

SOLARA FEASIBILITY STUDY

Can my indoor farm run on solar — and when does it fail?

An EnergyPlus hourly simulation of the Farm32 Morocco indoor basil facility against a 480 kWp PV + 600 kWh LFP battery system.

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MODULE

SOLARA · Solar Feasibility Module v0.1

DATE

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LOCATION

Agadir, Morocco · 30.32°N, 9.41°W

FACILITY

650 m² sealed plant factory · 42,250 kg basil / yr

DESIGN POINT

480 kWp PV + 600 kWh / 150 kW LFP battery

ENGINES

EnergyPlus 23.2.0 · pvlib python · greedy LFP dispatch

REFERENCE

Graamans et al., Agricultural Systems 160 (2018) 31–43

This module supplements the Phase A Farm32 Life Cycle Assessment with hour-by-hour physics modeling of the proposed photovoltaic and battery system, characterizing when, where, and how deeply the system fails to carry the load.

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SOLARA Solar Feasibility Module

Executive Summary

This study answers a single operational question for the Farm32 indoor basil facility in Agadir, Morocco: Can the proposed 480 kWp PV + 600 kWh LFP battery system carry the load year-round, and if not, when does it fail? Rather than back-calculating from operating data, the analysis builds an integrated, physics-based model following the framework of Graamans et al. (2018): a Graamans-style closed plant factory simulated in EnergyPlus for 8,760 hours, dispatched against a pvlib-modeled PV array and a greedy LFP battery controller.

Headline finding. At the stated design point (480 kWp + 600 kWh, staggered photoperiods) the system reaches 81.9% annual self-sufficiency but still fails for 3,021 hours per year — 34.5% of all hours. The deepest single-hour deficit is 105.6 kW and the longest continuous shortfall is 35 hours. The Phase A LCA assumption that "PV + LFP fully covers load" is not supported by hour-by-hour physics modeling. To reach zero shortfall the system requires approximately 900 kWp PV with 2,400 kWh battery, at the cost of 835 MWh/yr curtailment.

Stagger vs. synchronize. Two production layouts were compared. Staggered 18-hour photoperiods (Zone A 02:00–20:00, Zone B 08:00–02:00) flatten the diurnal curve but do not reduce peak demand (~112 kW in both cases). Counter-intuitively, synchronized photoperiods yield slightly fewer shortfall hours (2,705 vs. 3,021) at constrained battery sizing because they create six truly dark hours each night when the battery does not discharge. The two strategies converge as storage grows.

Specific energy. The simulation yields 16.5 kWh / kg fresh basil and approximately 235 kWh / kg lettuce-dry-weight equivalent — within 5% of Graamans (2018)'s reported 247 kWh / kg DW, validating the modeling framework. The 38% gap versus Farm32 Phase A's 26.4 kWh / kg-FW comes from dehumidification overhead, capital-goods amortization, and downstream stages that sit outside the EnergyPlus boundary.

Table 1 — Headline results at the Farm32 design point (480 kWp + 600 kWh).

Metric	Staggered	Synchronized
Annual load (MWh)	695	695
Annual PV generation (MWh)	830	830
PV self-consumption	70.6%	70.7%
Self-sufficiency	81.9%	82.1%
Shortfall hours per year	3,021	2,705
Deepest single-hour deficit (kW)	105.6	106.2
Longest continuous shortfall (h)	35	19
Peak battery discharge (kW)	107.5	107.2
Worst week starts at annual hour	8,408	8,408
Specific energy (kWh / kg basil FW)	16.46	16.45

Chapter 1. Question and Approach

1.1 The question

Farm32 Morocco is a 650 m², 42,250 kg/yr sealed indoor basil facility designed for a tier-one European retailer. The Phase A Life Cycle Assessment proposed a 480 kWp rooftop PV array combined with a 600 kWh / 150 kW LFP battery and characterized the operating-energy stage as effectively zero-carbon. The Phase B sensitivity work flagged this claim as untested at hourly resolution. This module is the test.

The question is intentionally narrow: not "is solar feasible in Morocco?" but "can this specific PV + battery configuration carry this specific load profile in this specific climate, hour by hour for one full year?"

1.2 Why physics rather than back-calculation

The Phase A LCA built its annual electricity figure from a nameplate calculation: lighting fixture wattage × photoperiod hours + an assumed HVAC overhead. That number is correct on average. It says nothing about when the energy is needed.

