000 kWp and 3,000 kWh (1,500 simulated years each). "Days/yr" counts calendar days with at least one hour below 120 kW.

- **Weather spread is the largest uncertainty.** Raising the clearness standard deviation from 0.35 to 0.45 multiplies the Low-case shortfall by 3.1, and 0.55 by about 6. We have no measured spread for the site. The multipliers are relative to the base row of Table 20 (8.1 MWh a year, new battery, 1,500 years), not to the 9.6 MWh of Table 17, which averages 12 annual battery-health states and is therefore higher.
- **Battery health matters more than PV size.** At 70% health the design fails on about 150 days a year (Table 11 shows the same cliff at smaller batteries).
- **One battery string out.** Losing one of three strings leaves 2,000 kWh, below the cliff, and the design fails on about 163 days a year. N+1 on storage would need a 4,500 kWh battery, costing about $76,964 (INR 73 lakh) a year more (27%).
- **Minor factors.** Limiting battery power to 0.15 C (450 kW) changes nothing. Day-to-day correlation of 0.3 lowers the shortfall by about 15%, and 0.85 raises it by about 24%. Protecting the winter heating, which is the same as always serving a 130 kW load, adds about 8%; switching the heating off (a 120 kW load only) removes about 19% (Section 5.3).

5.7 Phased deployment

Phase	Capex, USD (INR cr)	Cost, USD/yr (INR lakh/yr)	Unserved, MWh/yr Mid	Unserved, MWh/yr Low	Short days/yr Mid	Short days/yr Low
1: 1,100 kWp / 3,000 kWh	$1,539,273 (14.6)	$225,619 (214)	24.3	37.7	34	51
2: 1,500 kWp / 3,000 kWh	$1,750,132 (16.6)	$251,977 (239)	11.0	15.8	15	22
3: 2,000 kWp / 3,000 kWh	$2,024,249 (19.2)	$284,660 (270)	6.1	8.1	8	11

Table 21: Phased deployment with a new battery. The whole battery is installed in phase 1 because the battery, not the array, sets the cliff (Table 11).

Phase 1 alone leaves about 38 MWh a year unserved (Low) and phase 2 about 16 MWh. Because the cliff is set by the battery, the whole battery belongs in phase 1.

5.8 Storm and snow-burial tests

Table 22 and Figure 8 show a 7-day December storm at 20% PV and a 7-day snow burial at 0% PV.

Case (2,000 kWp, 3,000 kWh; 7 days from 10 December)	Unserved in week, MWh	Load served in week, %	Hours short in week	First shortfall after
Mid, PV 20%	9.9	51	92	22 h
Mid, PV 0% (buried)	18.8	7	157	11 h
Low, PV 20%	11.4	44	100	20 h
Low, PV 0% (buried)	18.8	7	157	11 h

Table 22: Storm and snow-burial tests (battery new). The test week starts at midnight on 10 December after mean-weather days, when the battery is about 58% charged (it has been discharging since sunset). "Load served" is the share of the 20.2 MWh (7 × 24 h × 120 kW) delivered in the 7 days. "First shortfall" is measured from that midnight.

