Two weeks off-grid in winter: a pumped-hydro store for a family home with wind, solar, two greenhouses and two electric cars

TechUPGRADE Digital Twin Platform

TechUPGRADE technical report TU-TR-2026-005 (tenant `vawt`)

5 November 2026

Preprint: 4/8 requirements met, 3 partial

Abstract

A family of five lives all year in a house on the Varna coast with two 100 m^2 greenhouses and two electric cars, supplied by five 1.5 kW vertical-axis wind turbines (TU-TR-2026-004), 15 kWp of solar panels and a 14.4 kWh battery, and connected to the grid. The site must survive at least two weeks off-grid in winter. Ten years of hourly weather show that the site needs about 20,191 kWh a year, that most of its grid import falls in winter, and that the worst winter fortnight needs 1,306 kWh from storage (median 268, 90 % of fortnights $\leq$ 678). We designed a pumped-hydro store for it on the TechUPGRADE platform: 1,400 kWh usable in two covered concrete tanks of 20 $\times$ 71 m with 5 m of working depth, 100 m apart in height (the site is to be found), two 6 kW Pelton turbines and two 5.5 kW pumps, one of each enough to keep the house served. Within the client's first limit of 2 $\times$ 100 m^2, water could hold only 20–160 kWh. Holding the store full all winter as the outage reserve costs self-sufficiency (61.2 % against 74.6 % if used freely). A reserve floor set each day from the 7-day weather forecast, tested on 199 winter days of archived forecasts, never left the site short and raised self-sufficiency over the period from 58.0 to 68.7 %. The store, its state machine and a live simulation are on the platform.

1 The site and its balance

The client's picture: the house (150 m^2, all-electric with heat pumps), two greenhouses of 5 $\times$ 20 m kept above 12 °C for vegetables, two cars at 15,000 km a year each. Every figure below is an assumption written as one line in the scripts. The site needs about 20,191 kWh a year against 26,734 kWh generated; even so, the grid import (7,016 kWh) falls almost entirely in November to March, when heating peaks and the sun is lowest (Fig. 1). More solar mainly adds summer surplus, and storing the season's surplus in water would need some 115,000 m^3: the store is for days, not seasons.

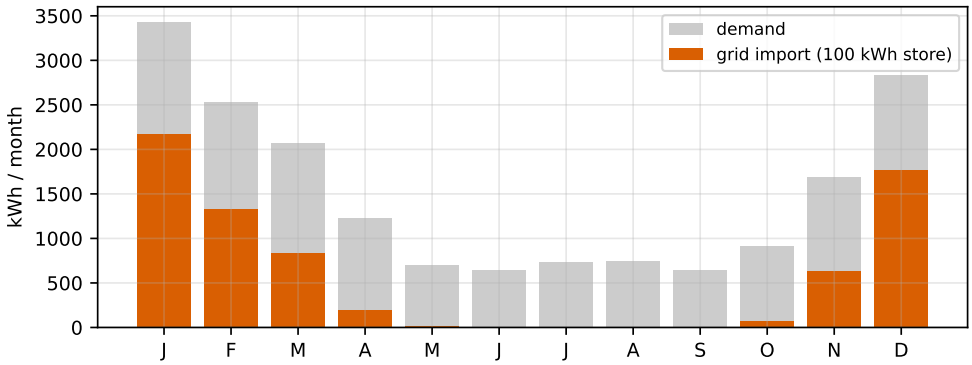


Figure 1: Demand and grid import by month (ten-year mean), with a 100 kWh store.

2 Two weeks off-grid

Off-grid the house keeps full comfort, the greenhouses fall to a survival minimum of 8 °C and the cars to 30 km a day (about 64 kWh a day in winter). For each of 1,359 winter fortnights in ten winters, the battery and the store start full; the

store must give what wind, solar and the battery cannot (Fig. 2). The worst fortnight (from 2016-12-31) needs 1,306 kWh; the store is 1,400 kWh usable. Heat is 84 % of that fortnight's electricity. The coldest hour needs 14.9 kW (two thirds of it the greenhouses' heating) but 99.9 % of winter hours stay below 10.7 kW. Two turbines of 6 kW leave only 16.0 fortnights a few kWh of greenhouse heat short (a 1 m^3 hot-water buffer takes them); with one turbine out the house is always served and the greenhouses fall back to frost protection in the worst cold. Two 5 kW pumps refill the empty store in 12 days.