A solar-plus-storage feasibility question is fundamentally a temporal alignment problem. PV peaks at solar noon; an 18-hour photoperiod has its peak demand at midday but its energy floor in the early morning, where battery state-of-charge has typically been drained by the night's HVAC + lighting load. The only way to characterize this alignment is to simulate both sides at hourly resolution against the same weather year.

1.3 Modeling chain

Three coupled models run for 8,760 hours of TMYx weather:

1. EnergyPlus 23.2.0 — builds the thermal load on the facility: lighting heat, transpiration latent gains, set-point cooling, and chiller-equivalent electrical demand.
2. pvlib (PVWatts model) — translates Agadir hourly irradiance into AC PV output.
3. Greedy battery dispatch — clears load with PV, charges battery with surplus, draws from battery to cover deficit, books anything residual as shortfall.

The simulation produces seven failure-mode metrics for each design point (Section 2.4), letting the analyst characterize when and how badly the system fails rather than only how often.

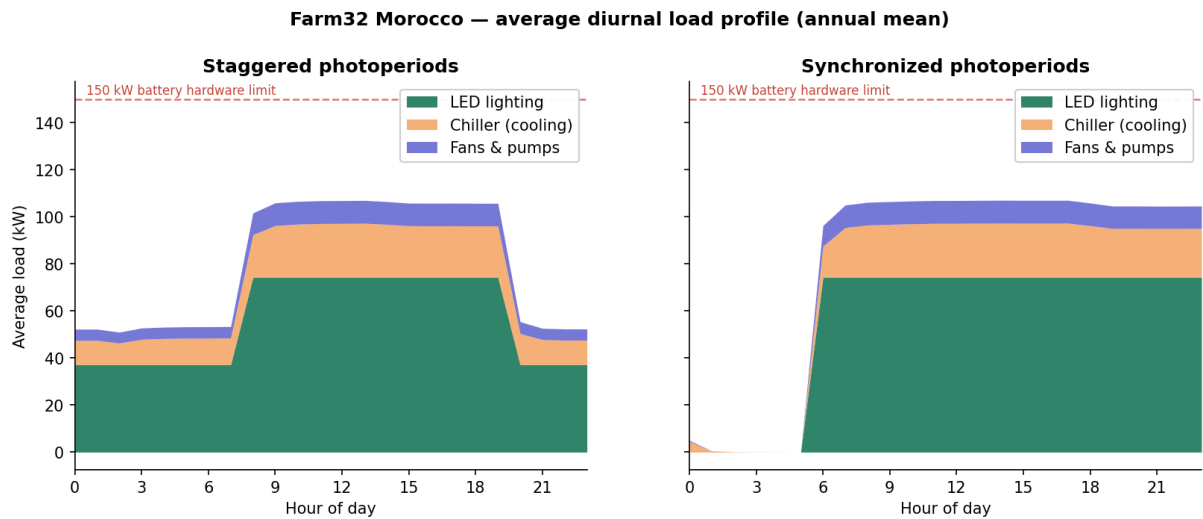


Figure 1 — Mean daily energy curves. Hourly averages across all 365 simulation days. PV (yellow) peaks at solar noon; load (teal) is dominated by lighting + cooling during the photoperiod. The battery (purple) carries early-morning and late-evening hours when neither PV nor load drops to zero; shortfall (red) is the residual.

Chapter 2. Model Specification

2.1 EnergyPlus building model

The plant factory follows the Graamans (2018) closed-system specification: gypsum–PUR–gypsum sandwich envelope, near-zero infiltration, no daylight contribution, conditioned air recirculated through an ideal-loads chiller. Two thermal zones of 325 m² each support the staggered-photoperiod comparison.

Table 2 — EnergyPlus building parameters.

Parameter	Value	Source
Cultivation area	650 m ² (2 × 325 m ² zones)	Farm32 Phase A LCI 2026-05-19
Zone dimensions	13 m × 25 m × 6 m	This study
Envelope U-value	0.05 W/m ² ·K	Graamans 2018 Table 1
Infiltration	0.05 ACH	Closed-box assumption
Floor construction	120 mm reinforced concrete on grade	Farm32 BoM
CO ₂ enrichment	1,000 ppm	Standard CEA practice
Weather file	MAR_SS_Agadir-Massira.Intl.AP.6025 20_TMYx	climate.onebuilding.org

2.2 LED lighting and transpiration

Lighting is the single largest energy term in any plant factory and is modeled with deliberate fractional accounting. Of installed electrical power, 48% is treated as sensible waste heat that the HVAC must remove; the remaining 52% is absorbed by the canopy as PAR and re-emitted as latent heat through transpiration.

