# Solar Hop Universal Charging Pod — Design Reference

Nov 1, 2026 · @Collin Blaine George

## Bottom line

One charging pod serves every site. The pod itself — landing pad, charger, storage battery and controller in one weatherproof case — never changes. What changes is the power kit plugged into its two side ports: a large solar kit, a small folding solar kit, a grid kit, or a solar kit and a grid kit together.

A Solar Hop drone lands on the pad, charges in about an hour instead of most of a day, and flies on to the next pad or its recovery point. The pod needs no radio link, stores no mission data, and is safe to touch when no drone is on it. If a pod is dead or occupied, the drone falls back to charging from its own panels, so the network speeds the mission up but the mission never depends on it.

## Design principle

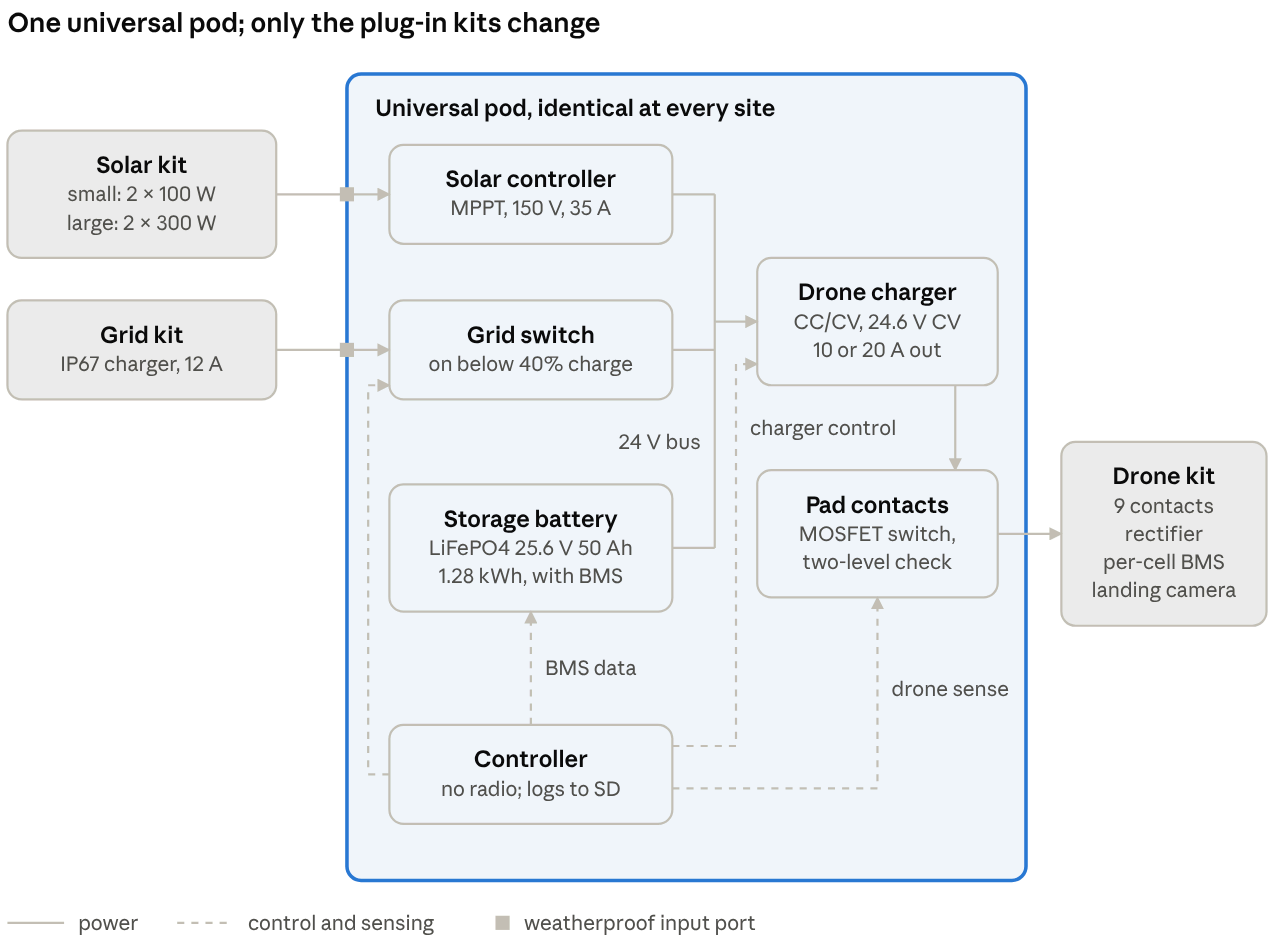
Every pod is built the same way. Site differences are handled outside the case by plug-in kits, so a pod can be built, tested and stocked as one part number and assigned to any site. This works because the pod's inputs are sized beyond the largest kit: the solar controller accepts up to 150 V and 1,000 W of panels at 24 V, and the grid input is a separate weatherproof port that stays capped where there is no grid. The only per-route setting is a switch inside the case that selects the drone type (quad 10 A, VTOL 20 A, or L1 9 A for both L1 aircraft); the hardware is identical.

The operating rule is the same in every configuration. Solar charges the storage battery first. If a grid kit is attached, the controller switches it on only when the storage battery falls below about 40% charge and off again at about 80%. The drone charger draws only from the storage battery, never directly from a kit, so drone charging behaves the same whatever is plugged in.

| Configuration | Plugged in | Behavior | Typical site |
|---|---|---|---|
| Fixed site, grid available | Large solar kit + grid kit | Solar first; grid tops up below 40% | Rooftop, farm building, depot |
| Remote, off-grid | Small folding solar kit | Solar only; pod declines a charge it cannot finish | Field route, ridge line, temporary survey |
| Grid only | Grid kit | Always ready; no solar | Shaded or indoor site, test bench |

A remote site with room can take the large kit instead when it needs more daily charges. The pod does not need to know which kit is attached.

## Engineering schematic




Pod schematic · power and control paths

Either kit feeds the 24 V bus through its own weatherproof port; the drone charger draws only from that bus. The controller powers the pad contacts only after a low-current sense check confirms a drone battery is connected. The controller has no radio hardware: it reads the battery and solar controller over wires and switches the grid input and the charger.

## Subsystem engineering

### Storage battery

A 25.6 V, 50 Ah lithium iron phosphate (LiFePO4, 8 cells in series) pack, 1.28 kWh, with a built-in battery management system (BMS). At rest its voltage is about 26 V at 20% charge (lower under load) and reaches 28.4–28.8 V at the end of charging; the BMS disconnects near 20 V. LiFePO4 is chosen over the drone's lithium-ion chemistry because it tolerates thousands of full cycles and is much less prone to thermal runaway in a sealed case left in the sun.

The pack must meet four requirements: a BMS rated for at least 50 A continuous; a charge rating of at least 25 A (0.5C); a low-temperature charge cutoff (typically no charging below 0 °C); and a wired data port (RS-485, CAN or UART). Many packs ship with Bluetooth; choose one without it, or one where it can be removed.

Currents are moderate at 24 V. The largest load, a VTOL charge, draws about 23 A from the pack (about 540 W). The largest charge input, the large solar kit plus the grid kit, could reach about 33 A (about 21 A of solar plus 12 A of grid). The controller therefore turns the grid input off whenever solar current exceeds 13 A, which holds total charge current at or below 25 A. The solar controller's own maximum charge current is also set to 25 A, because the large kit alone can reach about 27 A in cold, bright sun. The main battery fuse is 50 A, on 6 AWG cable rated above that. It must be a Class T or MRBF-type fuse with an interrupt rating above the pack's short-circuit current.

**Recovery from a flat battery.** Several measures keep a pod from stranding itself after a long cloudy spell:

- Drone charging stops at the 20% reserve.
- A low-voltage disconnect drops every load except the controller's sleep supply at 10%.
- The BMS must keep its charge path open while it is in undervoltage cutoff, so the solar controller and grid charger can still reach the cells.

- The latching grid relay is forced on by a hardware comparator below 15%, independent of firmware. This takes precedence over the firmware's solar lockout, which is why the pack's charge rating must cover 37 A (40 A specified).

Whether the specific solar controller and grid charger start into a deeply discharged pack must be confirmed on the bench.

## Solar input

A Victron BlueSolar MPPT 150/35 charge controller, rated 35 A and 1,000 W at 24 V. It is the model without Bluetooth and reports over a wired VE.Direct serial port. Two datasheet rules govern the panel strings:

- Panel voltage must exceed battery voltage by 5 V before the controller starts, and by 1 V while it runs.
- Open-circuit voltage must stay under 150 V in the coldest conditions (145 V to start).

Both kits are therefore two panels in series:

- **Large kit:** 2 × 300 W rigid panels. Each must have an open-circuit voltage of 40 V or less at standard test conditions (STC). The pair is then about 80 V at STC. Panel voltage rises in cold weather; at −40 °C, the NEC 690.7 correction puts the pair at about 100 V, still well under the 145 V limit. The 150 V controller is specified instead of a 100 V model because a 100 V model would be exceeded by common 72-cell 300 W panels (about 45 V each) on a cold morning.
- **Small kit:** 2 × 100 W folding panels. Each must have a maximum-power voltage of 20 V or more at STC. The pair runs at about 40 V. Panel voltage falls about 0.42% per °C as cells heat; at a 45 °C ambient (about 80 °C cell temperature) the pair drops to about 30.8 V, which still clears the 29.8 V the controller needs while finishing a charge (28.8 V plus 1 V). Simulation 1 showed 19 V panels fall to 29.2 V at that temperature and stop charging near full; the failure is lost output in extreme heat, not damage.

The large kit uses about 60% of the controller's rating. The controller's full output is rated up to 40 °C ambient (see Thermal design below).

## Grid input

An external Victron Blue Smart IP67 24/12 charger (120 VAC version, 100–135 VAC input, 12 A output, about 300 W at bulk-charge voltage and about 340 W at absorption voltage). It lives outside the case and plugs into the grid port, so the pod never carries mains voltage. Its Bluetooth is turned off permanently in VictronConnect before deployment; that

setting cannot be reversed. Inside the case, the grid input passes through an ideal diode and then a latching DC relay. The diode blocks reverse polarity and keeps the port pins dead when the lead is unplugged; the latching relay draws no coil power. A hardware comparator forces the relay on below 15% storage charge. The controller sets the relay:

- On below 40% charge, off at 80%. Both thresholds can be set; a grid-only site may hold a higher range.
- Off whenever solar current exceeds 13 A. The controller reads solar current about once a second over VE.Direct, so at a cloud edge total charge current can briefly reach 37 A (25 A solar plus 12 A grid) for up to about 2 seconds. That is within the 50 A BMS and fuse ratings.

Refilling from 40% to 80% (about 510 Wh) takes about 1.7 hours on grid alone. The grid also switches on whenever a drone is waiting that storage alone cannot finish, and the start decision credits 80% of the grid output over the charge. Without that rule, simulation 3 showed grid pods sitting idle with a drone waiting.

## Drone charger

A buck-boost constant-current/constant-voltage (CC/CV) DC-DC converter. Buck-boost is required because the storage battery (about 24 to 28.8 V) can sit below the drone pack's 25.2 V full-charge voltage; a buck-only converter loses regulation when storage is low. The converter must meet all of these:

- 20 to 29.2 V input.
- At least 25 A continuous output at 50 °C ambient.
- CV setpoint accuracy within ±0.5% (±0.13 V, or ±21 mV per cell).
- An enable input, and a current setpoint by analog, PWM or serial command.
- Efficiency of 93% or better.

Low-cost hobby modules sold as "600 W" typically need about 50% derating in a sealed case, so they do not meet this requirement as sold.

Charge current is set by the drone-type switch, once per route, with three positions: 10 A (1C) for the reference quad, 20 A (0.9C) for the reference VTOL, and 9 A (1C) for the L1-Q and L1-W. The pod cannot identify a pack (it has no data link, and cell count cannot be read from voltage), so a mismatched drone is not detected by the pod; the drone's own BMS is what protects it (see Contacts and drone detection). Each pack's cell datasheet must allow its rate; if a pack is rated only to 0.5C, halve the current and double the charge time.