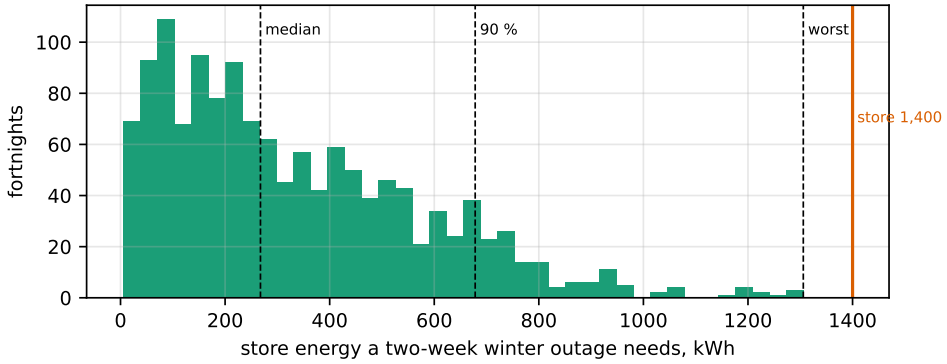


Figure 2: The store energy every winter fortnight of ten winters would need for a two-week outage.

3 How big, how high

Usable energy $E = \rho g H V \eta_t$ ($\eta_t = 0.72$ at the turbines' output): for 1,400 kWh, head × volume is about 713,558 m^4. The client first limited the basins to 2 × 100 m^2; at 50–80 m of head and 10 m deep they hold 98–157 kWh, enough for the house alone with the greenhouses unheated, not for the requirement. The client then asked for basins of sufficient size, at most 5 m deep, with a larger head, and a site to be looked for. At 100 m of head each basin is 20 × 71 m (7,136 m^3 of working water); Fig. 3 gives the size for any head.

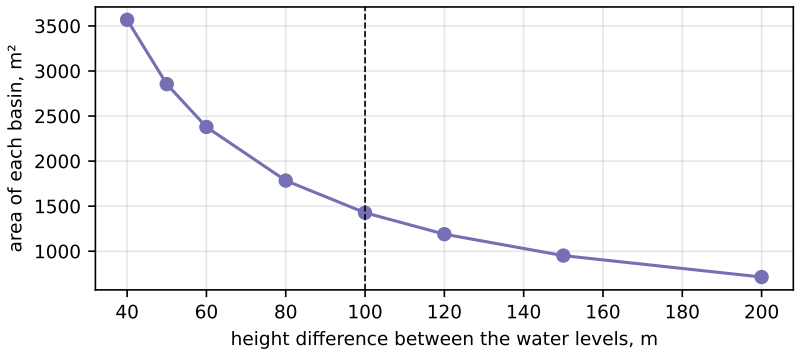


Figure 3: The area of each of the two basins (5 m working depth, 1,400 kWh usable) against the head.

4 The hydraulics and the machines

One penstock serves both directions: HDPE PE100 SDR11, OD 200 mm, about 250 m along the slope, losing 1.1 % of the head at full flow. Each **Pelton turbine** (net head 99 m, 8.3 L/s) has a runner of 253 mm at 1,500 rpm, one 15.6 mm jet and 23 buckets [2]; a spear valve keeps its efficiency down to about 15 % of rated, so it serves the house's typical 0.6–1 kW nights. Each **pump** is a vertical multistage centrifugal pump on a variable-speed drive, 13 m^3/h against 95–105 m, standing in a dry pit 3 × 3 m whose floor (−7.0 m) is level with the lower tank's floor, so the suction is flooded at every water level (the pit came with the detailed 3D model; the first layout had the pumps on the house floor, up to 6.5 m above the water). **Surge:** the wave speed in the pipe is 312 m/s; even an instant stop of both turbines (Joukowsky [3]) raises the pressure to 131 m against PN16's 163 m; the jet deflectors shed load without changing the flow and the nozzles close in 30 s (+1.3 m). The tanks are covered reinforced concrete [4], two cells each so one can be emptied while the other works; first sizing: walls 0.35 m propped by a 0.25 m roof slab on columns, about 1,389 m^3 of concrete

per tank. Covered tanks do not evaporate. The site's backed-up AC bus becomes three-phase on three inverter-chargers (19.2 kW against the island's 14.9 kW peak); the turbines are AC-coupled through hydro inverters (Fig. 4).