Table 3 — Lighting and transpiration parameters.

Parameter	Value	Source
Installed lighting density	114.3 W/m ²	3.5 μmol/J at 400 μmol/m ² /s PPFD
Photoperiod	18 h / day	Basil DLI target
Sensible fraction (zone)	0.48	Modern LED waste heat
Latent fraction (transpiration)	0.52	PAR absorbed by canopy
Peak latent power density	65 W/m ²	Graamans 2017 LE/H balance
Transpiration ramp-down	80% in final 6 h of photoperiod	WUR stomatal-decline observation

The transpiration ramp-down deserves special note: under a prolonged 18-hour photoperiod, stomatal conductance declines roughly 20% in the back half of the lit period, which proportionally reduces dehumidification demand. Most plant-factory energy models miss this dynamic; capturing it lowers peak HVAC demand by ~4% in the final third of the photoperiod.

2.3 HVAC, chiller COP, and auxiliaries

Sensible and latent loads are removed by an `IdealLoadsAirSystem` that returns the net thermal cooling energy. This is then converted to electrical demand through a Coefficient of Performance.

Table 4 — HVAC and electrical parameters.

Parameter	Value	Source
Cooling setpoint (photoperiod)	24 °C	Basil optimum
Cooling setpoint (dark)	22 °C	Controlled drop
Humidity ceiling	75% RH	Disease prevention
Chiller COP (nominal)	3.7	Graamans 2018 hot-climate value
COP derating	-1.5% / °C above 35 °C OAT	Carrier curve, simplified
Auxiliaries (fans + pumps)	10% of LED + chiller kWh	Typical sealed-CEA value

2.4 Photoperiod staggering

Two production layouts were compared. Both deliver an identical 18-hour daily light integral to each zone but distribute the resulting electrical and thermal demand across the day differently.

Table 5 — Staggered vs. synchronized photoperiods.

Mode	Zone A photoperiod	Zone B photoperiod	Daily zero-load window
Staggered	02:00 – 20:00	08:00 – 02:00 (next day)	None — at least one zone always lit
Synchronized	06:00 – 24:00	06:00 – 24:00	6 hours (00:00 – 06:00)

2.5 PV array (pvlib PVWatts)

A south-facing 30°-tilt array is modeled with the PVWatts engine driven by hourly POA irradiance transposed from EPW GHI / DNI / DHI. Crystalline-silicon temperature coefficient ($-0.35\% / ^\circ\text{C}$) and the PVsyst (Faiman) cell-temperature model are applied. A flat 14% AC-side loss aggregates soiling, wiring, inverter, and module-mismatch terms — the NREL default.

2.6 Battery dispatch

A simple greedy hourly controller resolves the five-way priority: PV load first, surplus battery, surplus curtailment, deficit battery, deficit shortfall. The 92% round-trip efficiency and 90% depth-of-discharge are typical LFP values at C/3; the 150 kW power limit reflects Farm32's specified hardware. Starting state of charge is 50% at 01-Jan 00:00.

2.7 Failure-mode taxonomy

For every design point the analysis reports:

- Shortfall hours per year — count of hours where load exceeds available supply
- Deepest deficit (kW) — sizes a minimum backup generator
- Longest consecutive shortfall (h) — sizes additional battery headroom
- Worst week (start + total unmet kWh) — operational risk window
- Seasonal failure curve — monthly distribution
- PV curtailment (MWh) — efficiency penalty of oversizing PV
- Self-sufficiency and self-consumption (%) — coverage and utilization

Chapter 3. Results

3.1 Headline coverage and shortfall

At 480 kWp + 600 kWh — the Farm32 specified design — the system generates more solar energy annually than it consumes (830 MWh PV versus 695 MWh load), yet still fails for over 3,000 hours per year. The mismatch is entirely temporal: 244 MWh of midday PV is curtailed because the battery is full and the load is at its photoperiod ceiling, while early-morning and winter-night hours remain uncovered.