**The 10 A and 20 A settings are valid only for the reference packs this document models (6S 10 Ah and 6S 22 Ah).** On a smaller pack the same current is a higher C-rate: on a pack of about 194 Wh, such as the L1-W's, 20 A is about 2.2C. Before a pod charges any other pack, set the current to no more than the lower of 1C (in amps, the pack's amp-hour rating) and the cell maker's maximum charge current. Then rerun the charge, thermal and protection simulations for that pack. For the L1 aircraft this has been done: the setting is 9 A (see Applying the design to the L1 aircraft).

CV is fixed at 24.6 V (4.10 V per cell). With the converter's ±0.5% accuracy the steady-state ceiling is 4.12 V per cell. That stops at roughly 90% charge and extends pack life. A charge from a 25% arrival takes about 1.1 hours (quad) or 1.3 hours (VTOL), per simulation 2, and an L1 charge from its 30% divert level about 0.86 hours (simulation package, section 14), plus 2% for the sense re-checks.

**Start and stop.**

- **Turn-on.** The converter is pre-biased just below the pack voltage before the switch closes, then current ramps from zero to the setpoint over 100 ms. Turn-on therefore never exceeds the setpoint (simulation 6).
- **Probe and pre-charge.** Every charge starts with 10 s at C/10 and stays at C/10 until the pad voltage under charge exceeds 19.5 V.
- **Already full.** A pack whose sense reading is 24.4 V or more is refused without powering the pad and without a fault. Powering it would hold the pad inside the overvoltage trip band.
- **End of charge.** Charging ends when current tapers to C/20 plus 0.3 A in CV, or after a 3-hour timer. The 0.3 A allows for the drone's avionics, which must draw no more than that while charging.

Revision 1's 25.2 V full-charge mode is removed: it cannot coexist with an overvoltage trip held at or below 4.20 V per cell.

The converter is not trusted to stop itself. Two independent paths open the pad (simulation 6):

- **Hardware.** A pad-side MOSFET switch opens within 10 µs when a latched comparator trips: overvoltage at a nominal 25.05 V (trip band 24.89–25.21 V, at most 4.20 V per cell), or more than 30 A. No firmware is in this path.
- **Firmware, at 1 kHz.** Overvoltage at 25.05 V; overcurrent at 1.25 × the present setpoint; undervoltage (below 15 V, or 2 V below the highest pad voltage seen in this charge, which catches a short); a two-level sense re-check every second in a 20 ms pause,

which catches a conductor bridging the strips; and a pad overheat alarm at 80 °C. Only these electrical faults count toward lockout. Ambient out of range, the timer and the storage reserve end a charge without a fault.

The drone pack's per-cell BMS is a third layer. Contact and cable resistance only lower the voltage the pack sees during charging, and that drop shrinks to zero as current tapers, so it cannot cause overcharge.

## Contacts and drone detection

**Pad.** Eight alternating positive and negative strips, 110 mm wide with 15 mm gaps (pitch 125 mm), spanning 0.985 m. The strips are gold- or hard-silver-plated copper or brass. Stainless steel is not used: its oxide layer gives high and unstable contact resistance.

**Drone.** A contact plate under the drone carries nine spring contacts, 10 mm across, on a 3 × 3 grid at 150 mm spacing. Each contact is rated at least 25 A, because all the charge current can pass through one contact.

**Rectifier.** Each contact has its own ideal-diode pair, one to the drone's positive rail and one from its negative rail, powered by the pack. Landing heading therefore does not matter. Revision 1 used shared LT4320 bridge controllers; the review showed that the return current could then pass through MOSFET body diodes when the positive and negative contacts sit on different controllers, at about 16 W per diode.

Simulation 5 verified this layout:

- every heading and offset puts at least one contact on each polarity;
- no contact can bridge two strips;
- it still holds with any two contacts failed, and with ±10 mm placement error;
- on the finite pad, at least 99.997% of landings succeed with landing scatter within σ = 100 mm.

Revision 1's five contacts failed on about 21% of landings if one contact failed.

**Sense check.** The pad is unpowered until the controller passes a two-level sense check:

- It applies about 29.5 V through a current limit of about 3 mA, then about 1 mA.
- A drone's pack clamps the pad near its own voltage at both levels. A battery changes by at most 0.12 V between levels; a film of water or debris changes by at least 2 V. With a pack on the pad, a wet film below about 47 kΩ is rejected; a higher-resistance film is accepted, because it can draw no more than about 0.5 mA.

- The controller accepts if the 3 mA reading is between 17.6 and 27.6 V and the two readings differ by 0.30 V or less.

An empty pad reads at least 28.5 V; a short reads near 0 V. Simulation 7 found no false accept and no false reject in 490,800 cases, across part tolerances, both rectifier conduction modes, and −20 to 60 °C. At 3 mA and under 30 V, the sense current is harmless. During charging the check repeats every second in a 20 ms pause, so a conductor that comes to bridge the strips while a drone sits on them is caught within a second.

**What the pod cannot detect.** The pod cannot tell cell count from voltage. A 5S pack, or a 6S pack with a shorted cell, reads inside the window, and charging it to 24.6 V would put 4.92 V on each cell. **Every drone pack must therefore carry a per-cell BMS:**

- per-cell overvoltage cutoff at 4.25 V;
- undervoltage cutoff;
- charge overcurrent cutoff at 35 A or more (above the pod's 30 A hardware trip, so the pod acts first);
- an NTC thermistor on the cells inhibiting charge outside 0–45 °C;
- a charge FET the flight controller opens before arming, so the contacts never break current at take-off; avionics drawing no more than 0.3 A while the pack charges, so the taper rule can end the charge.

Packs without such a BMS must not be used with the pod.

**Output switching.** The output path is a back-to-back MOSFET switch (normally off, rated 60 V, 40 A continuous, 150 A interrupt) followed by a sealed relay, with a bidirectional TVS and an RC snubber across the output to clamp the spike when the switch opens 30–80 A. The relay closes before the switch turns on and opens after it turns off, so it isolates but never switches current. Generic low-cost "DC SSR" modules are excluded: their voltage drop is high (about 30 W of heat at 20 A for a 1.5 V drop), and their current ratings are often overstated.

**One drone per pod.** With no radio, a drone cannot know a pod is occupied, so route plans must never schedule two drones to one pod at the same time.

## Cell balancing

A pad contact carries only the main charge leads, not a balance connector. An active 6S balancer mounted permanently on the drone pack keeps cells matched during every charge and in flight. Its added mass (an estimated 30 to 60 g) is to be confirmed on the

chosen part.

## Precision landing

Four 180 mm AprilTags sit on the pad's 200 mm insulated border, one per side. They cannot be printed on the strips, because ink over a strip insulates it. A downward camera of at least 120° horizontal field of view and at least 1,920 pixels across, with a 4:3 sensor, reads them. The companion computer computes the pad centre from whichever tags are in view and sends it to ArduPilot as MAVLink LANDING_TARGET messages. ArduPilot's documentation names AprilTag explicitly and describes the accuracy as "centimeter-level", without a measured figure.

Section 10 of the simulation package gives the geometry. With that camera, a tag spans at least 20 pixels below about 5 m and stays in view down to 0.42 m at the worst heading with a 4:3 sensor (a 16:9 sensor would lose the tags at 0.56 m). GPS brings the drone within view at 5 m, and the last 0.42 m is flown on the held target estimate. Revision 1's 120 mm tags left a 60° camera's view below 1.1 m.

The contact geometry needs landing scatter within σ = 100 mm. That figure is the acceptance criterion for landing tests on this airframe, in wind, rain and low light.

## Controller

A microcontroller board with no radio hardware (RP2040 or STM32 class). An ESP32 with radios disabled in firmware is not used, because the absence of a radio should be a hardware fact, not a setting.

It reads:

- the BMS (RS-485, CAN or UART);
- the solar controller (VE.Direct);
- the pad sense circuit and output current;
- shaded ambient, interior and pad (overheat alarm) temperatures;
- a lid tamper switch.

It drives:

- the grid relay;
- the output relay;
- the charger's enable and current setpoint, and the pad MOSFET switch (which the hardware comparators can also open on their own).

It logs charge sessions and faults to an SD card for collection on site.

Idle draw of the whole pod is about 1 to 2 W (25 to 50 Wh per day): the controller, the BMS, the solar controller's 15 mA at 24 V, and the sense circuit. The grid relay is latching and the output relay is energized only while charging, so neither adds to idle draw.

## Thermal design

The worst internal heat load is about 66 W: a VTOL charge at full sun, made up of 38 W from the converter, 18 W from the solar controller, 6 W of battery $I^2R$ loss, 2 W from the controller and 1.5 W from the pad switch. Simulation 8 (a steady-state lumped model) shows that a sealed case with that heat inside reaches 54 °C at only 25 °C ambient if white, or 62 °C if dark. That is above the 45 °C charging limit of both LiFePO4 storage and lithium-ion drone cells. The case is therefore:

- white;
- shaded on the lid and sides by the pad, which overhangs the case on standoffs;
- fitted with a through-wall aluminium heat-sink plate (0.25 K/W or better) carrying the drone charger, the solar controller and the MOSFET switch. That removes 87% of the internal heat directly, a fraction derived from where the parts are mounted. With the solar controller left inside, the interior would reach 48 °C at 35 °C ambient;
- fitted with a pressure-equalizing vent. A sealed case would see about 14 kPa (3.7 kN on the lid) over a 40 K daily swing.

With these measures the interior runs about 7 K above ambient, and the plate stays under 50 °C. The interior reaches the 42 °C derate point at 34.8 °C ambient (42.2 °C at 35 °C), so full-rate charging holds up to 34 °C ambient in full sun. An interior above 42 °C halves drone charge current, and above 45 °C the charge ends without a fault. In full sun the interior passes 45 °C at about 40 °C ambient even with no drone charging, from solar gain and the solar controller's loss. The integrated simulation confirmed this on a 43 °C day: the pod refused to start a charge at 41 °C ambient, and the storage BMS blocked solar charging for about 5 hours. The practical envelope is therefore full rate to 34 °C ambient in full sun, half rate from 34 to about 40 °C, and no charging above about 40 °C in full sun. Hot sites need shade over the case or a grid kit for evening charging. These are steady-state figures; the 12 kg battery's heat capacity slows the rise by hours.

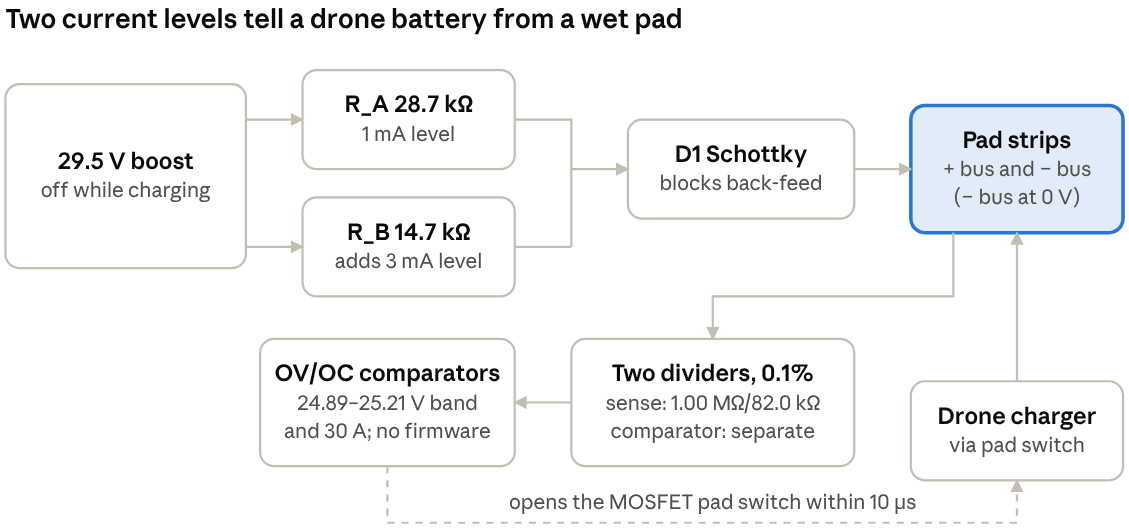
The pad surface reaches 50–65 °C in sun (plated strips have low emissivity and shed little heat by radiation), so pad temperature is not a proxy for cell temperature. Drone charging is gated by the pack's own NTC (in its BMS) and by a shaded ambient sensor on the pod

(0–45 °C). A pad sensor remains only as an overheating alarm (above 80 °C). A measured sun test must confirm the model before the case is committed.

