Crew time as the binding constraint of a bioregenerative food system for a fifteen-person, 500-sol Mars surface mission: design reconciliation and a 14-sol meal plan

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Abstract

Bioregenerative food production is a candidate countermeasure for the NASA Human Research Program risk of inadequate food and nutrition on long-duration surface missions, but published architectures are seldom closed simultaneously against their lighting, water, thermal, atmospheric and crew-labour budgets. This paper reports the design of ESPERANZA II, a food system sized for a crew of fifteen over a 500-sol (513.75 Earth-day) Mars surface rotation within a multi-rotation surface programme, developed for the 2026 NASA Mars to Table Challenge. The design premise follows from the challenge constraints: mass, power, volume and water are declared unconstrained, whereas crew time is bounded by a 45-hour workweek per five sols for each of two food specialists. The system comprises 373 m^2 of LED sole-source crop canopy, a 40 m^2 cyanobacterial photobioreactor, 48 m^2 of *Tenebrio molitor* rearing and 50 m^2 of fungal culture, coupled to regolith processing and fermentation modules. Electrical demand is 58.1 kW mean and 64.0 kW peak; photoperiod tessellation holds canopy lighting peak within 9 % of its 30.4 kW mean. Canopy transpiration derived from absorbed light is 644 L per sol, recovered at 98.5 %. Photosynthetic fixation of 20.7 kg CO_2 per sol exceeds crew respiration (15.4 kg), with the deficit drawn from the Martian atmosphere; oxygen release is 116 % of crew demand. A 14-sol rotation of 78 distinct meals delivers 3060 kcal per crewmember per sol against a 3035 kcal target. Recomputation of all 1,004 ingredient operations of the rotation under a batch-processing protocol yields 15.40 h of galley labour per sol (range 13.35–19.03) and a worst rolling five-sol window of 80.3 h across the crew; the two specialists' load peaks at 79.5–81.2 h of the 90 h budget, the range depending on whether grain milling is assigned to them or to the all-crew cooking rotation. Earth-provisioned energy is 41.2 % of menu calories on a per-ingredient audit (per-sol range 33.0–47.1 %) and 47.0 % on a conservative crop-nameplate basis, both below the 50 % cap; producing the EVA energy supplement in situ makes compliance independent of the EVA profile. Technology maturity ranges from TRL 3 (regolith mineral classification) to TRL 6–7 (LED crop production, fermentation). Workbooks and reconciliation scripts are released.

Keywords: bioregenerative life support, Mars surface mission, crew time, food system design, controlled-environment agriculture, in-situ resource utilisation, NASA Mars to Table

1. Introduction

The NASA Human Research Program lists inadequate food and nutrition as a risk of performance decrement and crew illness on exploration missions (NASA Human Research

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Program, 2026). For a Mars surface stay the risk is compounded by the shelf-life of pre-packaged food over mission durations of two to three years, by the absence of resupply, and by the psychological load of a fixed menu (Douglas et al., 2020; Smith et al., 2021). Bioregenerative food production—the cultivation of crops, microorganisms and other organisms within the habitat—has been studied as a countermeasure since the closed-ecosystem experiments of BIOS-3 (Gitelson et al., 1989), the MELiSSA loop (Lasseur et al., 2010) and Lunar Palace 1 (Fu et al., 2016), and has flight heritage in small-scale hardware aboard the International Space Station (Massa et al., 2017). Reviews of this work identify a recurring gap: crop productivities and radiation-use efficiencies are well characterised under controlled environments (Wheeler et al., 2008; Wheeler, 2017), whereas system-level designs rarely reconcile lighting, water, heat rejection, atmospheric exchange and crew labour as one coupled budget (Monje et al., 2003).

The 2026 NASA Mars to Table Challenge (NASA and Methuselah Foundation, 2026) requested a complete food-system concept for a crew of fifteen over a 500-sol surface rotation, with a solution summary, a concept of operations, a 14-sol meal plan with per-ingredient lifecycle accounting, a design layout and a video walkthrough. The challenge rules state explicitly that mass, power, volume and water are *not constrained*, and constrain one resource with mandatory language: all components of continuously maintaining the food system must be executable within a 45-hour workweek over five Martian sols for each of two specialists, without overtime. That asymmetry defines the design problem addressed here. Any production shortfall can be met with additional growing area, lighting and radiator surface at the cost of resources the rules do not ration; crew time is the one resource that cannot be expanded, and it therefore governs the architecture.

This paper documents the resulting system, ESPERANZA II, and its reconciliation. The contributions are: (1) a system architecture in which crop, cyanobacterial, insect and fungal production lines are sized against a fixed crew-time budget rather than against mass or power; (2) resource ledgers for electrical power, lighting, water, carbon, oxygen and heat rejection that are closed against one another rather than against independent sources, a method which exposed and corrected a five-fold error in an earlier transpiration estimate; (3) a crew-time accounting method based on batch processing of ingredient events, recomputed here from the 1,004 ingredient lines of the delivered 14-sol meal plan and evaluated on rolling five-sol windows; (4) an Earth-provisioned energy audit on two declared bases together with a sensitivity analysis showing that in-situ production of the EVA energy supplement decouples rules compliance from the EVA schedule; and (5) a technology-maturity assessment that states the gaps to be closed for each element. Section 2 states the mission context and requirements, section 3 the architecture, section 4 the reconciliation methods, section 5 the results, and section 6 the discussion and limitations.

2. Mission context and requirements

The design scenario is a relief crew of fifteen taking over a surface habitat and food system already in production, operating it for 500 sols and handing it over to the next crew during a 50-sol overlap. The system is required to sustain four or more consecutive rotations (approximately 5.6 Earth years) without mid-rotation cargo resupply; consumables are replenished by each incoming crew. Table 1 lists the quantitative requirements taken from the challenge rules and from NASA-STD-3001.

Two requirements interact in a way that shapes the design. The EVA supplement is meal-plan energy and is therefore subject to the 50 % cap; the cap must hold on every sol, not only on the rotation average. And because the crew-time requirement is assessed per specialist over a five-sol window, compliance depends on how galley labour is partitioned between the two specialists and the remaining thirteen crew, which the rules leave to the design.

Table 1: Design requirements. Nutritional targets follow the spaceflight values of NASA-STD-3001 Vol. 2 §7.1 (NASA, 2023; Smith et al., 2021); constraint language follows the challenge rules, Appendix B (NASA and Methuselah Foundation, 2026).