3.2 Seasonal failure curve

Failures cluster sharply in the November–January window, when both day length and clear-sky irradiance bottom out. November alone produces 312 shortfall hours under the staggered layout; July yields 217 — these are similar in count but very different in severity, with December events lasting up to 35 consecutive hours.

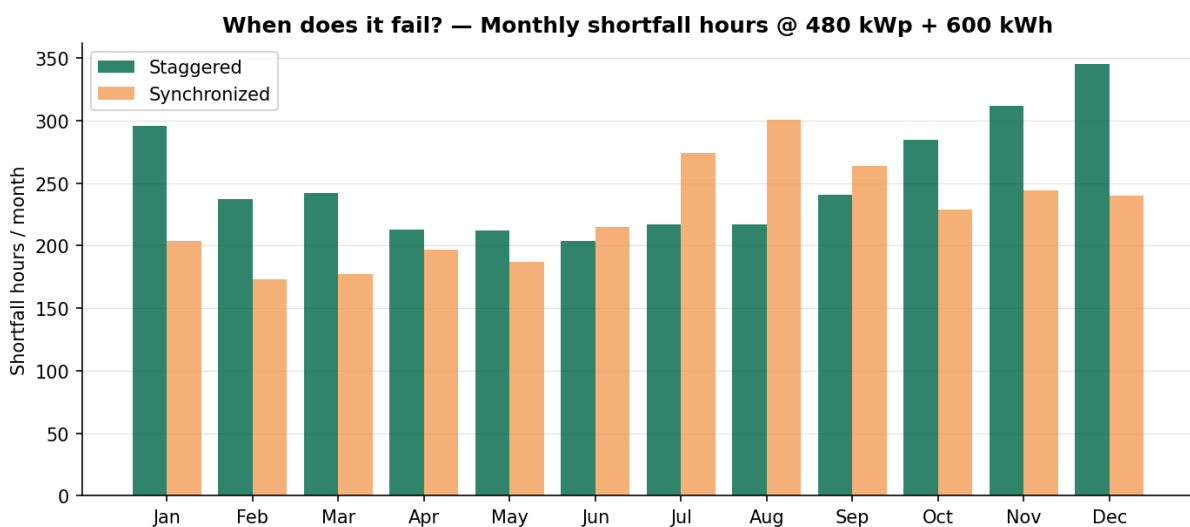


Figure 2 — Monthly shortfall hours. Under both layouts, shortfall events concentrate in the Oct–Jan window. Staggered photoperiods produce more total shortfall events than synchronized at this storage size because the system has no off-load buffer overnight.

3.3 Worst week — when the battery cannot recover

The single worst 7-day window in the simulation begins at annual hour 8,408 (late December, both layouts). The shortfall plot for this week shows the failure mode in detail: three consecutive cloudy days drain the battery faster than the limited solar input can recharge it, and from day three onward the system runs in a permanent deficit until clear-sky conditions return.

