Compute Waste Heat as a Low-Grade Thermal Offset for Lunar ISRU

A quantified, thermodynamically-bounded case: data-center / GPU waste heat can supply the low-grade thermal demand of lunar water-ice ISRU, but not the high-grade reduction heat. It is well-matched to the PSR water route and nearly useless for the others.

Version 0.2 (2026-07-01). Backed by the `lpem` model in this repository (`python -m lpem --waste-heat`). A companion architecture study (PSR co-location) is a separate document; this paper makes only the narrow, defensible claim. This version derates delivery through an explicit heat-exchanger pinch and effectiveness, and updates the route totals to the v0.13 model (which charges every route, including water, its continuous standing losses).

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1. The idea, and its hard limit

Space compute (lunar-surface data centers, autonomy/processing hardware) generates large quantities of waste heat that must be rejected. Lunar ISRU is thermally limited. The tempting pitch is "use the compute waste heat to power ISRU." Stated that broadly, it is wrong, and a reviewer will reject it on the Second Law: **heat flows only to lower temperature.** Compute waste heat rejects at roughly **315-350 K** (GPU junctions ~360- 375 K; coolant/radiator interface lower). The reduction and electrolysis routes need **high-grade** heat, hydrogen reduction 1073-1373 K, carbothermal ~1900 K, molten regolith electrolysis ~1900 K, molten-salt ~1200 K. You cannot drive any of them with 350 K heat. Compute waste heat therefore **cannot replace** the dominant ISRU heat demand.

There is exactly one exception, and it is the strategically important one.

2. Where grade matches: PSR water-ice sublimation

Thermal mining of polar water ice raises icy regolith from the PSR floor (~40-110 K) to the sublimation point (~273 K) and supplies the heat of sublimation **at ~273 K**. A heat source at 315-350 K is comfortably above that, so it is thermodynamically valid to drive the entire water-extraction thermal chain with compute waste heat. The same is true, marginally, of the *cold slice* of feedstock preheating for any route (from feed temperature up to ~350 K), but that is a tiny fraction of the heat a reduction route needs.

3. Method

We extend the `lpem` common-basis energy model (which already resolves each route's heating demand against temperature) with a grade filter: given a reject temperature `T_reject`, the usable source temperature is first derated by a heat-exchanger approach delta-T (nominal 15 K, range 5-30) and delivered heat is scaled by an exchanger effectiveness (nominal 0.85, range 0.70-0.95). The **offsettable** energy is then the electrical-equivalent heating that derated source could displace: the sensible slice from feed temperature up to `min(T_react, T_src)` for regolith routes, and the full thermal-mining term for the water route when $T\_src \geq 273$ K. High-grade reaction heat, fusion, and all *electrical* loads (electrolysis work, liquefaction, compression) are excluded by construction. See `src/lpem/waste_heat.py`; reproduce with `python -m lpem --waste-heat`.

4. Results

Offsettable low-grade thermal demand at `T_reject = 350 K` (per kg O2, electrical- equivalent displaced after pinch and effectiveness; route totals from the current `lpem` model, v0.13):

Route	Offsettable (kWh/kg O2)	% of route total
PSR water mining	**1.77**	**11.1%**

Route	Offsettable (kWh/kg O2)	% of route total
H2 reduction (ilmenite)	0.96	3.0%
Carbothermal (CH4)	0.10	0.5%
Molten regolith electrolysis	0.10	0.4%
Molten-salt (FFC)	0.06	0.3%

The water route is the clear beneficiary: its **entire** thermal-mining demand is low-grade and so fully offsettable (scaled only by the exchanger effectiveness), ~11% of its total energy. The high-temperature routes gain almost nothing (the share is even smaller than in earlier model versions, because their totals rose once continuous reactor heat loss was charged; the low-grade preheat slice is a sliver of a larger denominator, and the energy that matters, the 1073-1900 K reactor heat, is untouchable by a 350 K source).