Parameter	Value	Source
Crew	15	Rules
Surface rotation	500 sols (513.75 Earth days)	Rules
Programme duration	$\geq$ 4 rotations ($\approx$ 5.6 yr)	Rules (multi-year objective)
Energy target	3035 kcal per crewmember per sol	NASA-STD-3001 Vol. 2
EVA supplement	+200 kcal per crew-EVA-hour	Rules, p. 12
Earth-provisioned food	$\leq$ 50 % of meal-plan calories	Rules, Appendix B Table 3
Crew time	$\leq$ 45 h per 5 sols per specialist, 2 specialists, no overtime	Rules, Appendix B (*must*)
Mass, power, volume, water	Not constrained	Rules, Appendix B
Habitat atmosphere	56.5 kPa (8.2 psi), 34 % O_2, 18–27 °C	Rules
Surface gravity	3.71 m/s^2	—
Fire safety in hyperoxic volumes	Fire-rated enclosures, O_2 trim	NASA-STD-3001 Vol. 2 §9.8.2

Table 2: Growing and preparation areas. Only the crop canopy draws canopy lighting; photobioreactor illumination is internal to the cyanobacterial module, and the insect and fungal lines are heterotrophic.

Zone	Area (m^2)	Note
Crop canopy, 11 species	373	Canopy LED, DLI 14–24 mol/m^2 per sol
Cyanobacterial photobioreactor	40	Illumination internal to module
Tenebrio molitor racks	48	Heterotrophic
Pleurotus ostreatus racks	50	Heterotrophic
Total growing area	511	
Crew food deck (galley 14, dining 22, pantry 8, cold store 6, seed bank 4)	54	

3. System architecture

3.1. Production lines and growing area

ESPERANZA II produces food through four pathways occupying 511 m^2 of growing area (table 2): a hydroponic crop canopy of eleven species under LED sole-source lighting; a cyanobacterial photobioreactor (*Arthrospira platensis* for biomass, *Anabaena* for nitrogen fixation at low partial pressure of N_2 (Verseux et al., 2021)); *Tenebrio molitor* rearing on inedible crop biomass (van Huis et al., 2013); and *Pleurotus ostreatus* culture on crop residues. A galley, dining area, pantry, cold store and seed and culture bank occupy a further 54 m^2. The pressurised food-system volume is 1058 m^3.

Table 3 gives the production nameplate by source, 24 141 kcal per sol in total; four sources (wheat, *Tenebrio*, *Arthrospira*, potato) supply 83 % of fresh energy. Crop parameters follow the crop tables of the Life Support Baseline Values and Assumptions Document (Anderson et al., 2018), which attributes them to the Kennedy Space Center Biomass Production Chamber and Utah State University work (Wheeler et al., 2008; Bugbee and Koerner, 1997); the wheat figure uses the BVAD harvest index rather than the record yields of that literature.

The crop chambers hold an atmosphere independent of the habitat: 56.5 kPa total pressure, approximately 21 % O_2 and 1,200–1,500 ppm CO_2, airlock-separated and exporting O_2 to the habitat. All staple crops (wheat, soybean, potato, tomato, pepper) are

Table 3: Fresh production nameplate by source (steady state, sols 60–450). Percentages are of fresh energy. Yields are design values traced to Anderson et al. (2018) (Tables 4-97, 4-105, 4-117, 4-119) and have not been confirmed at 56.5 kPa (section 6.4).

Source	Area (m^2)	kcal per sol	% fresh
Wheat	150	6027	25.0
Arthrospira (photobioreactor)	40	5800	24.0
Tenebrio molitor (racks)	48	5600	23.2
Potato	80	2640	10.9
Soybean	80	1784	7.4
Pleurotus (racks)	50	1375	5.7
Radish	8	307	1.3
Lettuce and kale	15	248	1.0
Tomato	20	144	0.6
Pepper	15	130	0.5
Herbs	5	86	0.4
Total	511	24 141	100.0

C_3 species; at the habitat's 34 % O_2 the oxygenase reaction of Rubisco competes more strongly with carboxylation and net photosynthesis falls by an estimated 15–25 %, which would render the crop-table yields optimistic. LED driver electronics are housed in a normoxic bay with DC distribution to the luminaires.

3.2. Regolith processing and substrate

Three modules process Martian regolith into a growth substrate. A regolith mineral classifier (random forest and Gaussian-process regression trained on published lunar and Martian compositional datasets; TRL 3) ranks candidate feedstock. A perchlorate bioremediation stage uses perchlorate-reducing bacteria of the *Azospira* group, whose *pcrA*/*cld* pathway is characterised (Melnyk et al., 2011), to reduce perchlorate from the 0.4–0.6 wt % measured at the Phoenix site (Hecht et al., 2009) to a design gate of 0.017 wt % by sol 24 of the substrate cycle; the acceptance criterion for crop tissue is the U.S. EPA reference dose of 0.7 µg/kg per day (U.S. Environmental Protection Agency, 2005). Perchlorate is treated as a hazard to be removed rather than as an oxygen resource (Davila et al., 2013): chlorite dismutase generates O_2 intracellularly and the organism respires it in situ, so no oxygen from this stage is credited to the atmospheric balance. The substrate is a blend of 32.1 % lunar regolith (transported as transit radiation shielding and repurposed as a calcium and magnesium corrector), 21.3 % treated Martian regolith, 20 % cyanobacterial biomass, 24.4 % composted organics and 2.2 % biopolymer binder; the rationale for regolith-based substrates follows the reviews of Duri et al. (2022) and Fackrell et al. (2024).

3.3. Fermentation and operations layer

A fermentation module produces miso, tempeh, kefir, bread and vinegar and hosts the insect line. An operations layer (NEXUS) aggregates approximately 200 sensors across the modules, schedules galley and cultivation tasks, and proposes per-crewmember portioning from non-invasive wearable data; it proposes and the crew decides, and the nutritional targets of the meal plan are met in full if the layer is ignored. The inference step on which its state detection rests was demonstrated by the author on public NASA flight data (Puerta Angulo, 2026a) and is discussed in section 6.

4. Methods

4.1. Reconciliation principle

Every budget was closed against its neighbours rather than against an independent source. The lighting power that drives the electrical budget is the same energy that drives canopy transpiration and heat rejection; the ingredient list that drives the Earth-provisioned fraction is the same list that drives galley labour. This principle is stated first because it is how the largest error in the design history was found (section 4.3).