# Detailed design

This section turns the simulation findings into buildable values. Each item traces to a simulation in the package (numbers in brackets).

## Sense and protection circuit




Sense and protection circuit · component values

The controller runs the two-level check with the output switch open and the charger disabled. With Q1 off, the boost drives the pad through R_A alone (about 1 mA into a short); with Q1 on, R_B sits in parallel (9.72 kΩ, about 3 mA). The sense divider stays across the pad at all times. It is high-impedance (1.08 MΩ) and built from 0.1% parts, so an open pad reads at least 28.5 V, outside the window by itself. D1 keeps the charger's output out of the sense source during charging, when the boost is disabled. The boost must have a true output disconnect, because an ordinary boost converter passes its input straight through when disabled.

The hardware overvoltage comparator has its own divider (0.1%, 10 ppm/K) and reference (0.1%, 20 ppm/K). With comparator offset and drift over −20 to 60 °C, its trip band is 24.89–25.21 V around a 25.05 V nominal: at most 4.20 V per cell, and 0.17 V above the CV maximum of 24.72 V. With 1% parts the band would be 24.3–25.8 V, which fails both ways (simulation 6).

The comparators are latched, and firmware clears the latch only while the switch is off. The sense check puts up to 29.5 V on an empty pad, which sets the overvoltage latch harmlessly because the switch is off then; firmware clears it and confirms it stays clear before turning the switch on.

Revision 2 put the band at 25.30–25.50 V. That is 4.22–4.25 V per cell, above the cell limit, and the second review caught it.

| Part | Value | Tolerance and rating | Why |
|---|---|---|---|
| Boost source | 29.5 V, ≤50 mA, true output disconnect | ±1%; enable pin | Stays under 30 V at +1%; open pad reads above the window |
| R_A | 28.7 kΩ | 1%, 0.25 W | ~1 mA level |
| R_B | 14.7 kΩ | 1%, 0.25 W | R_A ‖ R_B = 9.72 kΩ, ~3 mA level |
| Q1 | Small-signal P-MOSFET | ≥60 V; gate clamped by a 12 V zener | Switches R_B in; gate-source limit is ±20 V on a 29.5 V rail |
| D1 | Schottky, BAT46-class | ≥100 V, ≥150 mA | Blocks back-feed while charging |
| Sense divider | 1.00 MΩ / 82.0 kΩ | 0.1% | 29.5 V to 2.2 V; high impedance |
| ADC path | Unity-gain buffer, 12-bit ADC, external 3.3 V reference | Reference 0.2% (ADC path only; the OV comparator has its own 0.1% reference); Monte Carlo allows ±0.5% gain | The 76 kΩ divider source needs a buffer |
| OV comparator | Own 0.1% / 10 ppm/K divider, 0.1% / 20 ppm/K reference; nominal 25.05 V; latched | Band 24.89–25.21 V over −20 to 60 °C | Opens the MOSFET switch with no firmware in the path |

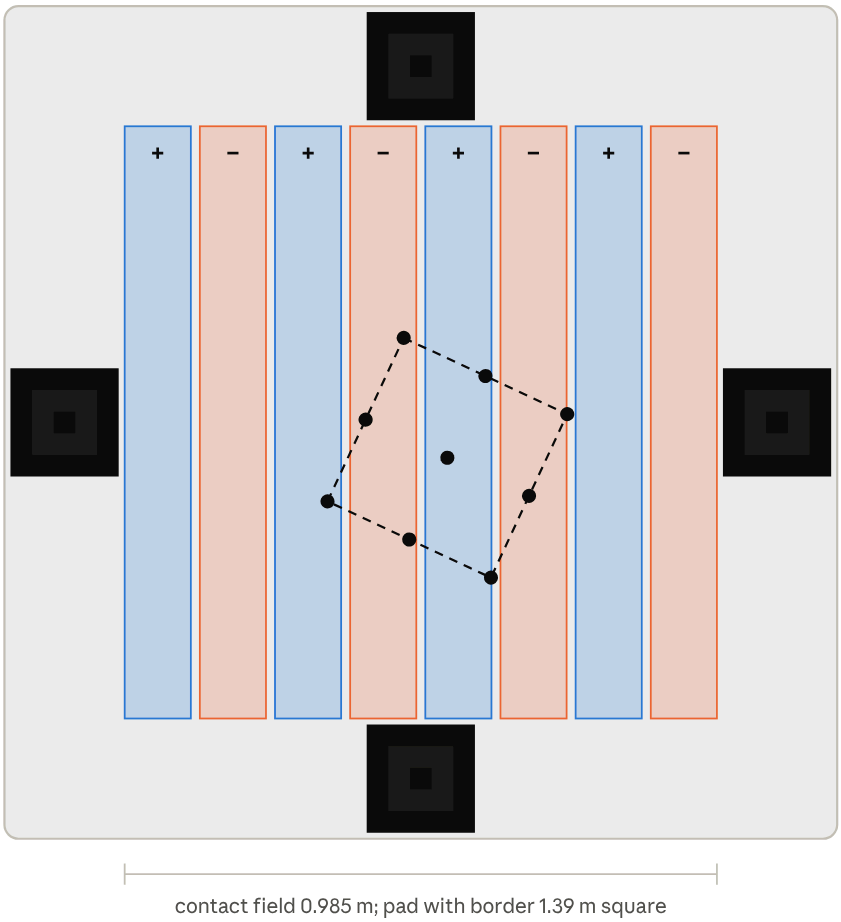
| Part | Value | Tolerance and rating | Why |
|---|---|---|---|
| Pad output clamp | Bidirectional TVS (≥30 V standoff, ≤58 V clamp) and RC snubber | Sized for opening 80 A into lead inductance | Keeps the 60 V switch inside its rating when it opens |
| OC comparator | 30 A on a 1 mΩ shunt | ±1% | 1.5 × the largest setpoint |
| Output current sense | 1 mΩ shunt and current-sense amplifier | ±1% | Firmware overcurrent at 1.25 × setpoint, taper rule |
| Pad output switch | Back-to-back N-MOSFETs with a high-side driver | 60 V, 40 A continuous, 150 A interrupt | Simulation 6 peak was about 80 A for 10–20 µs |

The firmware constants come from the tolerance Monte Carlo (two runs of 600 builds at −20, 25 and 60 °C; 490,800 cases; no false accept or false reject). Every build drew both rectifier conduction modes (active ideal diode, or MOSFET body diode) [7]:

- **Accept window:** 17.6 to 27.6 V on the 3 mA reading. Pack readings span 17.93–26.87 V, and the open pad reads at least 28.5 V.
- **Maximum change between levels:** 0.30 V. Packs change by at most 0.12 V; films inside the window change by at least 2.0 V.
- **Pre-charge:** every charge starts with 10 s at C/10 and continues at C/10 until the pad voltage under charge exceeds 19.5 V. The decision uses the voltage under current, when the rectifier conducts actively, so the rectifier's offset at milliamp levels (up to 1.25 V in body-diode mode) cannot mislead it. A sense reading of 24.4 V or more ends the session without powering the pad and without a fault (pack already full).

# Pad and contact layout

**Nine contacts on 110 mm strips reach both polarities at any heading**




**Strips**
8 strips, 110 mm wide
15 mm gaps, 125 mm pitch
alternating + and −
gold or hard-silver plated

**Drone contact plate**
9 contacts, 3 × 3 grid
150 mm spacing, ±3 mm
10 mm across: none can
bridge a 15 mm gap
works with 2 contacts failed

**Landing tags**
4 × 180 mm AprilTags on
the 200 mm insulated border
camera ≥120°, ≥1,920 px

**Requirement**
landing scatter σ ≤ 100 mm
gives ≥ 99.997% success

Pad and contact layout · top view, to scale

The contact field is eight alternating strips, 110 mm wide with 15 mm gaps, 0.985 m across [5]. The drone's contact plate has nine contacts on a 3 × 3 grid at 150 mm spacing. The four 180 mm AprilTags sit on a 200 mm insulated border, so the pad is 1.39 m square. The companion camera computes the pad centre from whichever tags are in view and sends that point as the MAVLink landing target. If a drone's contact grid is not 300 mm square, scale the strips by the rule in the drawing and re-run simulation 5.

## Controller states

| State | Pad | Entry | Actions | Exit |
|---|---|---|---|---|
| IDLE | Unpowered | Power-up; drone gone | Every 2 s: two-level sense check; shaded ambient 0–45 °C | Check passes → START |
| START | Unpowered | Sense passed | Pad empty → IDLE. Sense reading ≥ 24.4 V → DONE (already full). Required energy = charge energy minus 80% of grid output over the charge if a grid kit is present; grid on if needed | Storage can finish and a fresh sense check passes → CHARGE; storage short, or interior above 43 °C → WAIT |
| WAIT | Unpowered | Storage short | Pad empty → IDLE; grid on if present; recheck every 60 s | Storage sufficient and a fresh sense check passes → CHARGE |

| State | Pad | Entry | Actions | Exit |
|---|---|---|---|---|
| CHARGE | Powered | Relay closed; converter pre-biased below pack; switch on; current ramped over 100 ms | 10 s at C/10, then C/10 until pad > 19.5 V under charge; then 10, 20 or 9 A (drone-type switch); CV 24.6 V; interior > 42 °C halves current, > 45 °C ends the charge; every 1 s, 20 ms pause and two-level re-check | Faults (count toward lockout): OV 25.05 V; OC 1.25 × setpoint; UV (< 15 V, or 2 V below the running maximum; blanked during ramps); re-check showing a parallel path; pad > 80 °C; hardware OV 24.89–25.21 V or OC 30 A. Ends without fault: taper C/20 + 0.3 A at CV; open pad on the re-check (drone left, or its BMS opened the pack); 3 h; ambient out of range; interior > 45 °C; storage at 20% with no grid current → DONE |
| DONE | Unpowered | Taper, full, environment, timer, reserve | Switch off, then relay open; log session | Empty pad → IDLE |
| FAULT | Unpowered, latched | Electrical fault | Log; no retry for that drone | Empty pad → IDLE; 3 electrical faults in 24 h → LOCKOUT |
| LOCKOUT | Unpowered | Repeated electrical faults | Status light; out of service | Reset on site |

Every transition and trip in this table is implemented in the reference controller (controller.py, revision 3) and exercised by the test suite [6], including turn-on from START, a drone leaving during WAIT, a bridge across the strips during a charge, and a full pack landing.