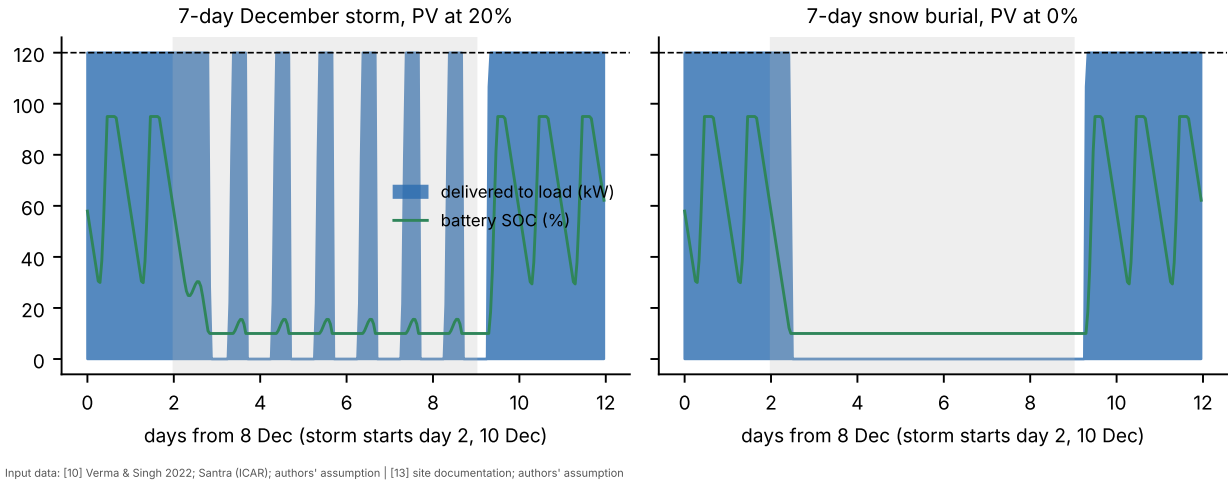


Figure 8: Hourly simulation of the 7-day tests (grey band), Low case, 2,000 kWp and 3,000 kWh. Power delivered (blue) and battery state of charge (green).

The battery carries the site for about 20 hours; over a storm week the array and battery together deliver only about 44–51% of the week's load, and a week of snow burial about 7%. A calculation for the selected array gives the storage needed to ride through a 7-day December storm at 20% PV as about 15–17 MWh nominal (Mid–Low), roughly 5 times the battery. Autonomy without PV at 130 kW (85% usable window, 95% efficiency) is 18.6 h warm, 15.8 h at 85% cold capacity and 13.0 h at 70%, against a December night of 14.3 h: a battery at 70% of capacity cannot carry the night.

6 Discussion

6.1 What the results mean

A PV–battery system can run a 120 kW load for about 99% of the energy, but not for every hour. The remainder arrives as night outages of about 7 hours, on about 13 days a year in about 6.7 events, concentrated in the weeks around the winter solstice. The system fails not because the array cannot make the energy, but because the battery empties during a night that follows a dark day, and a bigger array only refills it sooner. That is why PV has diminishing returns and why the battery, not the array, sets the cliff.

6.2 Engineering implications

1. **Size the battery for the end of its life.** The night before sunrise needs about 1.9 MWh at 130 kW, which is 2,305 kWh of nominal capacity when new and 2,881 kWh at 80% health (Table 12). A battery that is adequate when new can be inadequate by year 12 (Table 11); plan capacity checks and augmentation before 80% health.
2. **Battery power conversion.** The two or three cabinets of about 100 kW that suit the load cannot recharge a 3,000 kWh battery from a 2,000 kWp array. Separate battery power conversion of at least 450 kW (0.15 C) is enough in the simulations, and 750 kW (0.25 C) leaves margin.
3. **N+1 power conversion.** At 20% derating a cabinet gives about 100 kW, below the load, so three cabinets (200 kW with one out) serve the 130 kW load. There is no redundancy in storage (Section 5.6).
4. **Battery room.** A cold battery loses capacity and LFP cannot charge below about 0°C. Use a heated, seismically anchored building with a heat budget.
5. **String voltage.** Assume a 550 W-class module with $V_{oc} = 49.9$ V and $-0.26\%/°C$ (our assumption; use the datasheet): $V_{oc}(-35°C) \approx 57.7$ V. Use at most 25 modules per string. A 26-module string reaches $26 \times 57.7 = 1{,}500.2$ V, marginal at 1,500 V, and a 28-module string about 1,616 V.
6. **PV layout.** Steepest practical fixed tilt (45° or more), bifacial modules over snow, AC-coupled.
7. **Surplus energy.** About two thirds of PV output is curtailed, mostly in summer. Winter yield sets the array size, so use the surplus (water heating, thermal storage) rather than shrinking the array.
8. **Altitude ratings.** Check PV inverter, cabinet and battery power-conversion altitude ratings and, for servers, the 3,000 m limit.

6.3 Wind

Wind is not simulated, and the data are not encouraging. Records for Leh airfield show gale-speed surface winds from April to October and relatively weak winds from November to March [7]. Surface winds at the Merak (Pangong) solar-telescope site are mostly below 5 m/s [8]. Chushul is reported above 7 m/s at 100 m above ground, but that is another site, an annual figure, and tall-tower height [9]. At 3,780 m air density is about 0.64–0.71 of sea level (our calculation), so a given wind speed yields about one third less power. For a generic rotor and Rayleigh winds we estimate a capacity factor of about 17% at a 6 m/s winter mean, 24% at 7 m/s and 30% at 8 m/s. Because winter energy and winter weather spells set the shortfall, a turbine would help only if its measured November–March output is high and not correlated with the PV lulls. We would reserve a turbine site and run a 12-month mast at hub height, adding 100–200 kW only if the measured winter capacity factor is about 25% or more after allowing for icing downtime.