4.2. Lighting and electrical power

Canopy lighting power is computed from the daily light integral D_i (mol/m^2 per sol) and area A_i of each crop zone i, the fixture efficacy η (µmol/J) and the sol length $t_{\text{sol}} = 88\,775\,\text{s}$:

$$P_{\text{LED,mean}} = \frac{\sum_i D_i A_i}{\eta\, t_{\text{sol}}}, \qquad P_{\text{LED}}(t) = \sum_i \frac{D_i A_i}{\eta\, \tau_i} \mathbb{1}[t \in W_i], \tag{1}$$

where τ_i is the photoperiod of zone i, W_i its lit window within the sol and $\mathbb{1}[\cdot]$ the indicator function (1 when the zone is lit, 0 otherwise). The efficacy is taken as $\eta = 3.0$ µmol/J, achievable in current commercial horticultural fixtures at the favourable end of the range; a sensitivity at 2.7 µmol/J is reported. Photoperiods are crop-physiology requirements first: soybean is a short-day species that does not flower under 16-hour days, and potato tuberisation favours short days, so both run on 12.33-hour windows; wheat (cv. USU-Apogee, bred for controlled environments and tolerant of continuous light (Bugbee and Koerner, 1997)) runs 24/0. The remaining electrical line items (ventilation with hypobaric density correction, dehumidification, thermal-loop pumping, nutrient pumps, substrate pasteurisation, galley, cold store, CO_2 capture) are estimated from stated bases (table 4).

4.3. Water

In a closed chamber the energy for evapotranspiration can only come from absorbed light. Gross canopy transpiration is therefore derived from the lighting budget:

$$E = \frac{P_{\text{LED,mean}}\, f_{\text{abs}}\, f_{\text{lat}}\, t_{\text{sol}}}{L_v}, \tag{2}$$

with absorbed fraction $f_{\text{abs}} = 0.90$, latent partition $f_{\text{lat}} = 0.65$ and latent heat of vaporisation $L_v = 2450\,\text{kJ/kg}$. An earlier revision of the design carried 3226 L per sol of transpiration; evaporating that mass requires 89 kW of latent heat against 30.4 kW of lighting, and the figure, together with a 50 L per sol in-situ water input that had been sized to it, was withdrawn. Condensate recovery at chamber condensers is taken as 98.5 %; make-up is drawn from habitat grey water. Condenser control uses hot-gas bypass with a 4–10 °C setpoint and a trip below 2 °C to avoid icing against a loop near Martian ambient.

4.4. Carbon and oxygen

CO_2 fixation by the canopy is computed from dry-matter production (23.5 g/m^2 per sol over 373 m^2, i.e. 8.77 kg dry biomass per sol, 307 mol C) and by the photobioreactor from its biomass yield; O_2 release follows photosynthetic stoichiometry (32/44 by mass). Crew respiration and oxygen demand use the baseline values of Anderson et al. (2018). Fermentation, composting and heterotrophic lines return CO_2 to the canopy; any residual deficit is met by capture and compression of Martian atmospheric CO_2 (0.6 to 56.5 kPa, 94:1).

4.5. Heat rejection

Essentially all electrical input becomes heat, less the fraction stored as chemical energy in biomass: $Q = P_{\mathrm{el}} - P_{\mathrm{chem}}$. The radiator is sized for the dust-deposited case (solar absorptivity $\alpha \approx 0.55$) rather than the clean case ($\alpha \approx 0.15$), at a 40 °C loop with vertical north–south panels; the cleaning cadence is set by the same deposition rate and its EVA hours are charged to the calorie budget at 200 kcal per crew-EVA-hour. Global dust storms, which suppress surface photosynthetically active radiation by more than 90 % for weeks without reliable forecast (Zurek and Martin, 1993), are the first of three grounds on which conducted daylight was traded out of the lighting architecture; the others are pressure-shell penetrations and the conductive loss of a translucent boundary (15–46 kW over 373 m^2 at $\Delta T \approx 82$ K for $U = 0.5$–$1.5\ \mathrm{W/(m^2\,K)}$, against roughly 17 kW of optical gain).

4.6. Crew-time accounting

The delivered meal-lifecycle workbook records, for each of the 1,004 ingredient lines of the 14-sol rotation, a preparation, cooking and cleaning duration. Durations are charged per ingredient *event* under a batch-processing (mise en place) galley protocol: preparation once per ingredient per sol, cooking once per ingredient per meal, cleaning once per ingredient per sol; subsequent lines of the same ingredient within the batching scope carry zero. The unbatched line-by-line sum is retained as a reference because it double-charges mise en place for ingredients recurring across a sol's services (soybean oil alone appears on 130 lines).

For this paper the per-sol galley load G_s was recomputed directly from the workbook as the sum of the three duration columns over all lines served on sol s (script `01_recompute_from_deliverables.py`), and evaluated on the ten distinct rolling five-sol windows of the rotation, $\sum_{k=0}^{4} G_{s+k}$ for $s = 1, \ldots, 10$. Compliance is assessed on the two specialists' own load. Galley work is partitioned by activity: in-situ ingredient processing (fermentation, spirulina harvest, insect and mushroom handling, soy and grain processing) is retained by the specialists; Earth-ingredient preparation, cooking and galley cleaning are carried by an all-crew cooking rotation. Specialist non-galley duties (crop tending and harvest, HACCP and water and perchlorate monitoring, maintenance, documentation, planning) are added. The non-galley durations are design allocations stated in the concept of operations and are not recomputed here. The activity partition is examined two ways: as the design allocation (28.1 h per cycle retained by the specialists), and as a recomputation that classifies each workbook line by its *Production Method* field into in-situ processing (fermentation, insect, fungal, soy-processing and photobioreactor lines), crop preparation (hydroponic crop lines) and Earth stock, and sums the specialists' in-situ processing hours on the same rolling windows. The workbook does not separate grain milling from crop preparation, so the recomputation is a lower bound on the specialists' galley share and the design allocation an upper bound.

4.7. Earth-provisioned energy audit

The rules specify the Earth-provisioned fraction by calories, but the lifecycle workbook records source and mass without energy and the schedule workbook records energy without source. Each of the 177 distinct ingredient labels was therefore assigned an energy density from a named USDA FoodData Central reference item (U.S. Department of Agriculture, Agricultural Research Service, 2019), volumetric entries were converted to mass (cooking oil at 0.92 g/mL; all other volumetric entries at unity), and line energy was aggregated by source and by sol. A confidence class (high, medium, low) was recorded per label. The audit was validated by reconstructing the plan's own energy without fitting: 2992 kcal per crewmember per sol against the 3035 kcal target (98.6 %). Two bases are reported: the

Table 4: Electrical power ledger (mean, kW). Photobioreactor illumination, mixing and sparging are internal to the cyanobacterial module and are not part of the canopy figure; insect rearing is internal to the fermentation module.