## Configuration settings

| Setting | Value | Source |
|---|---|---|
| MPPT maximum charge current | 25 A | Simulation 3 |
| MPPT battery profile | LiFePO4, absorption 28.4–28.8 V per battery datasheet | Battery datasheet |
| Grid charger | LiFePO4 preset; Bluetooth permanently disabled | Victron manual |
| Grid on / off | Below 40% / at 80%; on for a waiting drone; forced on below 15% by hardware (takes precedence over the lockout) | Simulation 3; flat-battery recovery |
| Grid solar lockout | Grid off when solar current exceeds 13 A | 13 A + 12 A = 25 A |
| Grid energy credit | 80% of grid output over the charge | Simulation 3 |
| Drone CV | 24.6 V only | Simulations 2 and 6 |
| Drone current | Quad 10 A; VTOL 20 A; L1 9 A; 10 s C/10 probe; C/10 until pad > 19.5 V | Drone-type switch; simulation 6 |
| Turn-on | Converter pre-biased below pack; 100 ms current ramp; UV blanked during ramps | Simulation 6 |
| Already-full threshold | Sense reading ≥ 24.4 V: no charge, no fault | Simulation 6 |
| Interior start limit | No charge starts above 43 °C interior (WAIT until it cools) | Stress test |
| Charge end | C/20 + 0.3 A at CV, or 3 h; drone avionics ≤ 0.3 A while charging | Simulation 2 |

| Setting | Value | Source |
|---|---|---|
| Sense window / max change | 17.6–27.6 V / 0.30 V; re-check every 1 s (20 ms pause) during charge | Simulations 6 and 7 |
| Firmware trips | OV 25.05 V; OC 1.25 × setpoint; UV < 15 V or 2 V below running maximum; pad 80 °C | Simulation 6 |
| Hardware trips | OV 24.89–25.21 V (nominal 25.05 V); OC 30 A; latched; 10 µs | Simulation 6 |
| Lockout | 3 electrical faults in 24 h (environment, timer and reserve ends do not count) | Simulation 6 |
| Temperature | Shaded ambient 0–45 °C; drone cell NTC 0–45 °C (BMS); interior > 42 °C halves current, > 45 °C ends the charge | Simulation 8 |
| Load disconnect | 10% storage charge | Flat-battery recovery |

## Sizing

The figures below are outputs of simulation 3: a one-minute energy balance run over 14 days for each configuration, with a drone always waiting. The assumptions are stated so they can be replaced with site data:

- **Sun:** half-sine sun scaled to 4 peak-sun hours over a 12-hour day (a mid-latitude annual average), or 1.5 peak-sun hours over 9 hours (winter).
- **Losses:** a 75% derate from panel nameplate to energy stored.
- **Storage:** 98% discharge efficiency; used between 20% and 100% charge (1.02 kWh usable).
- **Idle draw:** 2 W.
- **Charge basis:** each drone arrives empty and is charged to 25.2 V, which overstates a typical charge. That draws 251 Wh from storage for the quad pack (6S, 10 Ah, 222 Wh) and 557 Wh for the VTOL pack (6S, 22 Ah, 488 Wh), per simulation 2.

| Configuration | Quad charges per day (4 / 1.5 PSH) | VTOL charges per day (4 / 1.5 PSH) | From storage alone (no sun) |
|---|---|---|---|
| Large kit, 2 × 300 W | 6.8 / 2.5 | 3.1 / 1.1 | 4 quad or 1.8 VTOL |
| Small kit, 2 × 100 W | 2.2 / 0.7 | 1.0 / 0.3 | 4 quad or 1.8 VTOL |
| Grid kit, ~300 W | 16 (charge time limits) | 12.7, one per 1.9 h (grid power limits) | Not limited |
| Large kit + grid | 16 | 14 | Not limited |

Under 30 days of random cloud cover averaging 4 peak-sun hours, the large kit averaged 6.8 quad charges per day (worst day 2, best 9), and the small kit 2.1 (worst 1, best 3). Storage never fell below the 20% reserve except by idle draw while no charge was running.

Winter sun is the binding case. Peak-sun hours can fall to roughly 1 to 2 per day in December at northern U.S. latitudes, and the 1.5-PSH columns cut the solar rows by about 60%. Size a site that must serve a set number of flights in winter on its worst month, using NREL PVWatts for that location, or give it the large kit or a grid kit.

**Spacing.** This is a design rule, not a derived value. Pods sit no farther apart than about 70% of the drone's rated range, leaving a reserve for headwind, a missed landing, and a diversion to the next pod. A pod that is occupied or faulted is treated as absent; the drone diverts or falls back to charging from its own panels.

## Parts list

The specification column is binding: a substitute part must meet every rating listed. Named products are examples that meet the specification, and none is required. Prices are single-unit estimates. Only the grid charger's price ($177.65, one U.S. retailer, November 2026) was checked against a listing; quote the rest before budgeting.

## Universal pod (identical at every site)

| # | Part | Specification | Purpose | Approx. cost |
|---|---|---|---|---|
| 1 | Storage battery | LiFePO4 25.6 V 50 Ah; BMS ≥50 A continuous; charge ≥40 A (covers the 37 A cloud-edge transient and the hardware grid force-on); low-temp charge cutoff; charge path stays open in undervoltage cutoff; wired RS-485/CAN/UART; no Bluetooth; 6,000-cycle cells for grid sites | Stores 1.28 kWh for drone charging | $450–650 |
| 2 | Solar charge controller | Victron BlueSolar MPPT 150/35 (150 V, 35 A, 1,000 W at 24 V, VE.Direct, no Bluetooth); maximum charge current set to 25 A | Charges storage from either solar kit | $250–300 |
| 3 | Drone charger | Buck-boost CC/CV; 20–29.2 V in; ≥25 A continuous at 50 °C; CV accuracy ±0.5%; enable and current-set inputs; ≥93% efficient | Charges the drone pack | $100–250 |
| 4 | Controller | RP2040 or STM32 board, no radio hardware; SD card; three-position drone-type switch (quad 10 A, VTOL 20 A, L1 9 A); independent hardware watchdog (100 ms) that turns the pad switch off and opens the relay if firmware stops | Charge logic, sense check, logging | ~$30 |

| # | Part | Specification | Purpose | Approx. cost |
|---|---|---|---|---|
| 5 | Relays (2) | Pad: back-to-back MOSFET switch (60 V, 40 A continuous, 150 A interrupt) plus a sealed isolation relay rated to break at least 150 A DC at 32 V (the backup if the switch fails closed); grid: latching DC relay behind an ideal diode. Not generic DC SSR modules | Switch grid input and pad output | $60–100 |
| 6 | Fuses | 50 A Class T or MRBF at battery; 15 A PV; 20 A grid; 30 A fast-acting pad output fuse; TVS and RC snubber across the pad switch output | Overcurrent protection | $70–90 |
| 7 | Landing pad | 1.39 m square overall: 0.985 m contact field plus a 200 mm insulated border carrying 4 × 180 mm AprilTags; rated for 2 kPa snow load; 8 alternating strips of gold- or hard-silver-plated copper or brass, 110 mm wide with 15 mm gaps; mounted on standoffs to shade the lid | Landing target, charge contacts, sun shade | $250–450 |

| # | Part | Specification | Purpose | Approx. cost |
|---|---|---|---|---|
| 8 | Sense circuit | 29.5 V boost with output disconnect; R_A 28.7 kΩ and R_B 14.7 kΩ (1%); Schottky blocking diode; 1.00 MΩ / 82.0 kΩ divider (0.1%) and ADC buffer; OV comparator with its own 0.1% / 10 ppm/K divider and 0.1% / 20 ppm/K reference; 30 A OC comparator; 1 mΩ shunt (see Detailed design) | Confirms a drone before the pad is powered | ~$25 |
| 9 | Enclosure | IP65/IP67 rugged case, white, pressure-equalizing vent; through-wall aluminium heat-sink plate ≤0.25 K/W carrying the charger, solar controller and pad switch | Weather and impact protection | $260–400 |
| 10 | Weatherproof ports | MC4 bulkhead (solar); Anderson SB50 or IP68 circular (grid); capped service port | Kit connections without opening the case | ~$60 |
| 11 | Sensors | Shaded ambient, interior and pad (overheat alarm) temperature probes; lid tamper switch; DC surge protector at the PV port (Type 2, Ucpv ≥120 V) | Temperature limits, tamper log | ~$60 |
| 12 | Wiring | 6 AWG battery leads; 10 AWG PV and output; ring terminals; cable glands | Internal power wiring | ~$50 |

| # | Part | Specification | Purpose | Approx. cost |
|---|---|---|---|---|
| 13 | Mounting | Adjustable legs; 4 auger ground anchors rated ≥1.5 kN each (covers 35 m/s wind with SF 1.5, even with all uplift on the windward pair); tie-down straps | Level and secure the pod | ~$120 |
| | **Pod subtotal** | | | **~$1,800–2,600** |

## Input kits (choose per site)

| Kit | Contents and binding specification | Approx. cost |
|---|---|---|
| Large solar | 2 × 300 W rigid panels, each Voc ⩽40 V at STC (wired in series); ground or roof frame; 10 m PV cable with MC4 | $350–500 |
| Small solar | 2 × 100 W folding panels, each Vmp ⩾20 V at STC (wired in series); stakes; 5 m PV cable with MC4 | $250–350 |
| Grid | Victron Blue Smart IP67 24/12 (120 VAC), Bluetooth permanently disabled; grid-port lead; plugs into a GFCI-protected outdoor outlet | ~$180–220 |

## Drone-side kit (fitted once per drone)

| Part | Specification | Approx. cost |
|---|---|---|
| Contacts | Contact plate with 9 spring contacts on a 3 × 3 grid at 150 mm spacing, 10 mm diameter, gold plated, each rated ⩾25 A continuous and 150 A for 20 ms, placed within ±3 mm | $20–40 |
| Ideal-diode rectifier | One ideal-diode pair per contact (9 pairs: high-side to the + rail, low-side from the − rail), MOSFETs ⩾60 V, ⩾25 A continuous, ⩾150 A for 20 µs | $30–60 |

| Part | Specification | Approx. cost |
|---|---|---|
| Active balancer | 6S active cell balancer | $15–25 |
| Landing camera | Camera board with on-board AprilTag detection, or a companion computer with radios disabled; MAVLink LANDING_TARGET output | $65–90 |

Each drone pack also needs a per-cell BMS (see Contacts and drone detection), about $20–40 if the pack lacks one. The camera needs a horizontal field of view of at least 120° and at least 1,920 pixels across. The whole drone-side kit adds an estimated 0.30 kg. By simulation 10 that costs a 3 kg multirotor about 13% of its endurance and a 3 kg fixed-wing about 9% of its range, so pod spacing must use the reduced range. Weigh the kit on the chosen parts.

# Deployment and operations

## Siting

1. Place pods along the planned route at no more than 70% of drone range apart.
2. Choose a level spot with open sky above the pad (no wires or branches within about 5 m) and, for solar sites, a clear southern view (northern in the southern hemisphere) from mid-morning to mid-afternoon.
3. Keep the pad at least 0.5 m off the ground where snow, standing water or tall grass is likely.
4. Record each pod's coordinates and pad heading in the flight plan; the drone uses GPS to reach the pod and the AprilTag for the final landing.

## Setup at a site

1. Set the pod on its legs, level it, and fix it with four auger anchors rated at least 1.5 kN each. Wind uplift on the pad exceeds the pod's weight at about 18 m/s (40 mph). Anchor the large-kit frame, and stake folding panels at every corner or bring them in before storms. At fixed sites, bond the case and pad frame to an earth rod.
2. Set the drone-type switch inside the case for the route's airframe: quad (10 A), VTOL (20 A) or L1 (9 A, both L1 aircraft). This is done once, at build or assignment.

3. Fixed site: mount the large panels on a ground frame, or on a roof subject to the code notes below. Run PV cable to the MC4 port. Plug the grid kit into a GFCI-protected outdoor outlet and the grid port.
4. Remote site: unfold the small panels beside the pod, angle them toward the sun, stake them, and connect them to the MC4 port.
5. Open the case only to read the SD card or update firmware; normal setup does not open it.
6. Confirm the status light: it shows storage charge and confirms the pad is unpowered.
7. Run one test landing and charge before adding the pod to live routes.