6.4 Logistics

The design needs no fuel and no trucking, so road-closure risk for fuel disappears. Snow clearing, array snow loading and battery-room heating remain. We recommend measuring irradiance on the tilted plane, snow cover, temperature and hub-height wind from day one, and logging every hour below 120 kW; a year of site data would tighten the largest uncertainty, the weather spread.

6.5 Limitations

- **Value of lost load.** No VoLL is given for the site. The choice of 2,000 kWp follows from our working value of $5.27/kWh (INR 500/kWh) and is not robust to values below about $3.48 (INR 330) or above about $9.17 (INR 870).
- **Weather model.** Symmetric Gaussian clearness with an AR(1) correlation of 0.6 that we chose; no measured clearness spread, no seasonal difference, no snow-cover persistence, no soiling. Observational work at Leh points the same way: a sky radiometer has measured aerosol optical and radiative properties there for a year [21], a ceilometer shows frequent multi-layer cloud [22], and long visual cloud records exist at Hanle [23]. None of these gives a daily broadband irradiance series, so none was used to calibrate σ or ρ; the measured NIWE time series and reanalysis series in Table 7 could. The shortfall scales strongly with the spread (Table 20), and the summer risk is partly an artefact of the model.
- **Irradiance data.** The irradiance is a coarse reanalysis checked against other published figures and against measured monthly means at a station 34 km away and 528 m lower (NIWE, Section 5.2), not against measurements at the site. Digitised monthly values carry about $\pm 20\,\mathrm{W\,m^{-2}}$, and sources differ by about 10% on the annual mean, winter most. We could read only one source (Verma and Singh) in full and the others only as search snippets or short pages. Tilt gains, snow losses, performance ratio and derating are estimates. We also make no claim that independent solar-resource estimates agree at the site: satellite-derived products such as the ISRO VEDAS Solar Calculator (GHI from INSAT-3D and KALPANA-1) were not queried at the site coordinates, and a value for a different Ladakh location, product or averaging period is not a test of the NIWE comparison above.
- **Heating dispatch.** The dispatch serves the 10 kW heating whenever energy is available and has no look-ahead, so the core-load shortfalls include the effect of heating on the battery (Section 5.3). A dispatch that sheds heating early, or a protected-heating optimisation, would give different sizing results.
- **Battery ageing.** A linear fade from 100% to 80% over 12 years is our assumption, represented by 12 equally weighted annual health states. Calendar and cold-temperature ageing, cell imbalance and augmentation are not modelled, and the 12-year annualisation has no replacement.
- **Costs.** Only the diesel price, the ground-mount PV benchmark and the C&I LFP range have sources, and those are not for this site. The C&I LFP range comes from industry commentary by a company executive, who gives no source for it, and not from an independent market-price survey, so the battery cost is an assumption anchored to an indicative range. Remote multipliers and the discount rate are ours. The rupee figures are not quotes; the shape of the optimum is what matters.
- **Resolution.** One-hour steps and a half-sine PV profile; no sub-hourly cloud, no inverter clipping, no inverter efficiency curve beyond the 0.80 performance ratio.
- **No load flexibility.** We did not simulate throttling. If the load could be throttled, the same energy gap equals about 90 kW of average available power on a short day instead of 120 kW, but we cannot say how many outages it would remove.
- **Documented figures.** The documented figures for the initial configuration were used only as checks, and the underlying design was not available to us.

7 Conclusions

For a continuous 120,kW load at 3,780,m in Ladakh, the solar PV–battery system alone supplies 99.1

Data and code availability

All simulation, statistics and plotting code is in `ladakh_pv_battery_mc.py` (Appendix B). Every table and figure in this paper is produced by one run of that script, except the NIWE comparison of Section 5.2 (Table 9, Figure 2), which is produced by `niwe_crosscheck.py`.