Line item	kW	Basis of estimate
Six process modules	10.7	Classifier 0.6, bioremediation 2.1, substrate 0.4, cyanobacteria 4.8, fermentation 1.9, operations layer 0.9
Canopy LED	30.4	Equation (1), 373 m^2
Canopy ventilation	5.0	8 % of lighting load × 1.84 hypobaric correction (ρ 0.667 vs 1.225 kg/m^3)
Dehumidification and condensate	2.2	17.8 kW latent rejected passively; pumping only
Thermal loop and pumps	2.5	≈ 4 % of rejected thermal load
Nutrient and aeration pumps	2.5	5–8 W/m^2 hydroponic practice
Substrate pasteurisation	1.2	Batch, sol-averaged
Work and corridor lighting	0.8	Task and egress illumination
Galley (mill, griddle, centrifuge)	0.7	Equipment inventory
Mushroom chamber environment	0.6	90 % RH, elevated air change
Refrigerated store, 4 °C	0.8	Storage condition of the meal plan
Water treatment and condensate UV	0.4	Potable polishing
CO_2 capture and compression	0.3	3.1 kg per sol; isothermal ideal work 8.8 W, ∼ 7× margin
Total, mean	58.1	Peak 64.0; installed 77

audited menu, and a conservative crop-nameplate basis in which the in-situ line is fixed at the crop-table production of 24 141 kcal per sol and any menu draw above it is booked to Earth stock as a declared reserve.

4.8. Reproducibility

The recomputation used Python 3 with `openpyxl` and `matplotlib`; it is deterministic and completes in seconds. The delivered workbooks are read unmodified; results are written to `results.json` and `per_sol.csv`. Figures are generated by `02_figures.py`. The lighting, water, gas, heat and EVA computations use the closed-form expressions above with the stated constants.

5. Results

5.1. Electrical power

Food-system demand is 58.1 kW mean, 64.0 kW peak and 77 kW installed (peak ×1.20). Table 4 gives the ledger. Canopy lighting is 52 % of the mean. At $\eta = 2.7$ µmol/J canopy demand rises to approximately 33.8 kW mean, within the installed capacity without redesign.

5.2. Lighting and photoperiod tessellation

Table 5 and fig. 1 show the canopy zones and the instantaneous load over one sol. Wheat runs as a continuous baseload; soybean and potato occupy opposite 12.33-hour windows; fruiting and leafy crops run 16/8. The resulting peak of 33.3 kW sits 9 % above the 30.4 kW mean, which is what allows a power plant of modest class to serve a 373 m^2 farm without a large battery.

Table 5: Canopy zones, daily light integral (DLI), photoperiod and lighting load. Instantaneous load applies while the zone is lit.

Zone	Area (m^2)	DLI	Photoperiod (h)	Instantaneous (kW)	Mean (kW)
Wheat, USU-Apogee	150	24	24/0	13.52	13.52
Soybean	80	22	12.33/12.33	13.22	6.61
Potato	80	20	12.33/12.33, opposite	12.02	6.01
Tomato, pepper, leafy greens	63	14–22	16/8	6.55	4.25
Canopy	373			33.3	30.4

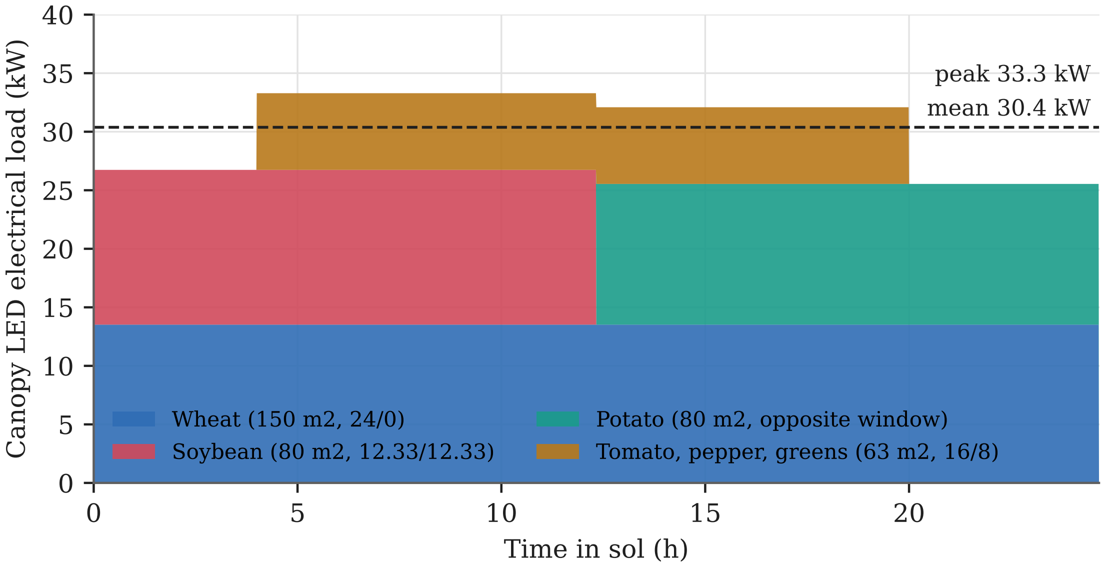

Figure 1: Canopy LED electrical load over one sol (24.66 h) by crop zone, stacked. Wheat (150 m^2) runs continuously; soybean and potato (80 m^2 each) occupy opposite 12.33-hour windows; fruiting and leafy crops (63 m^2) run 16/8. The dashed line is the sol mean (30.4 kW); the peak is 33.3 kW. Zone loads from table 5.

5.3. Water

Table 6 gives the water streams. Gross canopy transpiration from eq. (2) is 644 L per sol, of which 634 L is recovered as condensate; net make-up is 9.7 L per sol, supplied from the 12 L per sol of grey water received from the habitat ECLSS. The 12 000 L nutrient-solution inventory (32 L/m^2) is inherited with the habitat and is not a daily flow. The food system does not generate water; it conserves it, and initial water procurement lies outside its boundary.