## Charge sequence

1. The drone lands on the pad using the tag.
2. The controller runs the sense check. If the two-level sense check fails, the pad stays unpowered and the drone lifts and lands again.
3. The controller checks shaded ambient temperature (0 to 45 °C) and storage charge; the drone's BMS separately blocks charging if its cells are outside 0 to 45 °C. If storage cannot finish the charge, the pad stays unpowered. The drone then charges from its own panels or continues to the next pod.
4. The output relay closes, then the MOSFET switch turns on. The charger ramps up over 100 ms, runs 10 s at C/10 and stays at C/10 until the pad voltage under charge exceeds 19.5 V, then runs constant current at the switch-selected rate, then constant voltage at 24.6 V, and stops when current tapers to C/20 + 0.3 A. Every second it pauses for 20 ms and repeats the two-level sense check; a failed check ends the charge as a fault.
5. The MOSFET switch turns off, then the relay opens. The drone's flight controller opens its BMS charge FET before arming and departs on its schedule. The session is logged.
6. The MOSFET switch opens at once on overvoltage (firmware 25.05 V; hardware 24.89–25.21 V), overcurrent, undervoltage, a failed re-check, or a pad above 80 °C.

## Maintenance

- Every visit or monthly: clean the pad contacts and the AprilTag, wipe panels, check legs and straps, pull the SD log.
- Seasonally: check panel angle, clear vegetation, inspect seals and cable glands.
- Yearly: check storage capacity from the log, replace the drone-side contacts if worn.
- Any sustained fault in the log (failed charges, high case temperature, tamper events) means the pod is taken out of the route until inspected.

### Moving a pod

Because pods are identical, relocating one means unplugging its kit, moving the case and plugging in the kit that fits the new site. Nothing in the pod needs to be reconfigured.

## Safety, regulatory and open questions

### Safety

- **Electrical.**
  - The pad is unpowered unless the two-level sense check passes. The sense source is limited to about 3 mA at under 30 V.
  - The pod never carries mains voltage.
  - Every source and load is fused, and the battery fuse is rated to interrupt the pack's short-circuit current.
  - The grid input has an ideal diode, so its port pins are dead when unplugged and reverse polarity cannot pass.
  - The grid kit plugs only into a GFCI-protected outlet.
- **Overcharge.** Three independent layers protect the drone pack:
  - the charger's CV setpoint, 24.6 V, which is at most 4.12 V per cell with tolerance;
  - the overvoltage cutoff: a latched hardware comparator (24.89–25.21 V, at most 4.20 V per cell, opening a MOSFET switch in 10 µs) and firmware (25.05 V);
  - the drone pack's per-cell BMS. This is the only layer that protects a wrong-cell-count pack or an unbalanced cell, which is why it is mandatory.
- **Short circuits and failures.** A pad short is caught by the undervoltage trip even when the converter's current limit works. A conductor bridging the strips while a drone charges is caught by the two-level re-check every second, with at most about 0.2 kJ delivered into it. A converter that loses regulation is cut by the hardware path within 1 ms at any drone state of charge (simulation 6).
- **Thermal.**
  - LiFePO4 storage.
  - A white, shaded case with the charger and pad switch on a through-wall heat sink.
  - Drone charging gated by the drone BMS's cell NTC and the pod's shaded ambient sensor (0–45 °C), and derated above 42 °C interior.
  - Storage charging limited by its BMS.

    - The drone's lithium-ion pack is the higher fire risk; any voltage, current or temperature fault stops the charge.
- **Physical.** Four anchors rated at least 1.5 kN each hold the pod against wind uplift up to 35 m/s with a 1.5 safety factor, even if off-centre pressure puts all the uplift on the windward pair. The pad surface is non-slip, with rounded edges.
- **Surge.** A Type 2 DC surge protector at the PV port, bonded to the case. Fixed sites are bonded to an earth rod. The pod has no lightning protection against a direct strike.
- **Unattended charging.** A drone charging alone in a field is the main residual risk. The controls available without a radio link are the protection layers above, siting away from dry brush and structures, lockout after three faults in 24 hours, and logging every session.

## Regulatory (United States)

- **Flight rules.**
    - A pod network implies flights beyond visual line of sight. Under Part 107, that needs a waiver of 14 CFR 107.31 (visual line of sight), granted under 107.205.
    - The FAA's proposed Part 108 BVLOS rule (90 FR 38212, August 7, 2025) would create a standing path. Its final rule has been under OIRA review since July 10, 2026, and as of late October 2026 no publication date had been announced.
    - The drone needs Remote ID (14 CFR Part 89).
- **Electrical code.**
    - Fixed-site solar falls under NEC Article 690 and local permitting. The string's cold-weather maximum voltage is calculated under 690.7.
    - A roof-mounted array may bring in the rapid-shutdown requirements of 690.12; a ground mount avoids them.
    - A plug-in grid kit on an existing GFCI outdoor outlet usually needs no permit, but local rules govern.
- **Shipping.**
    - The storage battery (1.28 kWh) and both drone packs (222 Wh and 488 Wh) are lithium-ion batteries over 100 Wh. Each must be of a type tested under UN 38.3, with a test summary available, under 49 CFR 173.185(a).
    - Each falls outside the small-battery exception in 173.185(c) and ships as Class 9 hazardous material.
- **Land access.** Each pod needs the landowner's written permission. Public land generally needs a permit.

- **Radio-frequency emissions.** The pod contains switching converters and a microcontroller, so it is an unintentional radiator under 47 CFR Part 15 Subpart B. A marketed product needs Class A or B verification. A builder's own units fall under the home-built provision (47 CFR 15.23: no more than five, not marketed) but must not cause harmful interference. Mitigations: the metal heat-sink plate as a ground plane, short switching loops, and ferrites on the PV and pad leads.

## Open questions

1. **Contact reliability.** Wear and corrosion of plated strips and spring contacts over months outdoors. Needs bench mate/unmate cycling, salt-fog exposure and a season in the field, tracking contact resistance against the 5 mΩ assumption.
2. **Contact geometry on hardware.** Landing tests to confirm the simulated result: one contact on each polarity at every heading, no bridge, and tolerance to two failed contacts.
3. **Landing accuracy.** Landing scatter for this airframe in wind, rain and low light must be within σ = 100 mm, including the last 0.4 m flown on the held estimate. An illuminated or retroreflective tag may be needed.
4. **Drone mass and range.** The estimated 0.30 kg drone-side kit costs about 9–13% of range on a 3 kg airframe (simulation 10). Weigh it, then re-space pods.
5. **Thermal performance.** The steady-state model needs a sun test of the built case: interior, heat-sink and pad temperatures at full charge load.
6. **Snow, ice and debris.** Snow covers the contacts, and the pad must carry 1.9–3.8 kN of snow load. Decide whether cold sites need a sloped or heated pad.
7. **Start-up into a flat battery.** Confirm on the bench that the chosen solar controller and grid charger start into a pack whose BMS is in undervoltage cutoff.
8. **Charger and BMS interaction.** Confirm on real packs that the drone BMS's charge FET, balancer and avionics draw behave as modelled during a full charge, including taper termination.
9. **Theft and tampering.** At remote sites, the no-radio design can log these but not prevent them.
10. **Prior art.** The search so far finds:
    - US 11,728,663 B2 (priority 2018, active). Its claim 1 covers a solar-powered station with storage, a landing platform, and sensing of the drone before energy is transferred, by inductive charging. This pod charges through conductive contacts,

which claim 1 does not recite. That distinction needs review by a patent attorney before any claim of freedom to operate.

- Florczak et al. (2025). Solar-powered stationary and portable docking stations for quadrotors, operated as a networked system.
- DJI Dock 2. Requires an internet connection (Ethernet or 4G) for setup and operation.

Solar power, off-grid operation and drone sensing before charging are therefore not new on their own. What remains distinguishing is the combination: no radio hardware, a polarity-independent multi-contact conductive pad, and one identical pod with plug-in power kits. Novelty of that combination needs a full patent search.

## Simulation results

Revision 3 of this design rests on three checks, delivered in the release package SolarHop_Pod_v1.1.0.zip (code, executed notebook, figures):

- seven simulations;
- three engineering analyses;
- a 165-check pass/fail suite (119 pod checks, 37 on-board solar checks and 9 L1 checks), including the integrated mission, the doc-to-code audit and the stress test below.

Two independent reviewers, each given only this document and the code, found 15 problems in revision 1 and 19 in revision 2, two of them critical each time. Each was reproduced, then fixed or stated as a limit; REVIEW.md in the package lists every finding and its fix. That a second review still found critical problems is the reason this design is not called finished. The analyses also covered areas revision 1 had not analysed: thermal, wind, snow, enclosure pressure, contact physics, tag visibility, drone mass, wiring, surge, emissions and storage life.

| # | Check | Finding | Status |
|---|---|---|---|
| 1 | PV string voltage, −40 to +45 °C | 150 V controller holds with 60- or 72-cell panels (95.6 / 109.0 V); a 100 V controller fails with 72-cell panels. Small-kit panels at Vmp 19 V stop charging near full at 45 °C | Small kit Vmp ≥ 20 V |

| # | Check | Finding | Status |
|---|---|---|---|
| 2 | CC/CV drone charge | Quad 1.08 h, VTOL 1.29 h from 25%. Steady-state ceiling 4.12 V per cell at +0.5% | 24.6 V only; full-charge mode removed |
| 3 | Energy balance | Solar charges per day confirmed (6.8 / 2.2 quad). Grid pods idled under the storage-only start rule | 80% grid credit; MPPT limit 25 A; cloud-edge transient ⩽ 37 A for ⩽ 2 s, within ratings |
| 4 | Sense check concept | A single-level check is fooled by water or debris films | Two-level check |
| 5 | Contact geometry | Five contacts lose about 21% of landings if one contact fails | Nine contacts on a 3 × 3 grid, 110 mm strips; tolerates two failed contacts and ±10 mm build error; ⩾ 99.997% with σ = 100 mm scatter |
| 6 | Fault injection, 10 µs plant, 1 kHz firmware | Rev 1 relay had to break up to 125 A; a pad short with a working current limit went undetected. Rev 2 could power the pad after a drone left during WAIT, missed a conductor bridging the strips under a drone, and never simulated turn-on | MOSFET switch with hardware OV/OC (opens within 1 ms at every state of charge, alone if firmware fails); UV trip; WAIT exits on an empty pad; fresh sense check before power; 1 s sense re-check (⩽ 0.2 kJ into any bridge); ramped turn-on; already-full refusal; full state machine implemented and tested |

| # | Check | Finding | Status |
|---|---|---|---|
| 7 | Sense circuit, component level, 1,200 builds | Rev 1 OV divider tolerance put the trip at 24.8–26.0 V; open pad could read inside the window; rectifier mode unmodelled. A 5S pack cannot be told apart by voltage | 0.1% dividers, 29.5 V boost, window 17.6–27.6 V: no false accept or reject in 490,800 cases. Per-cell drone BMS mandatory. Overvoltage trip moved to 25.05 V, band 24.89–25.21 V derived from tolerances and drift (rev 2's 25.30–25.50 V sat above 4.20 V per cell) |
| 8 | Case thermal | Sealed case with internal converter reaches 54 °C at 25 °C ambient. Pad surface reaches 50–65 °C. Leaving the solar controller inside gives 48 °C at 35 °C ambient | Heat-sink plate (0.25 K/W) carrying charger, solar controller and switch; white case; side shading: full rate to 34 °C ambient, reduced to about 40 °C, no charging above about 40 °C in full sun (confirmed by the integrated simulation). Pad temperature no longer gates charging |
| 9 | Wind, snow, pressure, contacts, magnetic field, wiring | Uplift exceeds weight at 18 m/s; sealed case sees 14 kPa; one contact can carry all 20 A; strip field is comparable to Earth's while charging; all wiring drops under 1% | 1.5 kN anchors (sized for all uplift on the windward pair); vent; 25 A contacts; no compass alignment until the charge ends |

| # | Check | Finding | Status |
|---|---|---|---|
| 10 | Tag visibility, drone mass, storage life | 120 mm tags leave view below 1.1 m on a 60° camera; kit costs 9–13% of range on a 3 kg drone; storage cycling gives 9–15 years at solar sites but about 4 years (3,000-cycle cells) at a grid site serving VTOLs continuously; a 16:9 camera loses the tags at 0.56 m | 180 mm tags, ⩾ 120°, ⩾ 1,920 px, 4:3 camera; spacing uses reduced range; 6,000-cycle cells for grid sites |

The simulations and analyses use representative coefficients, not measurements of purchased parts:

- panel temperature coefficients;
- pack resistances and cell OCV curves;
- solar derate and sun profile;
- convection coefficients;
- wind pressure coefficient;
- contact film resistance;
- the decodable tag size.