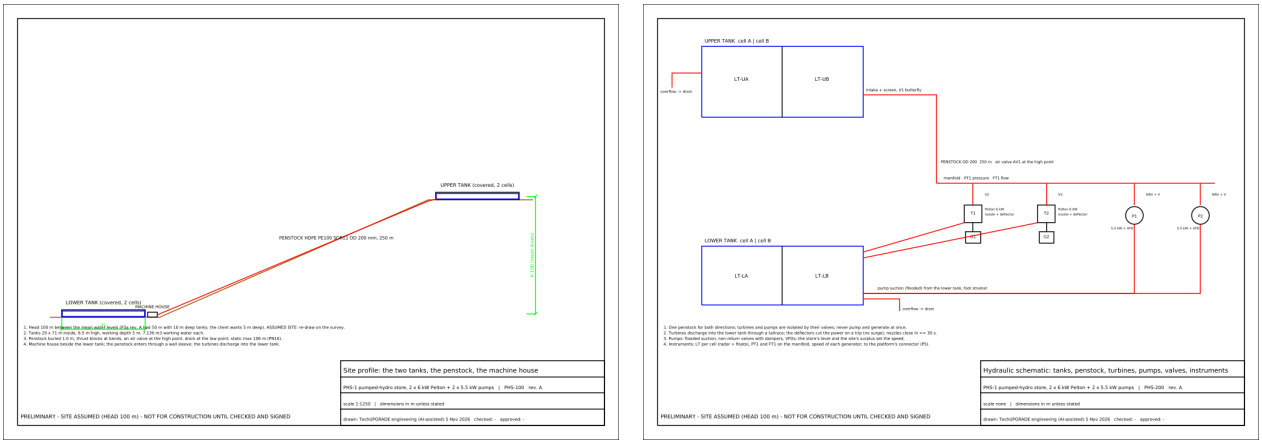


Figure 4: Drawings PHS-100 (site profile) and PHS-200 (hydraulic schematic). Preliminary: the site is assumed.

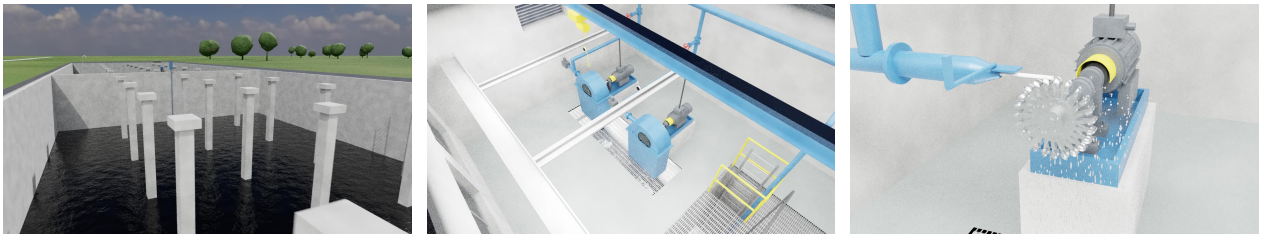


Figure 5: The 3D model (rev. B, 129 parts): the lower tank opened, the machine house from above with the pump pit, a Pelton runner with its jet and spray.

5 Control and the winter reserve

The store's controller is a state machine of 11 states (standby, pumping and generating with their start and stop sequences, the winter reserve, maintenance, fault, trip). The battery is used first. In ten years the machines start about 0.1–0.2 times a day. In winter the store is the outage reserve, and how much of it is held decides how much it helps in normal years (Fig. 6). **The forecast-based floor.** Each winter day the store holds $\min(1{,}400,\ 1.2\,E_{7,\text{forecast}} + W_7)$, where $E_{7,\text{forecast}}$ is