5.4. Carbon and oxygen

Table 7 and fig. 2 give the ledger. The canopy fixes 13.5 kg CO_2 per sol and the photobioreactor 7.2 kg, a total of 20.7 kg. Crew respiration supplies 15.4 kg (74 %); fermentation, composting and heterotrophic lines return 2.8 kg; the remaining 2.5 kg is drawn from the Martian atmosphere (3.1 kg captured, 0.6 kg buffered). Fifteen crew are not a sufficient carbon source to saturate 413 m^2 of photosynthetic area; the loop is closed on the resources that are scarce (water, organics) and deliberately open on the one that is abundant outside the habitat. Oxygen release is 9.82 kg per sol from crops and 5.20 kg from the photobioreactor, 15.02 kg in total against a crew demand of 12.95 kg (116 %); crops alone supply 76 %.

Table 6: Water streams (per sol). The transpiration figure is derived from the lighting budget (eq. (2)) and replaces a withdrawn earlier estimate of 3226 L per sol.

Stream	L per sol	Basis
Canopy transpiration, gross	644	30.4 kW × 0.90 × 0.65 / 2450 kJ/kg
Condensate recovered	634.3	98.5 % recovery
Net make-up	9.7	644 × 1.5 %
Grey water received from ECLSS	12	Habitat interface
Nutrient solution inventory	12 000	Standing volume, not a flow

Table 7: Carbon and oxygen ledger (kg per sol). Crew values from Anderson et al. (2018). No oxygen from perchlorate reduction is credited.

Stream	kg per sol	Basis
CO_2 fixed by crops	13.5	307 mol C; 8.77 kg dry biomass
CO_2 fixed by photobioreactor	7.2	35 % of total fixation
CO_2 from crew respiration	15.4	Metabolic baseline
CO_2 from fermentation, composting, heterotrophs	2.8	1.5 + 0.8 + 0.5
CO_2 captured from Martian atmosphere	3.1	0.6 buffered; 2.5 net
O_2 released by crops	9.82	Stoichiometry from 13.5 kg CO_2
O_2 released by photobioreactor	5.20	Stoichiometry from 7.2 kg CO_2
O_2 consumed by crew	12.95	Metabolic baseline
Total O_2 released	15.02	116 % of demand

5.5. Heat rejection

Thermal load to reject is 58.1 kW electrical less 1.7 kW stored in biomass, i.e. 56.4 kW. A clean radiator at mean conditions requires approximately 220 m^2; under dust deposition a 230 m^2 array fails to reject at local noon. The array is therefore sized at approximately 300 m^2, at a 40 °C loop, with vertical north–south panels and a scheduled cleaning EVA (2 crew × 4 h every 30 sols, 0.27 crew-EVA-hours per sol). Together with regolith acquisition for the substrate (10.5 kg of Martian regolith per sol, batched as 2 crew × 6 h every 30 sols, 0.40 crew-EVA-hours per sol), the EVA demand attributable to the food system is 0.7 crew-EVA-hours per sol, one twelfth of the 8 crew-EVA-hours per sol nominal mission envelope.

5.6. Crew time

Recomputed from the 1,004 ingredient lines, galley labour across the whole crew is 15.40 h per sol on average (preparation 6.55, cooking 6.23, cleaning 2.62 h), with a peak of 19.03 h on sol 3, a second peak of 18.72 h on sol 13 and a minimum of 13.35 h on sol 6 (fig. 3, left). The rotation totals 76.98 h per five sols on average; the worst of the ten rolling five-sol windows (sols 10–14) totals 80.27 h (fig. 3, right). The unbatched line-by-line sum is 21.03 h per sol, 37 % higher, which quantifies the labour value of the batch protocol.

Under the activity partition of section 4.6, the all-crew cooking rotation carries 48.9 h per cycle (Earth-ingredient preparation 4.7, cooking 31.2, galley cleaning 13.1 h; approximately 45 min per person per sol across thirteen crew) and the two specialists retain 28.1 h per cycle of in-situ ingredient processing. With 49.0 h per cycle of non-galley duties (crop tending and harvest 22.0, HACCP and water and perchlorate monitoring 9.0, maintenance 7.0, documentation 6.0, planning and inventory 5.0 h), the specialists' mean load is 77.1 h of 90 h (86 %), the worst window 81.2 h (90 %), the worst single specialist 40.6 h of 45, and none of the ten windows exceeds the budget. Without the cooking rotation the specialists would require 126 h per cycle. No specialist sol exceeds 9 h; the binding criterion is the five-sol window, not any single sol.

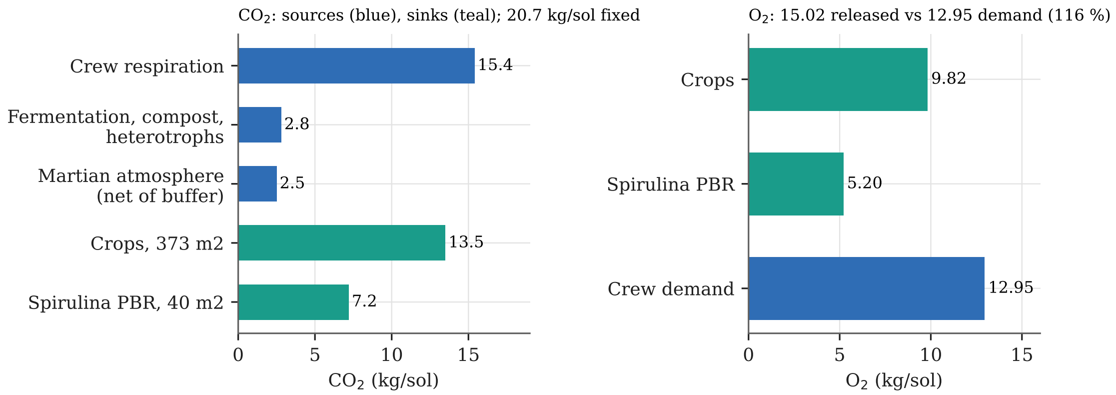

Figure 2: Carbon and oxygen ledger per sol. Left: CO_2 sources (crew, heterotrophic returns, Martian atmosphere net of buffer) and sinks (crop canopy, photobioreactor). Right: O_2 released by the two photosynthetic lines against crew demand. Values as stated in the design documents (table 7); not recomputed.