The pod mass (45 kg) and the drone-side mass (0.30 kg) are estimates. Every parameter sits in params.py or analysis.py so that measured values can replace it and the suite can be rerun. Revision 3 is a twice-reviewed, simulation-checked design that has not been built or tested. The open questions above list what only hardware can settle.

## Final integrated verification

The last check runs every model together, in sequence, over three days at one pod with the large solar kit and grid kit, at 1 s steps (simulation package, section 11). In each step:

1. sun and ambient set the solar controller (25 A cap) and the grid rules;
2. storage is balanced;
3. case temperature follows from the live internal losses;
4. a drone lands on the finite pad with σ = 100 mm scatter and a random heading;

5. the component-level sense circuit, from one randomly built pod, checks the pad;
6. the same reference controller used in the fault simulations decides;
7. the pack charges through the CC/CV physics with 0.25 A of avionics draw;
8. the drone's BMS watches its cells.

The three days are mild (15–28 °C), hot (27–43 °C) and cold (−4 to 12 °C). The 10 µs electrical transients are covered by simulation 6; here the controller runs at 1 s.

| # | Event | Expected | Outcome |
|---|---|---|---|
| 1 | Quad at 25% | Charge to taper | Charged to 91%; peak cell 4.09 V |
| 2 | Quad at 95% | Refused, no fault | "Already full"; pad never powered |
| 3 | Quad on a wet pad (30 kΩ film) until it dries | No power while wet | Waited 20 min unpowered; then charged to 91% |
| 4 | 2 Ω metal bridge appears 10 min into a charge | Fault | Caught by the 1 s re-check; 255 J into the bridge |
| 5 | First landing off the field | Re-land, then charge | One re-land; charged to 91% |
| 6a | 5S pack at 40% on the quad route | Ends safely | Stayed in C/10 pre-charge; timer ended it at 3.85 V per cell |
| 6b | 5S pack at 80% on the quad route | Drone BMS stops it | BMS opened at 4.25 V per cell; pod ended without a fault |
| 7 | VTOL at 20%, hot morning | Charge to taper | Charged to 91%, briefly derated |
| 8 | VTOL at 41 °C ambient, full sun | No charge (interior above 45 °C) | Ended at once, "interior temperature" |
| 9 | Converter fails high during a charge | Hardware trip | Cut by the overvoltage comparator |
| 10 | VTOL after two faults | Charge (no lockout yet) | Charged to 91% |
| 11 | VTOL at −3 °C dawn | Wait for 0 °C, then charge | Waited 120 min unpowered; charged to 91% |

| # | Event | Expected | Outcome |
|---|---|---|---|
| 12, 12b | Bridges on two more charges | Faults; lockout on the third within 24 h | Fault, then lockout |
| 13 | VTOL at the locked-out pod | Not powered | Pad never powered |

All 15 events ended as expected. On every one of the 259,200 steps:

- the pad was never powered without a drone, nor without a passing sense check immediately before power;
- no charged 6S cell exceeded 4.09 V, and the misloaded 5S pack stopped at 4.25 V per cell by its own BMS;
- storage never fell below 49%;
- lockout came at exactly the third electrical fault in 24 hours.

The integrated run found two things the separate simulations had not, both now corrected in this document and the code:

- **Drone BMS cutoffs counted as faults.** A drone BMS opening its pack (or a drone lifting off) showed up on the re-check as an open pad and was counted as an electrical fault toward lockout. An open pad now ends the charge without a fault; a parallel path is still a fault.
- **The heat envelope was overstated.** On the 43 °C day the interior passed 45 °C from sun alone at about 40 °C ambient. No charge could start, and the storage BMS blocked solar charging for about 5 hours. The stated envelope is now full rate to 34 °C, reduced to about 40 °C, and no charging above about 40 °C in full sun. At the 45 °C stop point the interior overshot by up to 1.1 °C for one 1 s step before the rule acted.

A doc-to-code audit then checked the exported text of this document against the code. All 38 design values the code relies on (re-run for release 1.1.0) appear here with the same numbers, from the CV setpoint and trip thresholds to the sense resistors, strip dimensions, heat-sink rating and anchor rating. No superseded value appears outside a sentence that says it was superseded. The overvoltage band derived from part tolerances (24.91–25.19 V) lies inside the specified 24.89–25.21 V.

**What this verification does and does not establish.** It shows that the design is internally consistent: the document, the parameters, the controller logic and the physics models agree, and the combined system behaves as specified across the scripted events. It does

not show that the models match the parts that will be built. That still takes a third independent review, ideally by a licensed electrical engineer, and the bench and field tests listed under Open questions.

## Stress test: weather, power and failures

The stress test drives the full system through random and extreme conditions, plus failures of the protection hardware itself (simulation package, section 12).

### Randomized campaign

400 independent campaigns of two days each (800 pod-days, 2,699 drone visits), at 1 s steps, each drawn at random:

- **Weather:** daily temperatures from −25 to 46.5 °C; cloud cover from overcast to clear; rain in 257 campaigns (wet-pad films 2 kΩ–2 MΩ); snow cover on the pad in 131.
- **Power:** storage starting anywhere from 12% to full; grid kit in 242 campaigns, with outages in 173; one solar panel failed in 86 and the solar controller failed in 77.
- **Drones:** random arrivals, route types and arrival charge; avionics draw 0–0.3 A; 155 misloaded 5S packs; 56 drones lifting off mid-charge.
- **Failures:** 202 injected electrical faults (metal bridges of 0.5 Ω–5 kΩ across the strips, converter runaways, pad shorts); an ambient sensor stuck at a wrong value in 25 campaigns.
- **Build:** a fresh random tolerance build of the sense circuit in every campaign.

Safety rules checked on every one of 69 million simulated seconds:

- no pad power without a drone and a passing sense check;
- no charged 6S cell above 4.20 V;
- no cell charged outside 0–45 °C;
- no film drawing more than 50 mW while powered;
- at most 600 J into any bridge or short;
- storage charge current at most 40 A;
- no charging with the interior above 46.5 °C.

Every visit that ended without a charge was also checked for a valid physical reason.

**Result: zero safety violations and zero unexplained refusals.** 1,646 of 2,699 visits were served. Every one of the other 1,053 had a valid cause:

- an injected fault (165);
- a drone lifting off (46);
- a misloaded 5S pack stopped by its BMS (98);
- the rest, cold below 0 °C, no stored energy, a wet or snow-covered pad, or a hot interior, alone or together.

Worst values seen:

- 6S cell 4.199 V;
- storage charge current 25.0 A;
- interior while charging 45.0 °C;
- 467 J into a bridge before the re-check cut it.

Storage drained to the 10% load disconnect in 5 campaigns that started low. It recovered in both campaigns where usable power returned. In the other 3 no usable power came back within the run: there was no sun and no grid, or it stayed below 0 °C, where the storage battery cannot be charged.

## Named extremes

| Scenario | Result |
|---|---|
| 10 dark days with the grid down, then sun | Drone charging stopped at the 20% reserve (storage minimum 29%); VTOLs refused for lack of energy; service resumed when the sun returned. No violations |
| Heat wave, 30–48 °C, full sun, no grid | Charging only in cooler hours (interior start limit 43 °C); 7 of 11 visits served; peak interior while charging 43.3 °C. No violations |
| Deep freeze, −25 to −5 °C, with snow cover | No charging at all: drone cells and the LiFePO4 storage cannot charge below 0 °C, and snow covers the contacts. No violations |
| Monsoon: conductive rain films, a 1 Ω bridge, a pad short and a converter runaway | Pad stayed unpowered on low-resistance films; all three faults cut (at most 96 J into the bridge). No violations |
| Ambient sensor stuck at 20 °C on a −15 °C day | The pod tried, but every drone BMS blocked charging by its cell NTC. No cell charged below 0 °C |

## Failures of the protection hardware itself

Each case below is run with the worst electrical fault, a converter running away to its input voltage, at 5%, 50% and 85% drone charge, for both drone types, at 10 µs resolution.

| Protection failure | Pad unpowered within | Peak current | Charge added after the fault |
|---|---|---|---|
| Hardware comparators dead (firmware alone) | 0.5 ms | 97 A | 0.013 mAh |
| MOSFET switch stuck closed (relay breaks it) | 15.3 ms | 150 A | 0.61 mAh |
| Switch stuck and comparators dead | 15.5 ms | 150 A | 0.63 mAh |

| Protection failure | Pad unpowered within | Peak current | Charge added after the fault |
|---|---|---|---|
| Firmware hung (comparators alone) | 0.3 ms | 81 A | 0.002 mAh |
| Firmware hung and comparators dead (watchdog) | 98.5 ms | 150 A | 4.1 mAh |
| Hung, comparators dead and switch stuck | 113.5 ms | 150 A | 4.7 mAh |
| Current sensor reads zero | Charge ends early (taper) or hardware trips | — | — |
| Voltage sensor reads low or high | Undervoltage or overvoltage fault at once | — | — |

In every case the pad is unpowered and the added charge is at most 4.7 mAh on a 22 Ah pack, far too little to move a cell's voltage. These cases set four new specifications, now in the parts list and controller sections:

- an isolation relay rated to break at least 150 A DC at 32 V;
- a 30 A fast-acting fuse on the pad output;
- contacts rated 150 A for 20 ms;
- an independent 100 ms hardware watchdog.

## Design changes from the stress test

- **Interior start limit.** No charge starts while the interior is above 43 °C; the pod waits for it to cool. Without this, a drone arriving into a hot case started and was stopped a second later.
- **Backup hardware.** The relay break rating, pad fuse, contact short-time rating and watchdog listed above.
- **Wet films.** With a pack present, films above about 47 kΩ are accepted, because they draw at most about 0.5 mA; lower ones are rejected.

### What “works no matter what” can and cannot mean

The stress test supports a narrower and more useful claim: under every condition tried, alone or combined, the pod never did anything unsafe, and it never refused a drone without a physical reason. It does not, and cannot, charge in every condition:

- **Below 0 °C** neither the drone's cells nor the LiFePO4 storage can be charged safely. Cold sites need battery heaters, which this design does not yet include.
- **Above about 40 °C in full sun** the case is too hot. Hot sites need shade over the case, or a grid kit for evening charging.
- **With no sun and no grid**, charging stops at the 20% storage reserve until power returns.
- **A snow-covered or heavily wetted pad** cannot make or keep safe contact.
- **A drone pack without a per-cell BMS** is not protected against a wrong cell count; the BMS is mandatory.
- **Three simultaneous independent failures** (pad switch stuck closed, relay welded and both protection paths dead) leave only the pad fuse and the drone BMS. That is accepted as residual risk.

The models still use representative, not measured, part data, so the hardware tests and an independent professional review listed above remain the remaining steps.

## On-board solar charging (drone side)

**Bottom line.** On-board solar is worth fitting to the VTOL and not, as a range extender, to the quad. Wing-integrated cells refill about three quarters of the VTOL pack on a clear summer day and add 30–36% endurance in daylight flight. The quad's body panel returns 38% of its pack per clear summer day but costs 4–6% endurance in every flight. With the mounting and rules below, on-board solar is safe under every single and double fault simulated and never conflicts with the pod (simulation package, section 13).