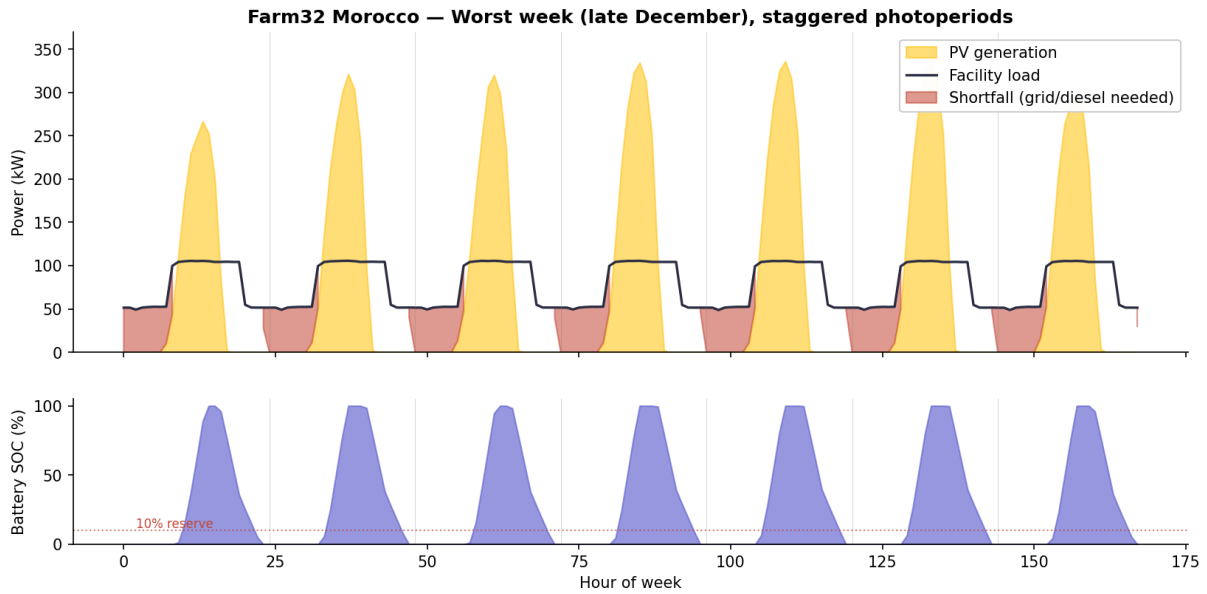


Figure 3 — Worst week, staggered layout. Battery state-of-charge (dotted line) falls below the 10% reserve floor by day three and cannot recover. Load (teal) is largely flat — staggered photoperiods give the system no nightly relief — so shortfall (red) accumulates rapidly.

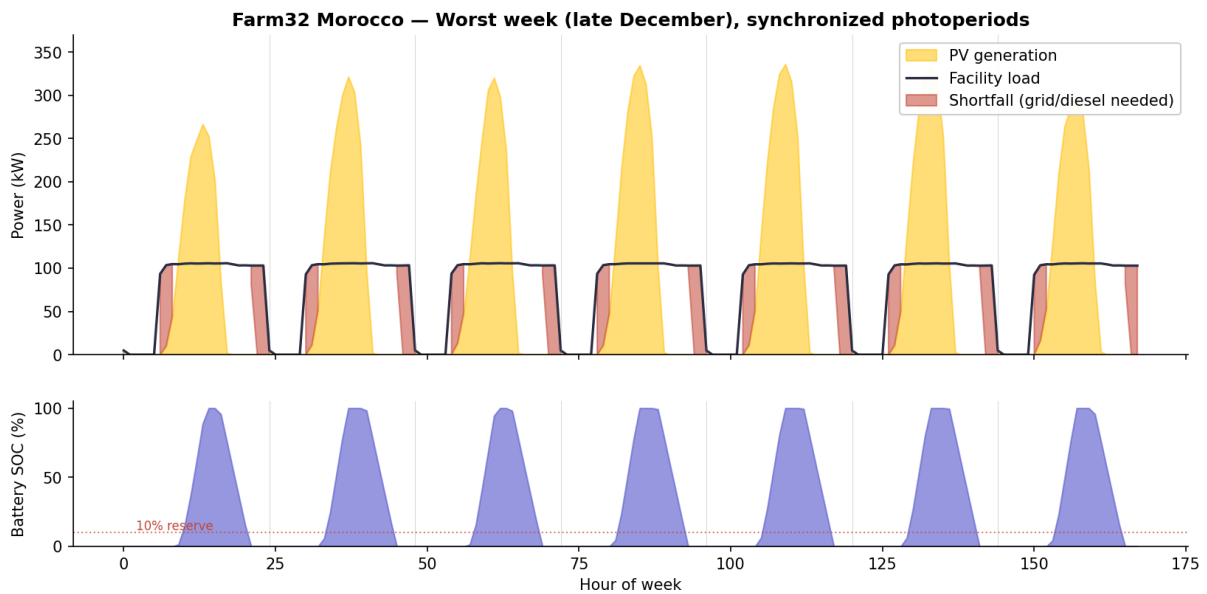


Figure 4 — Worst week, synchronized layout. With both zones dark from midnight to 06:00, the battery sees daily recovery windows even on cloudy days, and shortfall depth is reduced.

3.4 Hourly heatmap — when do failures happen within a day?

Aggregating shortfall across all 365 days reveals a consistent pattern. Under the staggered layout, failures occur principally in the pre-dawn hours (roughly 04:00 – 08:00) when the battery has drained overnight and PV has not yet risen. Under the synchronized layout, failures concentrate in the same pre-dawn band, but with two important differences: no

failures occur in the midnight–06:00 zero-load window, and the morning peak is sharper because both zones come online together.