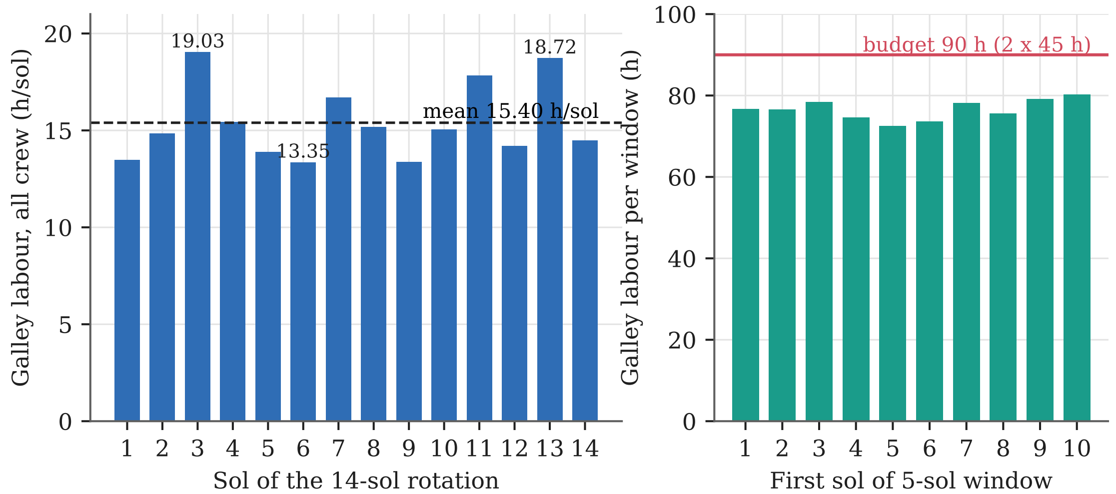

Figure 3: Galley labour recomputed from the delivered 14-sol meal plan (1,004 ingredient lines, batch protocol). Left: hours per sol across the whole crew; dashed line, rotation mean 15.40 h; labelled sols are the two peaks and the minimum. Right: labour in each of the ten rolling five-sol windows against the 90 h two-specialist budget; the worst window (sols 10–14) totals 80.3 h before partition between specialists and the all-crew cooking rotation.

The recomputed partition by production method gives 23.8 h per cycle of in-situ processing, 36.2 h of crop preparation and 17.0 h of Earth-stock handling (sum 77.0 h). In-situ processing peaks at 30.5 h in its worst five-sol window (sols 2–6, driven by fermentation batches on sols 2 and 3), which with the 49.0 h of non-galley duties gives a specialist load of 79.5 h (88 %) in the worst window and 72.8 h (81 %) on average. The design allocation, which additionally assigns grain milling to the specialists, gives 81.2 h; the two bases bracket the specialists' worst window at 79.5–81.2 h, and both satisfy the 90 h requirement with 9–11 % margin.

5.7. Meal plan and nutrition

The rotation comprises 78 distinct meals (no meal repeated within 14 sols) drawn from 12 food sources and 16 species or cultured organisms, with six primary protein sources (*Tenebrio*, soybean products, chickpea, *Arthrospira*, wheat gluten, *Pleurotus*). Recomputed from the schedule workbook, delivered energy is 3059.9 kcal per crewmember per sol on average (100.8 % of target; range 3035–3257), protein 123.1 g (target 91), fibre 57.7 g

Table 8: Earth-provisioned fraction (nameplate basis) versus crew EVA hours per sol, with the 200 kcal per crew-EVA-hour supplement sourced from Earth or produced in situ. Baseline: 21 384 kcal per sol Earth-provisioned of 45 525 kcal per sol total.

Crew-EVA-h per sol	Supplement (kcal per sol)	From Earth (%)	In situ (%)
0	0	46.97	46.97
4	800	47.89	46.16
8	1600	48.77	45.38
12	2400	49.63	44.62
13.8	2757	50.00	44.29
16	3200	50.45	43.89
24	4800	52.03	42.49

(target 30) and sodium 1852.5 mg (limit 2,300); carbohydrate is 423 g (target 380) and fat 94.2 g (93.3 % of target, 27.7 % of energy). Protein and fibre run above target by design, the former in support of bone and muscle countermeasures and the latter to feed short-chain fatty acid production (Turroni et al., 2020; Quinn-Bohmann et al., 2024). Micronutrient values are design estimates at 70 % yield derating rather than an audited roll-up: vitamin D follows the 25 µg per sol spaceflight requirement (18 µg from UV-treated *Pleurotus*, 7 µg from an Earth-provisioned premix); iodine (150 µg) is supplied entirely by the premix because perchlorate competitively inhibits thyroidal iodide uptake, and compliance is verified by urinary iodine and TSH every 90 sols; iron from whole foods is 20 mg per sol against the spaceflight ceiling of 8–10 mg (Smith et al., 2021), an open non-conformance discussed in section 6.4. Fermented foods carrying live cultures (kefir, miso, tempeh) are embedded in the rotation rather than supplied as supplements, following the rationale reviewed by Zhao (2024).

5.8. Earth-provisioned fraction and EVA sensitivity

On the per-ingredient audit the 14-sol menu supplies 24 619 kcal per crewmember from in-situ production and 17 258 kcal from Earth stock, an Earth-provisioned fraction of 41.2 %, with a per-sol range of 33.0–47.1 % (fig. 4, left); no sol exceeds the cap. On the crop-nameplate basis the fraction is 47.0 %: the menu draws 2628 kcal per sol above the 24 141 kcal per sol crop table and that draw is booked to Earth stock. The higher figure is carried as the headline. Of the 177 ingredient labels, 62 are high-confidence, 57 medium and 58 low; weighted by contribution, 67 % of calories come from high-confidence entries and 6.4 % from low-confidence entries, the latter dominated by spice blends of 1–3 g. Cooking oil is 3 % of ingredient mass but 15 % of plan energy and is Earth-provisioned; it is the dominant lever on the audited fraction. For reference, the same audit by mass yields 16.1 %; mass is not the metric the rules specify.

The EVA energy supplement is meal-plan energy and is subject to the cap. Table 8 and fig. 4 (right) show the fraction on the nameplate basis as a function of crew EVA hours per sol under two sourcing options. Supplied from Earth, the cap is breached at 13.8 crew-EVA-hours per sol, a cadence set by the surface architecture rather than by the food system. Produced in situ, the fraction decreases monotonically with EVA hours, from 47.0 % at zero to 42.5 % at the 24-hour design box; at the nominal 8 crew-EVA-hours per sol it is 45.4 %. The in-situ option costs 25 m^2 of additional canopy, 2.0 kW of LED, 13 m^2 of radiator and 0.6 L per sol of make-up water, moves the specialists' worst window from 81.2 to 82.8 h, and adds no launch mass. Roughly 80 % of the supplement is delivered as enlarged portions of foods the rotation already produces (a loading meal 60 minutes before egress, a compact bar at the airlock, a recovery meal within 30 minutes of ingress); no new process line is required.