No airframe data was supplied, so both airframes are representative assumptions. These are not figures for the L1 aircraft: the L1-Q and L1-W each carry about 194 Wh, and the L1-Q about 50 W of solar, so they have been rerun with their own values under Applying the design to the L1 aircraft. Every value sits in `drone_solar.py` for replacement.

| | Quad | VTOL |
|---|---|---|
| Airframe (with pack, before kits) | 3.0 kg, 6S 10 Ah Li-ion, hover 360 W | 4.5 kg, 6S 22 Ah Li-ion, cruise 170 W |
| Solar kit | 24 sixth-cut back-contact cells on the body top (outside the rotor discs), 0.061 m², 12 W STC, 0.135 kg | 26 cells in the wing skin, 0.398 m², 80 W STC, 0.30 kg |
| Alternative studied | Deployable flaps unfolded after landing, 0.245 m², 49 W STC, 0.495 kg | — |
| Charger | 4-switch buck-boost MPPT (LT8490-class), 6–80 V in, CV 24.6 V, 2.0 A | same, 4.4 A |
| Heater (fed from solar only) | 10 W film on the pack | 25 W film on the pack |

## Temperature: mounting decides it

The pack must not sit directly under the panel. The panel runs 35–50 K above ambient; directly under it the face cells sit about 20 K above ambient.

| Mounting | Hottest day with no heat stop | Pack peak, 45 °C day on sand | Verdict |
|---|---|---|---|
| Pack directly under the panel (5 mm gap) | 26–27 °C | 68–70 °C (above the 60 °C Li-ion storage limit) | Rejected |
| ≥15 mm vented gap, reflective faces (ε ≤ 0.05) on panel back and body top | 37–40 °C | 52–54 °C | Required |

Direct mounting also fails a single-sensor fault: with the face sensor reading 10 K low, face cells charged above 45 °C while the core BMS still read in range. With the vented gap the panel shades the body, so the pack runs no hotter than on the same airframe with no panel. Even vented, the VTOL pack reaches 62 °C parked on a dark roof at 48 °C in still air: do not park on dark roofs above 45 °C.

**Cold.** No charge below 2 °C (charger) or 0 °C (BMS), and at most 0.1 C below 10 °C (lithium plating). The solar-fed heater lets the VTOL take 333 Wh over two −6 to 4 °C March days, against 190 Wh without it. At 55 °N in December neither airframe charges: the sun cannot power the heater.

## Daily yield, day 1 from 20%, vented mounting

| Conditions | Quad fixed | Quad deployable | VTOL |
|---|---|---|---|
| Temperate summer, 45 °N | 38% of pack | 76% | 75% |
| Dark roof, summer, 40 °N | 38% | 76% | 76% |
| Hot summer, 22–38 °C | 37% | 76% | 72% |
| Desert, 27–45 °C (midday heat stop) | 14% | 45% | 31% |
| Temperate spring | 23% | 77% | 69% |
| Tropical, overcast (60% sun) | 20% | 77% | 59% |
| Temperate winter, −4 to 5 °C | 6% | 29% | 22% |
| Cold winter with snow, 55 °N | 0% | 2% | 1% |

## Flight: endurance and heating

In flight the panel output feeds the motor bus through its own gated output, limited to the load. It never charges the pack in flight.

| Configuration | Endurance change vs pod kit only |
|---|---|
| VTOL, noon, 45 °N, June (about 60 W solar) | +36% |
| VTOL, 09–15 h average, June | +30% |
| VTOL, noon, December | +4% |
| VTOL, no sun (mass only) | −7% |
| Quad fixed panel (9 W against 450 W hover) | −4 to −6% |
| Quad deployable (stowed, no output in flight) | −20% |

The quad's pack temperature is set by flight, not the sun. An 18-minute hover at about 2 C raises the pack 30 K; the VTOL's 90-minute flight raises it 6.5 K. At 30 °C ambient the quad pack needs 84 minutes parked before solar can start (40 °C) and 133 minutes before it is presented to the pod (35 °C). High-power cells with half the resistance halve the rise; specify them for the quad.

## Electrical design and pod hand-off rules

The on-board charger shares the pack's charge port with the pod rectifier. These rules keep the two chargers from conflicting; each was checked in simulation.

1. **Same setpoint.** CV 24.6 V (4.10 V per cell), ±0.5%, so at most 24.72 V: below the pod's hardware OV band (24.89 V minimum) even if both chargers are on.
2. **Own protection.** A latched OVP comparator at 25.05 V, below the BMS 4.25 V per cell. It resets when the panel goes dark at night; three trips lock the charger out. It refuses packs below 15 V and pre-charges at C/20 below 18 V, so it can bring a 15–17.6 V pack back into the pod's sense window.
3. **Gated by the BMS.** The charger's output switch closes only when the BMS allows charging. If solar could drive the rail while the BMS charge FET is open, the pod would read the rail as a full pack and never charge. The simulation shows that failure when the gating is removed.
4. **Pod has priority.** A hardware comparator on the contact-rail current shunt disables solar within 100 ms of pad current above 0.2 A. Solar re-enables only after 5 s below 0.05 A, so the pod's 20 ms re-sense pauses never re-enable it. With solar off, the pod's taper rule works as designed.
5. **Two sensors at the two extremes.** The charger's NTC sits on the cells nearest the panel; the BMS NTC sits in the core. Charging needs both inside their windows: solar 5–40 °C to start, 2–44 °C to run, derated above 40 °C; BMS 0–45 °C.
6. **Pack presented to the pod only at 10–35 °C.** Outside that range the drone holds its charge FET open, so the pod sees an empty pad and keeps sensing every 2 s. The drone also opens the FET if either sensor falls below 10 °C during a pod charge. This stops the pod's 1 C charge from plating lithium in cold packs and from overheating packs that land hot.
7. **BMS overvoltage releases only after discharge** (below 4.05 V per cell). Otherwise a 5S pack fitted by mistake is pushed to 4.25 V again on every pod sense cycle.
8. **Heater fed from solar only.** It is switched from the charger output with the charge switch open, so it never draws from the pack or the pod. It runs only when both sensors agree the pack is cold (core below 15 °C), so a drifted face sensor cannot

overheat the pack.

9. **In-flight output.** A separate ideal-diode output onto the discharge bus, enabled only when armed, inside the charger's temperature window and not locked out. It is limited to the measured bus load, so it never net-charges the pack in flight.
10. **Sleep on the pod.** The VTOL's awake draw (0.39 A) exceeds the pod's 0.3 A avionics budget and the quad's (0.29 A) leaves no margin, so both must sleep during a pod charge (19–29 mA).

The MPPT input stays in range at both limits: 25.2 V maximum string Voc at −30 °C (deployable kit) against 80 V; at least 10.4 V Vmp at 70 °C and 200 W/m² against a 6 V minimum.

## Verification of on-board solar

The model covers the sun (position, clear-sky beam and diffuse, hourly cloud), the cells (temperature coefficient, bypass diodes, MPPT input floor), a transient thermal network (panel sections, airframe interior, a two-node pack), the 6S pack with its BMS, the charger, the pod's charge logic and flight loads. Results:

- **Integrated missions.** Three days per airframe, 14 scripted events each, all pass: daylight flight with solar on the bus, warm landing, wilderness and dark-roof parking, a pod visit with the interlock, cloud, 50% shade and a cold front with the heater. On the pod the quad landed hot, was held until 35 °C, was interrupted once by the 45 °C limit in sun, then resumed and ended on taper.
- **Stress campaign.** 400 random two-day scenarios (−30 to 48 °C, latitudes to 60°, all seasons and ground types, random flights and pod visits) with 11 fault types injected singly or in pairs. Result: no safety violation with one, two or three faults, and no refusal without a physical reason. Without a CV fault, cells never exceeded 4.10 V while charging; with one, 4.248 V (the BMS cut-off).
- **Named extremes.** 32 cases, all as expected. These include a CV runaway with the charger's OVP failed (the BMS cuts at 4.25 V), an interlock failure through a 3-hour pod charge (both chargers at 24.6 V, no fault), and the two direct-mount sensor-fault cases that show why direct mounting is rejected.
- **Independent review.** It found 10 defects in the first model. All were corrected before the results above: shade was counted twice; the panel's electrical draw was charged at full MPP power even when the charger drew less; one lumped pack node hid the face

cells under the panel; the heater ignored the interlock and lockout; refusals were judged by the controller's own flags rather than the true state; the pod could charge at 1 C below 10 °C; and the in-flight output had no defined path.

- **Tests.** 37 pass/fail checks in `tests/test_drone_solar.py`; the full suite is 165 checks.

**Limits.** The airframes, panel-to-body coupling coefficients, pack resistance, cell data and flight power are representative values. Replace them with measurements:

- a sun test of the real airframe with thermocouples on the face and core cells;
- a flight-heating test at the planned hover time;
- the cell maker's charge-temperature and charge-rate limits, which must permit the pod's 1 C.

## References


1. Victron Energy, *SmartSolar MPPT 100/30 & 100/50 manual*, §9 Technical specifications (Vbat + 5 V start, Vbat + 1 V run). https://www.victronenergy.com/media/pg/Manual_SmartSolar_MPPT_100-30__100-50/en/technical-specifications.html
2. Victron Energy, *MPPT 150/35 datasheet* (35 A; 1,000 W at 24 V; 150 V absolute maximum, 145 V start/operate; −30 to +60 °C, full output to 40 °C; 15 mA at 24 V). https://www.upwatt.com/mpattachment/file/download/id/59
3. Victron Energy, *Blue Smart IP67 Charger manual*, Disabling Bluetooth (permanent and irreversible). https://victronenergy.com/media/pg/Blue_Smart_IP67_Charger_230V_manual/en/setup/bluetooth/disabling-bluetooth.html
4. Northern Arizona Wind & Sun, listing for Victron Blue Smart IP67 24/12, 120 VAC (100–135 VAC input, 12 A, $177.65). https://www.solar-electric.com/victron-energy-blue-smart-ip67-24-12-120-vac-battery-charger.html
5. ArduPilot, *Precision Landing and Loiter* (MAVLink LANDING_TARGET, AprilTag via companion computer, "centimeter-level"). https://ardupilot.org/copter/docs/precision-landing-and-loiter.html
6. Analog Devices, *LT4320 Ideal Diode Bridge Controllers* (9–72 V, DC to 600 Hz, polarity-agnostic input). Revision 1 component, superseded by one ideal-diode pair per contact. https://www.mouser.in/new/analog-devices/adi-lt4320-controllers/
7. 49 CFR 173.185, Lithium cells and batteries. https://www.law.cornell.edu/cfr/text/49/173.185

8. FAA, *Normalizing Unmanned Aircraft Systems Beyond Visual Line of Sight Operations* (NPRM), 90 FR 38212 (Aug. 7, 2025). Status: DroneBundle, *Part 108 NPRM: Status, Timeline and What Happens Next* (Oct. 7, 2026), https://dronebundle.com/blog/part-108-nprm; DroneRanker, *FAA Part 108 BVLOS Rule Status* (updated Oct. 21, 2026), https://www.droneranker.com/faa-part-108-bvlos-rule-status/
9. US 11,728,663 B2, *Drone recharging station* (priority July 24, 2018). https://patents.google.com/patent/US11728663
10. D. Florczak, M. Jacewicz, A. Kopyt and R. Głębocki, Autonomous solar-powered docking station for quadrotor drones: design and testing, SAGE (2025), doi:10.1177/09544100251331282.
11. RTKdata, *DJI Dock 2 integration* (internet via Ethernet or 4G required). https://docs.rtkdata.com/integration-hub/drones-and-uavs/dji-dock-2
12. NFPA 70, *National Electrical Code*, Article 690 (690.7 maximum voltage; 690.12 rapid shutdown).
13. Victron Energy, *SmartSolar MPPT 150/35 & 150/45 manual*, Technical specifications. https://www.victronenergy.com/media/pg/Manual_SmartSolar_MPPT_150-35__150-45/en/technical-specifications.html
14. 47 CFR Part 15, Subpart B (unintentional radiators) and §15.23 (home-built devices).
15. ASCE/SEI 7, *Minimum Design Loads*, free-roof net pressure coefficients (basis for the CN = 1.2 assumption in the wind analysis); NEC 690.7 temperature correction.