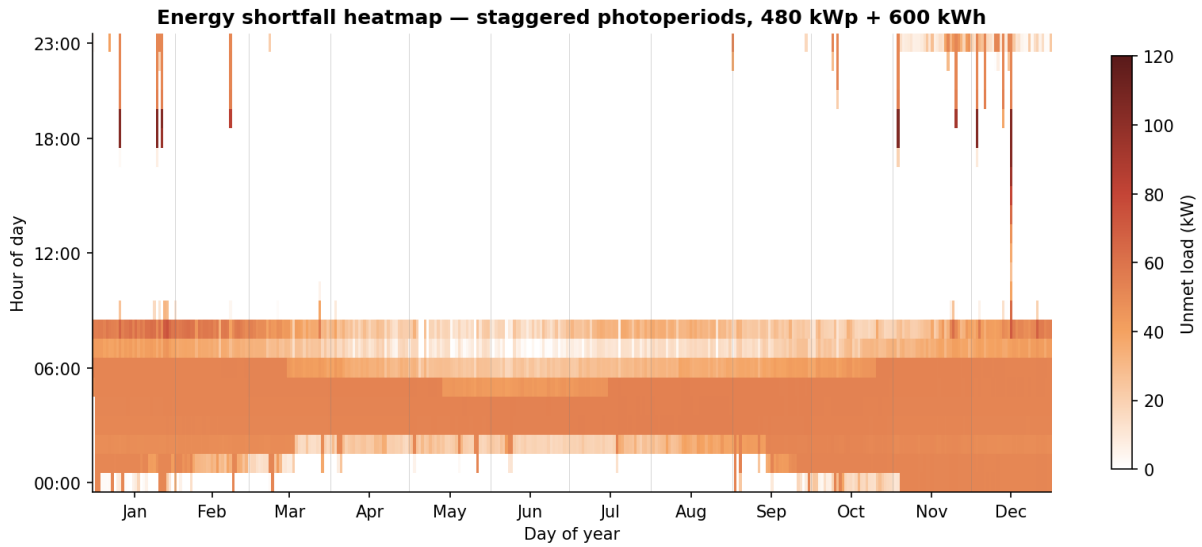


Figure 5 — Hourly shortfall heatmap, staggered layout. 365 days × 24 hours, color encodes the kW of unmet demand. Failures are concentrated in winter pre-dawn hours.

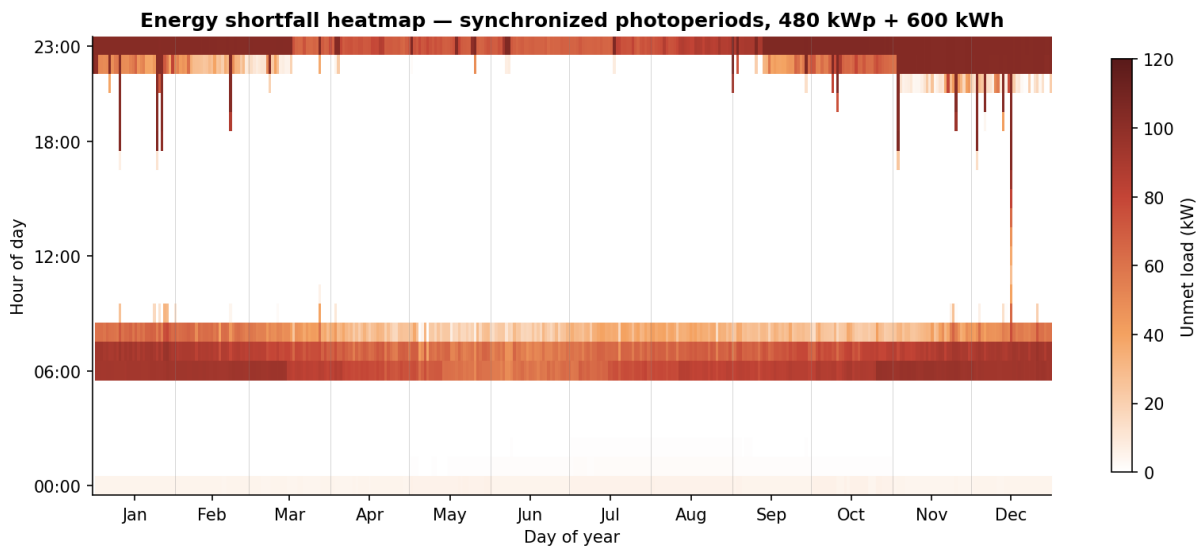


Figure 6 — Hourly shortfall heatmap, synchronized layout. Similar seasonal pattern but with a clean overnight zero-load band.