Magnitude. The constraint is not heat *quantity*; it is that the low-grade demand is small. A 50 t O2/yr water plant needs only ~**10 kW** of continuous low-grade heat, so a ~12 kW compute load covers it entirely, displacing that fission heating and ~**2.3 t of landed reactor mass** (at ~225 kg/kWe). Conversely, on energy grounds alone a 100 kW compute facility's rejected heat could serve the low-grade demand of roughly **500 t O2/yr** of water mining, far more than any near-term plant. Two caveats keep this honest. First, these supportable-throughput figures are energy-balance upper bounds, not delivery designs: moving the heat into a granular icy bed (effective conductivity ~0.001-0.01 W/m/K in vacuum, ~50-77 K driving delta-T) is conduction-rate-limited, and an illustrative contact-area estimate for conducting even 12 kW into the bed is on the order of 5,000 m^2 (k_eff = 0.003 W/m/K, 0.1 m path). Delivery engineering, not energy supply, is the binding constraint. Second, within the energy boundary, co-located compute waste heat does not merely help; it *saturates* the low-grade ISRU heat demand.

5. What this is, and is not

- It **is**: a free (otherwise-dumped) heat stream that covers the low-grade thermal demand of the PSR water route, eliminating ~11% of its production energy and the corresponding reactor mass, and giving a co-located compute facility a productive heat sink instead of a pure radiator load.
- It is **not**: a replacement for ISRU's high-grade reduction/electrolysis heat (Second Law), and it is **not** a large energy win in absolute terms (~1-3 kWh/kg O2). The value is that it is free, and that it lands specifically on the water route, the only route that yields complete propellant (LOX + LH2).

6. Limitations

- **Co-location is assumed, not shown.** Orbital data-center waste heat cannot reach the surface; this requires a *surface* (ideally PSR-adjacent) compute facility, and heat transport (heat pipes / pumped loops) from racks to the regolith, with losses not modeled here. The co-location architecture is treated in the separate PSR-co-location study.
- **Electrical loads dominate the water route** (electrolysis, LH2 liquefaction); waste heat does nothing for those, so the offset ceiling is ~11% regardless of how much compute heat is available.
- **Delivery is conduction-limited.** The model bounds the *energy* a waste stream can displace; it does not design the regolith-side heat exchanger. Conducting heat into a granular icy bed at cryogenic temperature is severely rate-limited (see Section 4), so the supportable-throughput numbers are upper bounds.
- **Solar-thermal concentrators** are the obvious competing low-grade (and high-grade) heat source; the case for compute waste heat rests on the compute existing anyway for its own reasons, not on heat being scarce.
- **Reject temperature.** We take the compute coolant-loop reject as ~330 K nominal (a 315-360 K band). The GPU *junction* is hotter (~360-375 K, i.e. ~90 C, the figure the program literature quotes), but the loop that actually reaches the regolith is cooler; this paper's reject temperature is the loop/radiator-interface value, not the junction. The water-route offset is insensitive to the exact value within this band: any post-pinch source temperature above the ~273 K sublimation target serves the *entire* low-grade thermal-mining slice, so the headline offset is the same at 330 K as at the 350 K used for the

table (at 330 K the derated source is ~315 K, still comfortably above 273 K). The pinch and exchanger effectiveness are now modeled explicitly (approach delta-T nominal 15 K, range 5-30; effectiveness nominal 0.85, range 0.70-0.95); the sublimation credit vanishes if the post-pinch source falls below 273 K.

7. Reproduce

```
pip install -e .
python -m lpem --waste-heat           # offset table + a 50 t/yr water heat balance
pytest tests/test_waste_heat.py
```

Sources

- `lpem` energy model (this repo), route thermal demand split by temperature.
- Leger et al. 2025 (PNAS); NASA CFM/CryoFILL, water-route thermal mining and liquefaction.
- Colaprete et al. 2010 (LCROSS), PSR ice grade and sublimation context.