A Weekly shortfall map

Wk	Dates	PV, Low MWh/d	P(shortfall), % Mid	Low	Short days, Low	Expected, MWh Mid	Low	Avg. kW, Low	If short, MWh, Low	95th pct. MWh, Low	Worst MWh, Low
1	1 Jan–7 Jan	6.4	19	28	0.54	0.26	0.39	2.32	1.38	2.34	10.3
2	8 Jan–14 Jan	6.4	18	26	0.51	0.25	0.37	2.20	1.40	2.36	12.4
3	15 Jan–21 Jan	6.4	17	26	0.50	0.24	0.36	2.14	1.40	2.31	12.9
4	22 Jan–28 Jan	6.4	17	26	0.50	0.24	0.36	2.16	1.40	2.21	9.9
5	29 Jan–4 Feb	7.0	16	23	0.44	0.21	0.31	1.84	1.33	2.03	9.8
6	5 Feb–11 Feb	7.4	14	20	0.38	0.20	0.29	1.70	1.41	1.99	13.1
7	12 Feb–18 Feb	7.4	13	19	0.36	0.19	0.27	1.61	1.41	1.89	14.7
8	19 Feb–25 Feb	7.4	14	20	0.37	0.18	0.27	1.59	1.36	1.80	11.4
9	26 Feb–4 Mar	8.8	13	16	0.29	0.17	0.22	1.30	1.36	1.53	10.1
10	5 Mar–11 Mar	9.8	10	11	0.20	0.14	0.15	0.89	1.38	1.03	8.2
11	12 Mar–18 Mar	9.9	9	10	0.18	0.12	0.13	0.76	1.28	0.87	7.4
12	19 Mar–25 Mar	9.9	9	10	0.18	0.12	0.13	0.77	1.31	0.92	7.6
13	26 Mar–1 Apr	9.9	9	9	0.17	0.11	0.12	0.72	1.29	0.84	7.7
14	2 Apr–8 Apr	10.5	7	7	0.13	0.09	0.09	0.54	1.21	0.61	6.5
15	9 Apr–15 Apr	10.5	6	7	0.12	0.09	0.09	0.53	1.34	0.49	9.6
16	16 Apr–22 Apr	10.4	7	7	0.13	0.10	0.10	0.60	1.35	0.64	7.6
17	23 Apr–29 Apr	10.4	7	7	0.13	0.09	0.09	0.55	1.27	0.62	7.3
18	30 Apr–6 May	10.9	6	6	0.12	0.08	0.09	0.51	1.33	0.45	6.8
19	7 May–13 May	11.0	6	6	0.11	0.08	0.08	0.49	1.34	0.34	10.0
20	14 May–20 May	11.0	6	6	0.12	0.08	0.08	0.49	1.34	0.40	6.2
21	21 May–27 May	11.0	6	6	0.11	0.07	0.08	0.46	1.26	0.34	6.1
22	28 May–3 Jun	11.3	5	5	0.09	0.07	0.07	0.41	1.32	0.05	6.5
23	4 Jun–10 Jun	11.6	5	6	0.11	0.07	0.08	0.45	1.32	0.26	7.6
24	11 Jun–17 Jun	11.6	5	5	0.10	0.07	0.07	0.43	1.34	0.12	8.9
25	18 Jun–24 Jun	11.6	5	5	0.10	0.06	0.06	0.37	1.16	0.11	8.2
26	25 Jun–1 Jul	11.6	5	5	0.10	0.07	0.08	0.46	1.43	0.10	8.0
27	2 Jul–8 Jul	11.0	6	6	0.11	0.08	0.08	0.48	1.31	0.39	8.4
28	9 Jul–15 Jul	11.0	6	6	0.11	0.08	0.08	0.47	1.30	0.32	9.0
29	16 Jul–22 Jul	11.0	6	6	0.11	0.08	0.08	0.50	1.30	0.40	11.1
30	23 Jul–29 Jul	11.0	6	6	0.11	0.08	0.08	0.47	1.26	0.30	8.6
31	30 Jul–5 Aug	10.8	6	6	0.11	0.08	0.08	0.48	1.32	0.32	7.1
32	6 Aug–12 Aug	10.7	6	6	0.11	0.08	0.08	0.48	1.27	0.37	10.2
33	13 Aug–19 Aug	10.7	7	7	0.12	0.08	0.08	0.51	1.22	0.52	6.7
34	20 Aug–26 Aug	10.7	7	7	0.12	0.08	0.09	0.51	1.28	0.57	7.0
35	27 Aug–2 Sep	10.7	6	6	0.12	0.08	0.09	0.52	1.38	0.38	7.5
36	3 Sep–9 Sep	10.7	6	6	0.12	0.08	0.08	0.50	1.30	0.43	11.9
37	10 Sep–16 Sep	10.6	6	7	0.12	0.09	0.09	0.53	1.33	0.48	9.4
38	17 Sep–23 Sep	10.7	7	7	0.13	0.09	0.09	0.56	1.30	0.67	12.1
39	24 Sep–30 Sep	10.6	7	7	0.13	0.10	0.10	0.61	1.40	0.55	10.9
40	1 Oct–7 Oct	10.1	9	10	0.17	0.12	0.13	0.76	1.34	0.92	8.0
41	8 Oct–14 Oct	10.0	10	11	0.19	0.14	0.15	0.87	1.38	0.95	11.3
42	15 Oct–21 Oct	10.1	10	11	0.19	0.14	0.15	0.90	1.38	1.08	11.3
43	22 Oct–28 Oct	10.1	10	11	0.20	0.15	0.16	0.96	1.47	1.14	9.9
44	29 Oct–4 Nov	8.3	13	16	0.29	0.16	0.21	1.25	1.29	1.46	8.5
45	5 Nov–11 Nov	6.9	15	22	0.42	0.21	0.31	1.83	1.37	2.02	10.6
46	12 Nov–18 Nov	6.9	15	22	0.42	0.20	0.30	1.77	1.36	1.99	9.7
47	19 Nov–25 Nov	6.9	16	23	0.44	0.21	0.31	1.87	1.37	1.98	10.7
48	26 Nov–2 Dec	6.6	16	24	0.45	0.21	0.32	1.89	1.31	2.06	9.7
49	3 Dec–9 Dec	5.8	23	33	0.68	0.29	0.47	2.80	1.41	2.69	12.1
50	10 Dec–16 Dec	5.8	23	34	0.71	0.32	0.50	2.98	1.48	2.91	11.9
51	17 Dec–23 Dec	5.8	22	33	0.70	0.32	0.50	3.01	1.51	2.95	12.7
52	24 Dec–31 Dec	5.8	25	37	0.81	0.35	0.56	2.92	1.50	3.04	13.8