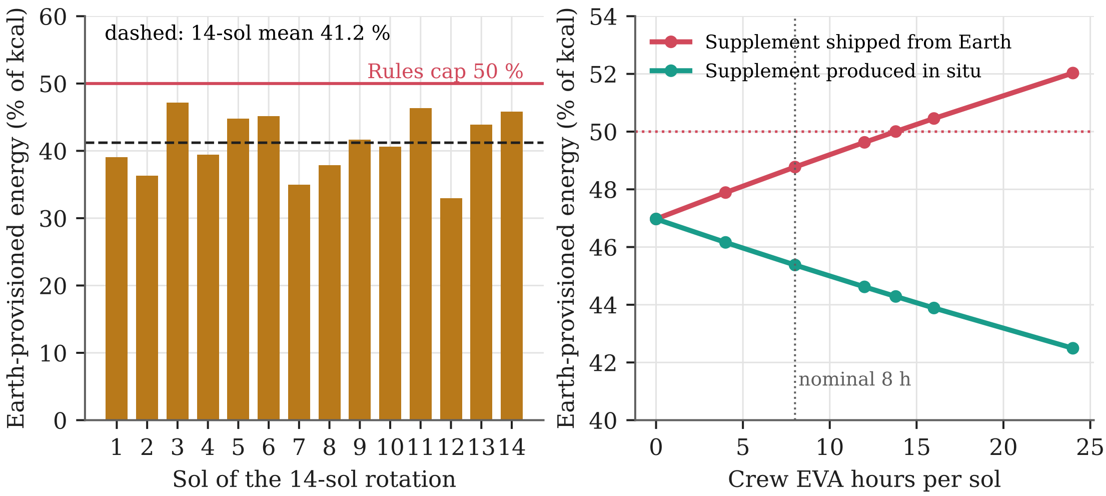

Figure 4: Earth-provisioned share of meal-plan energy. Left: per sol of the 14-sol rotation on the per-ingredient audit (bars), rotation mean 41.2 % (dashed) and the 50 % rules cap; no sol exceeds the cap. Right: nameplate-basis fraction versus crew EVA hours per sol with the energy supplement shipped from Earth or produced in situ (table 8); the dotted vertical line marks the nominal 8 crew-EVA-hours per sol.

5.9. Mass, multi-year operation and maturity

Launch mass attributable to the food system is 25 729 kg: biological starters 205 kg, micronutrient premix 180 kg, allergen-free emergency rations 1500 kg (90 sols), Earth-provisioned food 6274 kg, and system hardware, spares and consumables 17 570 kg, of which the six process modules are 2085 kg. For comparison, fully Earth-supplied food alone for 15 crew over 514 days at 1.8 kg per person per day is approximately 13 878 kg. The reserve of 4.10×10^6 kcal covers 90 sols at full ration or 180 sols at half ration. The programme load over four rotations is approximately 91×10^6 kcal ($15 \times 500 \times 3035 \times 4$), 53 % met in situ on the nameplate basis. Designed lifetimes are $\geq$50 000 h for the LED array (about 5.7 years continuous), $\geq$35 000 h with N+1 redundancy for recirculation pumps, one rotation for hydroponic and photobioreactor membranes, and 12 months for cyanobacterial starter cultures refreshed at each hand-over from Earth cryostock; a 16S rRNA drift assay per rotation triggers refresh at > 2 % drift.

Table 9 states the technology readiness of each element and the gap to be closed. Overall system maturity is governed by the least mature elements: the regolith classifier at TRL 3, the operations layer at TRL 3–4, and bioremediation and substrate at TRL 4.

6. Discussion

6.1. Principal findings

Three results carry the argument. First, sizing to crew time rather than to mass or power produces a system in which the two specialists operate at 81–86 % of budget on average and 88–90 % in the worst window, without overtime, only because two design decisions are load-bearing: the batch-processing galley protocol, which removes 37 % of the line-by-line labour, and the all-crew cooking rotation, without which the specialists would require 126 h per five sols. Neither is hardware. Growing more of a crop is free in power and volume under the rules and expensive in hours; the operations layer exists to buy hours back, not to add capability.

Second, closing the budgets against each other rather than against independent sources is a method with detection power. The withdrawn transpiration figure of 3226 L per sol was internally plausible (it corresponds to a canopy at DLI 120–130) and was only found

Table 9: Technology readiness and gaps.

Element	TRL	Maturity basis	Gap to close
Regolith mineral classifier	3	Random forest and Gaussian process on published datasets, 77 % accuracy; analytical only	Beneficiation hardware; breadboard on simulant before TRL 4
LED sole-source crop production	6–7	Veggie and Advanced Plant Habitat heritage (Massa et al., 2017); commercial vertical farming	Fixture lifetime ≥50 000 h under Mars surface conditions
Hydroponic staples (wheat, soybean, potato)	5–6	Controlled-environment literature (Wheeler et al., 2008)	Yield confirmation at 56.5 kPa
Cyanobacterial photobioreactor	4–5	Industrial *Arthrospira*; laboratory N_2 fixation at low pressure (Verseux et al., 2021)	Multi-year culture stability, strain drift
Perchlorate bioremediation	4	Pathway characterised (Melnyk et al., 2011)	Rate and completeness in Martian regolith matrix; scale-up
Regolith-derived substrate	4	Simulant studies (Duri et al., 2022)	Validation on in-situ or returned material
Tenebrio molitor rearing	5–6	Commercial industry (van Huis et al., 2013)	Closed-loop rearing on in-situ residues; Mars-gravity behaviour
Fermentation	6–7	Established process control	Starter viability across multi-year storage
Operations layer	3–4	Component algorithms (scheduling, sensor fusion) established in the literature; the state-inference step was demonstrated on a flight analogue by the author, as a preprint (Puerta Angulo, 2026a)	Closed-loop validation with human subjects in an analogue
Surface fission power	5–6	KRUSTY demonstration	Outside scope; cited as heritage

to be impossible when checked against the 30.4 kW of lighting that would have to supply its latent heat. The same coupling fixes the radiator area, the EVA cleaning cadence and, through the 200 kcal per EVA-hour rule, the calorie budget.

Third, rules compliance on the Earth-provisioned fraction is not a property of the menu alone. Sourced from Earth, the EVA supplement breaches the 50 % cap at 13.8 crew-EVA-hours per sol, a variable outside the food system's control; produced in situ, the fraction falls with EVA hours. Where a requirement couples to an external schedule, the compliant design is the one that makes compliance independent of that schedule.