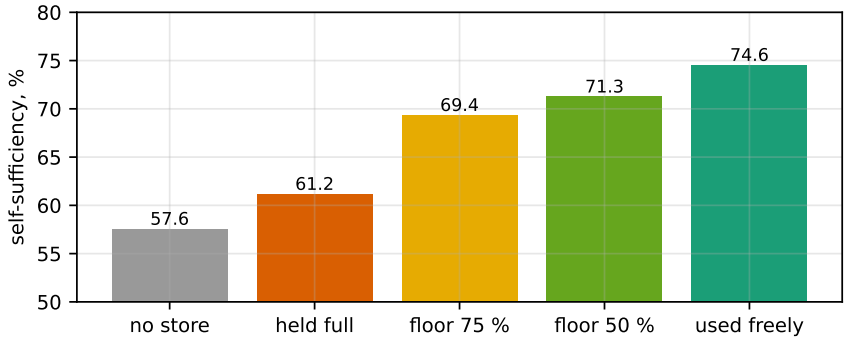


Figure 6: Self-sufficiency of a normal year (ten-year mean) by the winter reserve rule.

the island's need over the next 7 days from the weather forecast and W_7 = 840 kWh the worst 7 days of ten winters (for days 8–14, beyond the forecast). We tested it on archived forecasts at their lead times [6] for 2024-11-01 to 2025-12-18: on 199 winter days the floor would have carried a two-week outage that started that day; there were 0 unsafe days (Fig. 7). The forecast of the 7-day need erred by -72 to +47 kWh in 90 % of the days. Over the period, self-sufficiency rose from 58.0 % (full hold) to 68.7 % (2,539 kWh less import). Without a forecast for 24 h the floor returns to the full store.

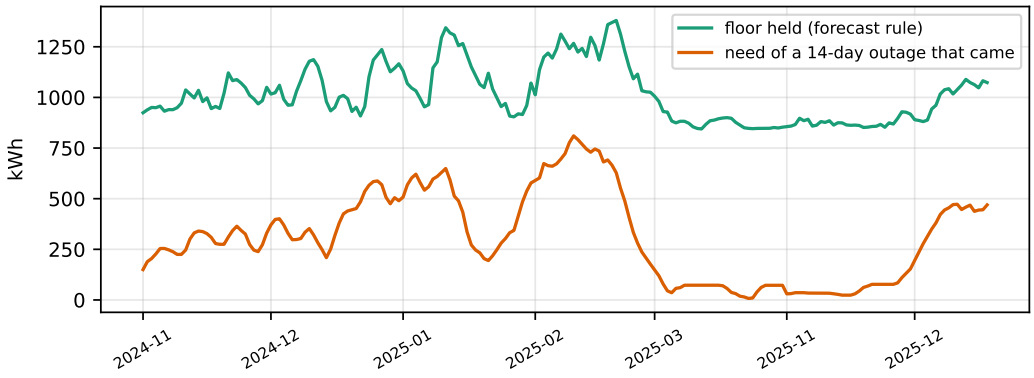


Figure 7: The floor held each winter day against what a two-week outage starting that day would have needed.

6 On the platform

The store is a location of the tenant `vawt`: a 3D board of the site with every part pickable and X-ray of the tanks and the machine house; a Control Board with the levels, flows, pressure, the powers and the controller's state; its state machine; and a live simulation that runs the controller's rules inside the site's balance (Fig. 8).

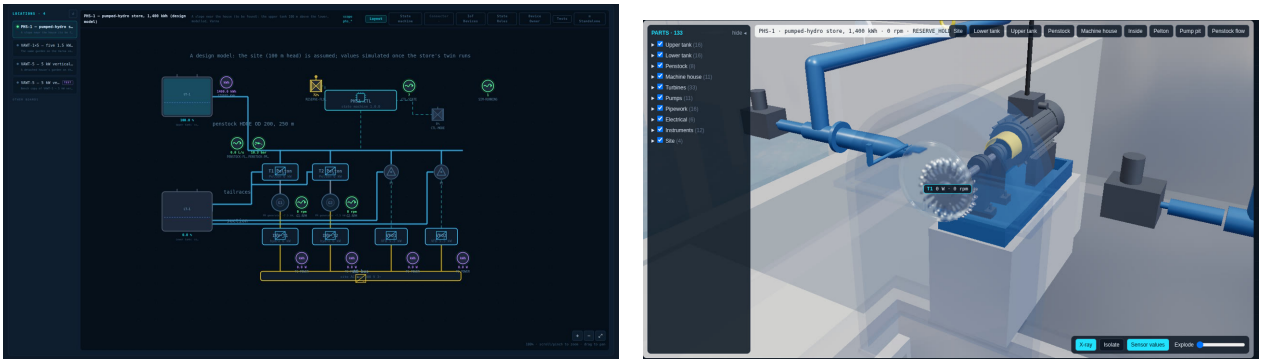


Figure 8: The platform: the Control Board and the 3D board with the simulated store (winter, the reserve held).