Wk	Dates	PV, Low MWh/d	P(shortfall), % Mid	Low	Short days, Low	Expected, MWh Mid	Low	Avg. kW, Low	If short, MWh, Low	95th pct. MWh, Low	Worst MWh, Low

Table 23: Week-by-week shortfall map for 2,000 kWp and 3,000 kWh. Weeks are 7 days from 1 January (week 52 has 8 days). "P(shortfall)": share of years with any hour below 120 kW in the week. "Avg. kW": expected unserved energy divided by the week's hours, i.e. the mean power deficit over the whole week. "If short": mean unserved energy in the weeks that do have a shortfall. 95th percentile and worst week are over all 6,000 simulated years per case (12 annual battery-health states, 500 years each).

B Reproducing the results

The archive has this layout:

```
data/csv/    input CSV files 00-16 (the data of Section 3)
data/json/   their JSON conversion, written by csv_to_json.py
out/         figures (out/fig_*.pdf, .png), out/tables/*.csv,
             out/summary.json, out/data_sources_used.json,
             out/niwe_summary.json
*.py         csv_to_json.py, ladakh_pv_battery_mc.py,
             niwe_crosscheck.py, fetch_nasa_power_leh.py, ...
pv_battery_ladakh_paper.tex / .pdf
```

The scripts need Python 3.9+ with numpy, scipy, pandas and matplotlib. A full run takes some tens of minutes on one core. Run from the archive folder:

```
python csv_to_json.py                          # only if a CSV file changes
python ladakh_pv_battery_mc.py --out out --seed 2026
python niwe_crosscheck.py --out out
python csv_to_json.py                          # refreshes JSON file 16
```

(The last call is only needed because `niwe_crosscheck.py` rewrites CSV file 16.) Options: `-data-dir` selects another folder of JSON files, `-pv` and `-battery` select another design, `-years`, `-grid-years` and `-sens-years` set sample sizes (their defaults are read from J13), and `-quick` runs a small test. `niwe_crosscheck.py` imports the first script, uses the same seeds and sample sizes, and writes CSV file 16, `out/fig_niwe.pdf` and `out/tables/niwe_case_*.csv`. The main script writes the figures, the tables, `out/summary.json` and `out/data_sources_used.json`, after the verification checks of Table 8. `fetch_nasa_power_leh.py` is a separate helper whose download step is untested; its offline self-test (`-selftest`) passes. To compile the paper, run `pdflatex` twice in the archive folder.

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