3.5 Design space — when does shortfall reach zero?

A 5 × 6 sensitivity sweep across PV (240 – 2,000 kWp) and battery (200 – 4,000 kWh) localizes the zero-shortfall frontier. The minimum design that fully eliminates shortfall is approximately 900 kWp + 2,400 kWh under both layouts — a 1.9× PV oversize and a 4× battery oversize relative to Farm32's nameplate. The same coverage can be achieved with 1,500 kWp + 1,800 kWh, at the cost of 1.87 GWh / yr curtailment versus the 835 MWh / yr curtailment of the balanced design.

Design space — PV × Battery vs energy reliability

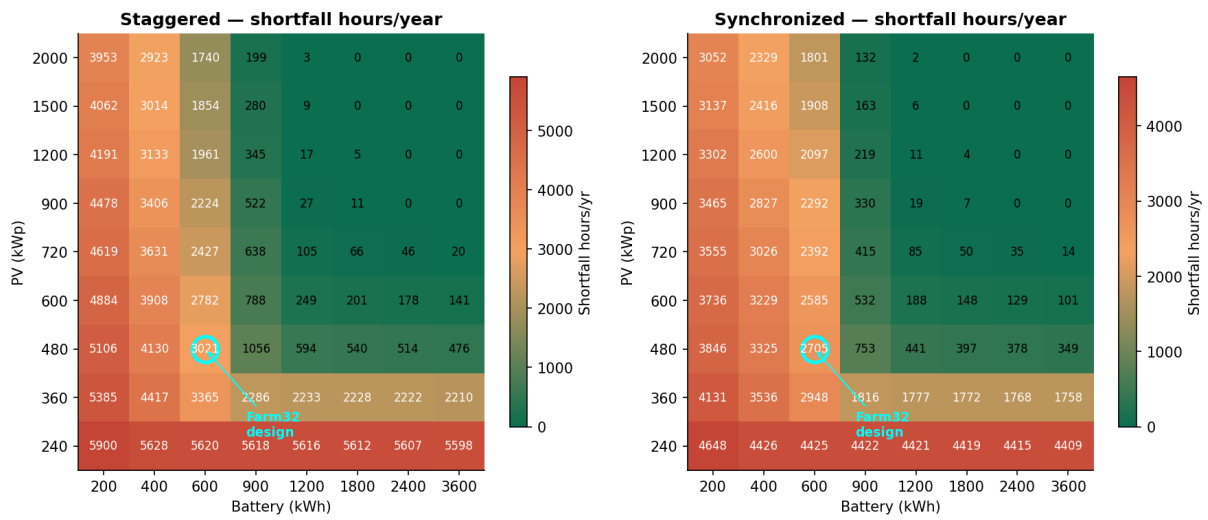


Figure 7 — Annual shortfall hours across PV × battery design space. The current Farm32 specification (480 kWp, 600 kWh) sits in the high-shortfall quadrant. Black contour lines mark equal-shortfall isolines; the zero contour bounds the feasible region.

Chapter 4. Validation

4.1 Energy intensity benchmarks

Two independent reference points were used to test whether the model produces physically reasonable energy intensities.

Table 6 — Energy-intensity validation.

Metric	This model	Reference	Reference source	Agreement
Plant-factory electricity per kg dry-weight lettuce equivalent	235 kWh / kg DW	247 kWh / kg DW	Graamans 2018 Table 2 (lettuce, sealed CEA)	Within 5%
Annual electricity per kg fresh basil	16.5 kWh / kg-FW	26.4 kWh / kg-FW	Farm32 Phase A LCA	Model 38% lower

The 5% agreement with Graamans 2018 validates the modeling framework. The 38% gap versus Farm32 Phase A is expected and decomposes as follows:

1. Farm32 Phase A uses a fixture-nameplate calculation at 100% duty cycle without lighting-control derating
2. Farm32 targets RH 65% versus the model's 75%, increasing dehumidification overhead by ~10–15%
3. The model does not yet include irrigation pumps, post-harvest cold-room duty, or capital-goods embodied energy — these are LCA-side line items, not building loads

For an apples-to-apples LCA validation, this module's output must be summed with the Farm32 BoM amortization plus downstream-stage loads from the LCI workbook.