7 Limitations

Nothing is built. The site (100 m of head) is assumed; the loads, the greenhouses' heat and the machines' efficiencies are models, not measurements; the structural and electrical figures are first sizings to be checked and signed; the forecast rule was tested on one and a half mild winters (worst actual fortnight 810 kWh against 1,306 in ten winters). Costs are not compared here, against more battery or a backup heat source for the greenhouses.

Contributions

- The two-week off-grid requirement of a real household's mix (house, greenhouses, cars) turned into a store size from 1,359 winter fortnights, with redundancy tested by taking a turbine out.
- The finding that the greenhouses decide: without their heat the house needs a sixth of the store (216 of 1,306 kWh).
- The cost of an outage reserve in self-sufficiency, and a forecast-based reserve floor tested on archived forecasts.
- A pumped-hydro store designed end to end (basins, penstock, Pelton sets, pumps, surge, tanks, electrics, control) and running as a live twin on the platform.

Publication requirements

Every TechUPGRADE technical report is assessed against eight requirements for a publishable paper (reproducibility, baselines, validation, statistics, sensitivity, generalisation, contribution, independent review). This report is a **preprint**:

4 of 8 requirements are met and 3 partly; the open items are listed.

requirement	status	evidence
R1 Reproducibility	met	Every number from scripts in docs/projects/home-energy-system (p0 loads.py, balance.py; p1 offgrid.py, turbine_choice.py, footprint.py) and docs/projects/pumped-hydro (p1 supply.py; p3 basins_hydraulics.py, p3b_design.py, drawings; p4 electrical_phs.py; p5 control_sim.py, forecast/reserve_eval.py; p6 cad, render, twin) and make_results.py; tools image tools/vawt-eng; data: ERA5 + Varna airport, ERA5 directions, Open-Meteo previous-runs forecasts (archived in the repository)
R2 Baseline comparison	partial	The store's size from two procedures (the worst-fortnight window over 1,359 fortnights; the year-long control simulation with the reserve rules) on one site model; surge by Joukowsky and by the timed-closure formula *Open:* a second, independent site model (e.g. a different load model or a transient hydraulic code)
R3 Validation	partial	The forecast-based reserve rule validated against real archived forecasts and the weather that came (199 winter days, no unsafe day); the plant itself is not built *Open:* measurements of a built store
R4 Statistical analysis	met	The two-week need over all 1,359 winter fortnights of ten winters (median, 90th and 99th percentiles, the worst, per winter); the forecast error distribution
R5 Sensitivity analysis	met	Head 40-200 m and depth 3-10 m; round-trip efficiency 42-58 %; turbine ratings 5-9 kW with one out; reserve floors 50-100 % and the forecast rule; the island's loads (greenhouse minimum 2-8 C, unheated, house only)
R6 Generalisation	partial	The reserve rule's constant W7 comes from ten winters of history; the rule was tested on forecasts from 2024-2025 that played no part in setting it *Open:* more winters of archived forecasts, including a severe one
R7 Scientific contribution	met	Contributions section
R8 Independent review	missing	– *Open:* review by an independent hydropower / energy-systems engineer

References

[1] TechUPGRADE Digital Twin Platform, *Five small vertical-axis turbines instead of one*, technical report TU-TR-2026-004, 2026.

[2] J. Thake, *The Micro-Hydro Pelton Turbine Manual*, ITDG Publishing, 2000.

[3] E. B. Wylie, V. L. Streeter, *Fluid Transients in Systems*, Prentice Hall, 1993.

[4] EN 1992-3:2006, Eurocode 2: Design of concrete structures – Part 3: Liquid retaining and containment structures.

[5] H. Hersbach et al., The ERA5 global reanalysis, *Q. J. R. Meteorol. Soc.* 146 (2020) 1999–2049.

[6] Open-Meteo, Previous Runs API (archived forecasts by lead day), `https://open-meteo.com`, accessed 5 November 2026.