6.2. Relation to prior closed-system work

BIOS-3 and Lunar Palace 1 demonstrated multi-month closure of gas and water loops with plant-based food supply for crews of two to four (Gitelson et al., 1989; Fu et al., 2016); MELiSSA formalised the compartment model that the present design follows in outline (Lasseur et al., 2010). The present work differs in scale (fifteen crew, 511 m^2), in the explicit crew-labour budget, and in the treatment of the Martian atmosphere as a legitimate carbon source: the crew of fifteen supplies only 74 % of the carbon fixed by 413 m^2 of photosynthetic area, and closing that gap from an atmosphere that is 95 % CO_2 is cheaper than shipping carbon. The photoperiod tessellation is a scheduling result rather than a horticultural one, but it rests on cultivar properties established for controlled environments (Bugbee and Koerner, 1997).

6.3. *The operations layer and human research*

The operations layer proposes per-crewmember portioning from a non-invasive wearable rather than from a laboratory panel, and demotes salivary cortisol from routine sampling to confirmation of a flagged state. That choice rests on two findings from the author's analysis of the SpaceX Inspiration4 public archive (NASA OSDR, $n = 4$, six timepoints) (Puerta Angulo, 2026a): a fused multi-modal representation separated pre- from post-flight state at leave-one-subject-out accuracy 0.708 against a permuted-label null of 0.489 ± 0.107 ($p = 0.026$), whereas no individual biomarker survived multiple-testing correction (0 of 1,112 at Benjamini–Hochberg $q < 0.05$); and eighteen cardiovascular readouts were not distinguishable in classification utility from 406 urine cytokine features at that sample size. The boundary of the claim is stated: the significant result belongs to the fused representation including laboratory modalities, the cardiovascular modality alone was not shown significant, Inspiration4 is a short-duration low-Earth-orbit civilian analogue, and the cited work is a preprint. The layer is therefore specified as a fused state detector whose sampling burden is minimised because sampling is crew time. Routine saliva sampling of fifteen crew at approximately 2.5 min per sample would cost about 0.63 h per sol; event-driven confirmation at an assumed two flagged events per five-sol week costs about 0.02 h per sol. Both durations are engineering assumptions to be confirmed in an analogue campaign.

6.4. *Limitations*

1. *No dynamic growth simulation.* Crop yields are taken from a crop table derived from controlled-environment literature; they have not been simulated dynamically nor confirmed at 56.5 kPa. The carbon ledger inherits this uncertainty.
2. *Crew-time durations are engineering estimates.* The per-ingredient preparation, cooking and cleaning durations were assigned during meal engineering and have not been measured in an analogue galley. The all-crew series and the partition by production method are recomputed here; the non-galley specialist durations (49.0 h per cycle) are design allocations and were not recomputed, and the specialists' worst window of 79.5–81.2 h is conditional on them.
3. *Energy-audit confidence.* One third of ingredient labels are low-confidence by energy density, although they carry 6.4 % of calories. The largest single uncertainty is *Tenebrio* flour at 5.20 kcal/g, which has no USDA entry and is derived from a declared composition of approximately 50 % protein and 30 % fat.
4. *Micronutrients.* Values other than macronutrients and sodium are design estimates at 70 % yield derating. Iron from whole foods (20 mg per sol) exceeds the spaceflight ceiling of 8–10 mg and the rotation as delivered does not meet that requirement. Spirulina and *Tenebrio* flour are the dominant iron sources; reducing their share in favour of soybean products and potato, with ferritin monitoring every 90 sols, is the intended correction and has not yet been applied to the menu.
5. *Maturity.* Three elements are at TRL 3–4. The regolith classifier is trained on published datasets, not on in-situ assay. The operations layer's inference step is demonstrated on a flight analogue but the loop to meal actuation has not been closed with human subjects.
6. *Fixture efficacy.* The 3.0 µmol/J efficacy is at the favourable end of current commercial fixtures; the installed margin absorbs a 10 % shortfall but not more.
7. *Cost and launch architecture.* No cost analysis is presented, and the 25 729 kg launch mass is stated without a delivery manifest.
8. *Evaluation context.* The design was developed for and submitted to a public challenge; it has not been reviewed by an independent engineering board.

6.5. Future work

Three activities would move the design most: an analogue galley campaign to measure per-ingredient durations and the WATCH event rate, replacing the engineering estimates of section 5.6; hypobaric yield trials for wheat, soybean and potato at 56.5 kPa and 21 % O_2; and in-situ pressing of soybean oil, which at 15 % of plan energy is the dominant lever on the Earth-provisioned fraction and would move the audited figure well below 41.2 %.

7. Conclusions

A bioregenerative food system for fifteen crew over a 500-sol Mars surface rotation can be sized so that two food specialists operate within a 45-hour five-sol workweek, provided that galley labour is batched by ingredient event and shared with an all-crew cooking rotation and that monitoring and scheduling are delegated to an operations layer. The system requires 58.1 kW mean electrical power, 511 m^2 of growing area and 9.7 L per sol of make-up water; it fixes more CO_2 than the crew produces and returns 116 % of the crew's oxygen demand. A 14-sol rotation of 78 distinct meals meets the NASA-STD-3001 energy target with 41.2 % of calories from Earth on a per-ingredient audit and 47.0 % on a conservative nameplate basis, and producing the EVA supplement in situ keeps that fraction below the cap for any EVA schedule. The reconciliation method—closing lighting, water, heat, gas and crew time against one another—is reported as a result in its own right, because it is how the design's largest error was found.

Declaration of generative AI in the writing process

During the preparation of this work the author used a large-language-model assistant for drafting, editing and consistency checking of text and for generating figure and analysis scripts under the author's direction. All design decisions, calculations and their verification are the author's; the author reviewed and edited all content and takes full responsibility for the published article.

Declaration of competing interest

The author declares no competing interests.

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Data and code availability

The delivered 14-sol meal plan workbooks (schedule and lifecycle), the reconciliation scripts (`01_recompute_from_deliverables.py`, `02_figures.py`), their outputs (`results.json`, `per_sol.csv`) and the design documents from which the ledgers are drawn will be deposited at Zenodo (Puerta Angulo, 2026b). The Inspiration4 analysis cited in section 6 is available at `https://github.com/engimine/HRP_Artemis_II` (DOI 10.5281/zenodo.21015202).

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