## Applying the design to the L1 aircraft

**Bottom line.** The pod can charge both L1 aircraft safely at **9 A**, which needs a new drone-type setting: the existing 10 A and 20 A settings must not be used on the L1 pack. With the pod kit fitted, the L1-Q's leg falls from 8.9 km to 7.2 km and the L1-W's from 36.3 km to 29.5 km in still air. Neither aircraft can use a pod as listed today: both lack the per-cell BMS and charge FET the pod requires, the listed landing camera fails the landing requirement, and L1 flight software v2.2.1 has no pod support. None of the L1 aircraft or pod software exists in built form; every figure below is simulated.

**Data used.** L1 values come from the L1 design reference and parts lists (v2.2.1). These are engineering estimates for aircraft that have not been built or flown. Both aircraft carry a 6S2P pack of Molicel P45B cells (about 194 Wh, 900 g). From the cell data sheet: 4.5 Ah typical per cell (4.35 Ah minimum), standard charge 4.5 A, maximum continuous charge 9 A (with faster capacity loss), charge temperature 0–60 °C, AC impedance at most 8 mΩ per cell. The pack is therefore 9.0 Ah: 1C is 9 A and the maker's maximum is 18 A. The

model takes the pack's ohmic resistance as 42 mΩ (an assumption: 1.5 times the AC figure plus wiring and BMS) plus 12 mΩ of polarization resistance, so at steady current the pack dissipates $I^2 \times 54$ mΩ. Gaps in the L1 data (frame size, panel strings, avionics draw, battery location) are filled with stated assumptions in `podsim/l1.py`.

## Pod charge current for the L1

| Pod setting | C-rate on the L1 pack | Within 1C | Within maker's maximum | 30% to 85% | 30% to taper end | Pack heat at full current, steady state ($I^2 \times 54$ mΩ) |
|---|---|---|---|---|---|---|
| **9 A (new L1 setting)** | 1.0C | Yes | Yes | 0.57 h | 0.86 h | 4.4 W |
| 10 A (quad setting) | 1.1C | No | Yes | 0.52 h | 0.81 h | 5.4 W |
| 20 A (VTOL setting) | 2.2C | No | **No** | 0.34 h | 0.63 h | 21.6 W |

The drone-type switch carries a third position, "L1: 9 A", used for both L1 aircraft (see Drone charger). Charging ends at 4.10 V per cell (about 92% charge), above the L1's 85% relaunch rule. Firmware overcurrent scales with the setting (1.25 × 9 A = 11.25 A); the 30 A hardware trip is unchanged.

## Pod results with the L1 pack

- **Protection.** Every protection case passes on the L1 pack: converter runaway cut by hardware alone within 0.33 ms at every state of charge and both ends of the OV band; all six protection-hardware failures (worst 113.5 ms, at most 125 A, under 10 mAh added); pad short; lift-off; current and voltage sensor failures.
- **Pod thermal.** Unchanged: full rate to 34 °C ambient. The interior heat that sets the envelope comes from parts off the heat-sink plate, which do not depend on drone current.
- **Charges per pod per day** (arriving at 30%, storage reserve kept): large solar kit 10.7 on a clear 4-peak-sun-hour day and 3.8 in winter sun (1.5 hours); small kit 3.3 and 1.1; grid only, or solar plus grid, 22.5 (limited by charge time).

## L1 range and pod spacing

The added mass is the 0.30 kg pod kit plus about 0.05 kg for the per-cell BMS the L1 lacks. A leg uses the L1's 107 Wh (85% to 30%). It allows 45 s of hover (L1-Q) or 30 s of extra vertical flight (L1-W) to centre on the pad. Power scales with mass to the 1.5 power for the

quad and its vertical flight, and in proportion to mass in cruise. Design spacing keeps 10% for routing. Both aircraft are timed on one basis: transit (forward flight, which sets the distance) and time in the air (transit plus hover or vertical flight).

| Aircraft | Published leg (no kit) | Leg with kit, still air | Max spacing, 5 m/s headwind | Design spacing, still air | Design spacing, 5 m/s headwind |
|---|---|---|---|---|---|
| L1-Q (4.05 kg, 596 W; 10.0 min transit, 10.8 min in the air) | 8.9 km | 7.2 km | 4.2 km | 6.5 km | 3.8 km |
| L1-W (5.35 kg, 161 W cruise; 27.3 min transit, 29.3 min in the air) | 36.3 km | 29.5 km | 21.3 km | 26.5 km | 19.2 km |

Space pods for the worst headwind expected on the route. The L1-Q's short leg makes a pod network for it dense: about one pod every 4 km in a 5 m/s headwind.

## L1 on-board solar

The study simulated both panels with the Genasun charger's efficiency and night drain. It applied this design's charging rules as if the external output switch listed under gaps were fitted. Each aircraft was run with the pack directly under the panel and with the vented gap.

| | L1-Q | L1-W |
|---|---|---|
| Hottest day with no heat stop: pack directly under panel / vented gap | 29 °C / 41 °C | 33 °C / 43 °C |
| Pack peak on a 45 °C day on sand: direct / vented | 69 °C / 52 °C | 69 °C / 54 °C |
| Clear summer day from 30% (vented) | full (about 89%) the same day | full (about 88%) the same day |
| Solar available on a clear summer day at 45 °N | 358 Wh | 599 Wh |
| Temperate winter day from 30% (vented, no heater) | 19 Wh | 66 Wh |
| Pack rise over one leg at 30 °C | +22 K (11 min) | +7.5 K (30 min) |

| | L1-Q | L1-W |
|---|---|---|
| In-flight solar if the bus output is fitted, with the gain in leg distance: noon in June; 09–15 h average in June; noon in December | 40 W, +7%; 37 W, +7%; 13 W, +2% | 70 W, +77%; 64 W, +66%; 22 W, +16% |

The clear-day figures are an upper bound. The L1 documents' own real-world averages (about 78 Wh a day for the L1-Q and 198 Wh for the L1-W) are lower. On an average day the L1-W still refills, while the L1-Q gains roughly 40% of its pack. The mounting rule holds for both aircraft: directly under the panel, the pack passes the 60 °C storage limit on a 45 °C day. Without a heater, both aircraft gain little on cold days, and nothing below about 2 °C.

## L1 gaps against the pod requirements

| # | Requirement | L1 v2.2.1 | Verdict and change needed |
|---|---|---|---|
| 1 | Per-cell BMS: 4.25 V cutoff, undervoltage cutoff, charge overcurrent at 35 A or more, NTC charge window 0–45 °C | INA228/INA226 monitor and MCP9600 thermocouple only | **Fails.** Fit a separate-port 6S BMS with these limits, its NTC in the pack core (about 0.05 kg) |
| 2 | Charge FET the flight controller opens before arming; active balancer | None | **Fails.** The BMS must expose a charge FET the flight controller can command; add the 6S active balancer from the drone-side kit |

| # | Requirement | L1 v2.2.1 | Verdict and change needed |
|---|---|---|---|
| 3 | Landing camera: at least 120° horizontal field of view, at least 1,920 px across, 4:3 | Raspberry Pi Global Shutter Camera (IMX296, 1,456 × 1,088) with a 6 mm lens | **Fails** field of view (45°) and pixel count; passes 4:3. Tags leave view below 1.75 m, against 0.42 m required. A 120° lens on the same sensor (about 1.45 mm) decodes tags only below 3.8 m, against 5 m required. Fit a camera meeting the specification |
| 4 | Pod-kit mass in the weight budget | Not included | **Applied above:** legs fall by about 19% on both aircraft; pod spacing uses the reduced legs |
| 5 | Vented gap of at least 15 mm with reflective faces between panel and battery | L1-Q panel "top-mounted"; L1-W cells in the wing skin | **Unconfirmed.** The L1-Q needs standoffs and an aluminised panel backsheet over the battery. The L1-W wing-skin cells meet the rule wherever the battery is not under the wing skin. If the battery bay sits under the centre section, leave cells off the bay or add a vented, reflective liner there |

| # | Requirement | L1 v2.2.1 | Verdict and change needed |
|---|---|---|---|
| 6 | Contact plate: 3 × 3 grid at 150 mm spacing (plate about 320 mm square) | Frame dimensions not in the data supplied | **Unconfirmed.** It needs landing-gear spread above about 340 mm. A slim VTOL fuselage will not carry it without a boom-to-boom tray. A 200 mm grid works on strips scaled to 73 mm with 10 mm gaps (12 strips; no failed landing at any heading or offset). But a 300 mm grid fails 7% of landings on those strips, so that would be a separate L1 pad, not the universal one |
| 7 | Pod-capable flight software | None (see below) | **Not written** |

**Charger.** The Genasun GVB-8-Li has no enable input, no battery temperature input on lithium models, no published latched overvoltage protection, and draws about 6 mA at night (about 3.5 Wh a day). The on-board charging rules need an added output switch driven by the BMS charge-allow signal, a 100 ms pod-current interlock, both NTCs and a latched 25.05 V comparator. Because it is a boost charger, the panel strings need Vmp below about 19.8 V at −10 °C and Voc below 24 V at −30 °C. The L1 documents do not give the strings, so this is unverified. The L1′s own rule (no charging below 0 °C or above 45 °C) is wider than this design′s: solar charging starts only at 5–40 °C and runs at 2–44 °C, and the pack is presented to the pod only at 10–35 °C.

**In-flight solar.** With the required charge FET open in flight, the panel can no longer feed the pack in flight. To keep the L1-W′s in-flight gain, add the gated, load-limited output onto the discharge bus described under on-board solar charging.

**Software that would have to be written** (none exists in L1 v2.2.1):

1. AprilTag pad detection on the companion computer and MAVLink LANDING_TARGET output to the flight controller, with a fallback when no tag is seen.

2. Pod approach and landing: route to the pod coordinates, descent onto the pad and touchdown confirmation.
3. Charge-FET control: open before arming and in flight; close on the pad only when both pack sensors read 10–35 °C; open if either falls below 10 °C.
4. Sleep on the pod at no more than 0.3 A; wake on charge completion (pack voltage at taper) or on schedule.
5. Relaunch logic: leave at 85% or more, or at taper end, within the launch window, after re-arming checks.
6. Solar handling: the hardware interlock does the switching; firmware logs it and keeps the solar output off in flight unless the bus output is fitted.
7. Pod-occupied and pod-dead fallback: wait, divert to the next pod, or land and charge on solar.

**What must change before an L1 uses a pod.**

- On the pod: add the 9 A setting.
- On each aircraft:
  - fit the BMS, charge FET and balancer;
  - fit a camera to the specification;
  - add the vented gap where the battery sits under a panel;
  - add the charger output switch and interlock;
  - confirm the contact plate fits, or build a 200 mm-grid L1 pad;
  - write and flight-test the software above;
  - recompute pod spacing with measured weights and power.

## Author note, license and disclaimer

**Author.** Collin B. George, CISSP, National Security Advisor, Sanctir (sanctir.com). Revision 3, released November 2026.

**License.** This document is released under the Creative Commons Attribution 4.0 International license (CC BY 4.0): anyone may copy, adapt, build and sell from it, including commercially, provided they credit the author and state what they changed. The simulation code is released under the MIT License. See creativecommons.org/licenses/by/4.0.

**Status and disclaimer.** The design has been simulated and reviewed but not built or tested. It is provided as is, without warranty of any kind. Anyone who builds from it is responsible for its safety and for meeting the electrical, aviation, radio-frequency and battery-transport rules that apply where they build and fly it, including the items under Regulatory above. Lithium batteries, high-current DC circuits and autonomous aircraft can cause fire, injury and property damage. Have the electrical design reviewed by a licensed electrical engineer before building it.

**AI disclosure.** AI assistance was used for source retrieval, verification against primary sources, and editing for tone and clarity. The analysis, judgments and text are the author's, and the author is responsible for the content and any errors.