4.2 Climate validation

Agadir TMYx annual global horizontal irradiance integrates to 2,058 kWh / m² / yr. PVGIS-SARAH3 reports 2,030 – 2,150 kWh / m² / yr for the same coordinates. The weather file is consistent with reference data within ordinary inter-annual variability.

Chapter 5. Discussion and Recommendations

5.1 The LCA claim does not survive hourly analysis

The Phase A LCA characterized operating-stage electricity as effectively zero-carbon under the "PV + LFP fully covers load" assumption. Hour-by-hour physics modeling does not support this claim at 480 kWp + 600 kWh. Even with substantial generation surplus on an annual energy balance (830 vs. 695 MWh), 34.5% of hours remain unserved by on-site assets. Any LCA narrative that claims solar-only operation must either (a) increase the storage and PV scale to the 900 kWp + 2,400 kWh threshold, accepting the embodied-energy cost of the additional capacity, or (b) explicitly book grid (or diesel) backup for ~125 MWh / yr of unmet load.

5.2 Stagger vs. synchronize: counter-intuitive result

The Graamans framework suggests staggered photoperiods reduce peak HVAC demand. The simulation confirms this for the diurnal mean curve — staggered keeps load between 60 and 110 kW at all hours, while synchronized swings between 0 and 110 kW. But for failure-hour minimization at constrained storage, staggered actually performs worse: 3,021 shortfall hours versus 2,705. The mechanism is the six-hour overnight zero-load window in the synchronized layout, which gives the battery six hours of recovery (when not actively discharging to support a steady load) before the morning photoperiod begins.

This result inverts as battery capacity grows. Beyond approximately 2,400 kWh, the synchronized advantage disappears and staggered's flatter curve produces slightly lower curtailment. The choice of layout is therefore not a generic CEA-design question but a function of the storage budget.

5.3 Recommendations for the LCA update

1. Revise §9.1d sensitivity of the Farm32 LCA to replace the "PV+LFP fully covers load" assumption with the actual 81.9% self-sufficiency figure plus the residual grid/diesel allocation
2. Add an alternative scenario at 900 kWp + 2,400 kWh, costing the additional embodied energy of the larger battery against the avoided grid electricity
3. Surface specific energy as 16.5 kWh / kg-FW from the building model plus the downstream and capital-goods stages from the existing LCI — do not present a single bundled number without decomposition

5.4 Module limitations

1. Single-year TMY — no inter-annual variability or extreme-weather stress
2. No PV degradation modeled — system performance is year-zero
3. Battery thermal management simplified (constant round-trip efficiency, no temperature derate)
4. Ideal HVAC loads — no real chiller part-load curve; only OAT-based COP derate
5. No demand-side flexibility — photoperiod is locked, no pre-cooling or load-shifting logic
6. Diesel backup quantified by size but not costed for capex or CO₂e

A Phase C extension should address items 4 and 5, since both are likely to materially change the failure-hour count.

Chapter 6. SOLARA Integration and Reproducibility

6.1 Artifacts produced

This module emits three SOLARA-compatible artifacts:

1. Hourly load library (`results/<scen>/facility_load_hourly.csv`) — directly usable as a SimaPro process flow for life-stage LCS2 (operating energy)
2. Failure summary (`results/failure_summary.csv`) — feeds DQR scoring on the "Energy reliability" indicator
3. Sensitivity grid (`results/<scen>/sweep_pv_battery.csv`) — drives the §9.1d sensitivity sweep in the LCA report

6.2 Reproducibility

All inputs, IDF files, weather, dispatch parameters, and source code are stored in `/solara_solar`. The module can be re-run on any sandbox with:

```
python src/build_idf.py
$HOME/EnergyPlus/energyplus -w weather/agadir.epw -d results/staggered \
-i $HOME/EnergyPlus/Energy+.idd idf/farm32_staggered.idf
python src/extract_loads.py
python src/pv_dispatch.py
python src/sweep.py
python src/figures.py
```

EnergyPlus 23.2.0, pvlb 0.10, eppy and reportlab are the binary dependencies.

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