

Can recovered data-centre heat supply solid-sorbent direct air capture regeneration?

A thermodynamic and carbon-accounting review of the proposed DACR–HSDC coupling, with falsifiable deployment gates

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Abstract

Background. Direct air capture (DAC) using temperature-vacuum swing adsorption requires electricity and low- to medium-temperature regeneration heat. Data centres reject heat that may be available for this purpose, but the temperature, timing and emissions intensity of that heat determine whether integration produces additional net atmospheric removal. An earlier design document by the author (the DACR–HSDC concept) proposed such a coupling with a two-phase carbon-dioxide compute-cooling loop and campus-scale removal estimates.

Questions. (1) Is the proposed two-phase CO₂ compute coolant at 45–60 °C physically feasible? (2) What thermodynamic bound governs lifting recovered compute heat to sorbent-regeneration temperature, and which measured quantities determine whether the coupling saves energy relative to separately operated facilities? (3) What accounting boundary converts gross captured CO₂ into net durable removal? (4) What measurements and decision gates would support or falsify the coupling before a site-specific demonstration?

Methods. Selective engineering review of the DAC, data-centre thermal-management and carbon-accounting literature, one closely related modelling preprint, and reference property data for carbon dioxide (NIST), combined with first-principles steady-state balances and a reversible-cycle bounding calculation. No experiment, site dataset or validated system model is presented.

Results. (1) No: pure CO₂ has a critical temperature of 30.98 °C, so saturated boiling at 45–60 °C is impossible; the two-phase loop is withdrawn and warm-water liquid cooling (ASHRAE W32/W40) is adopted as the reference case. (2) The reversible heating COP bounds performance at about 4.1–5.9 for refrigerant-side source temperatures of 24–37 °C (facility water 32–45 °C) and sink temperatures of 100–120 °C; achievable annual COP, avoided cooling energy and removal tonnage are not established and depend on hourly source-heat availability, temperature approaches, part-load behaviour and fallback rejection. (3) Net durable removal equals stored atmospheric CO₂ minus reversals minus attributable lifecycle emissions on one consistent boundary; a heat-pump COP is not a campus-wide removal ratio, and captured-carbon products do not confer durable storage. (4) Four sequential gates (validated process model; rack-level heat-recovery test; audited lifecycle and storage pathway; site demonstration) are specified with pass/fail criteria.

Conclusions. Data-centre heat can plausibly reduce part of the regeneration energy of solid-sorbent DAC, but only measured heat at an appropriate grade, additional low-emission electricity and verified durable storage, counted on a common boundary, would establish net removal. Earlier claims of water independence, subsidy-free economics and gigaton-scale deployment are withdrawn pending the gates defined here. Colorado siting constraints are used as a worked application of the gates, not as a validated deployment plan.

Keywords: direct air capture; data centres; waste heat recovery; heat pumps; carbon dioxide removal; lifecycle assessment; temperature-vacuum swing adsorption

Plain-language summary

Data centres release heat, and some machines that remove carbon dioxide from the air need heat. Connecting them could reduce the energy needed for carbon removal, but only if the heat is at a useful temperature and the added electricity comes from a sufficiently low-emission supply. This review corrects a design error in a longer project document: carbon dioxide cannot boil as a two-phase coolant at the proposed 45–60 °C chip temperatures. It treats warm-water cooling as the starting point and any carbon-dioxide coolant as a separate design to test. The paper describes measurements, safety reviews and carbon accounting needed before a combined facility could claim net removal. It does not report a working installation or a verified cost saving.

1. Introduction

Removing carbon dioxide from ambient air and storing it durably may help balance residual emissions and, if sustained net-negative emissions become feasible, reduce overshoot. This role remains additional to deep emissions reductions, not an alternative to them (IPCC 2023). Engineered direct air capture (DAC) must operate at low atmospheric carbon-dioxide concentration and is sensitive to energy source, ambient conditions, capital cost and storage availability (Sabatino et al. 2021; Wiegner et al. 2022). Meanwhile, electrical work supplied to servers and supporting equipment eventually becomes heat, though the fraction recoverable at a specified temperature varies by cooling technology, heat-exchanger approach and operating state (Ebrahimi et al. 2014).

One opportunity is to use recoverable computing heat as the low-temperature source of a heat pump supplying a solid-sorbent DAC regeneration process. Fang et al. (2026) model this general coupling across United States regions and report improved modeled removal and levelized cost under their assumptions. Their work is an arXiv preprint, not evidence that a particular campus has been built or that its modeled performance has been independently demonstrated. This paper asks whether, and under what measurable conditions, such an integrated concept could be made testable, and it applies the answer to an earlier technical brief by the present author that requires correction. The emphasis is on system boundaries and falsifiable performance rather than on a predetermined removal target.

1.1 Research questions

The review is organised around four questions. Each is answered in Section 3 and summarised in Table 3.

RQ1. Is the two-phase carbon-dioxide (R-744) compute-cooling loop proposed in the earlier DACR–HSDC document, boiling near 45–50 °C and returning at 55–60 °C, physically feasible?

RQ2. What thermodynamic bound governs the heat-pump lift from recovered compute heat to solid-sorbent regeneration temperature, and which measured quantities decide whether the coupled plant uses less energy than separately operated computing and DAC facilities?

RQ3. What accounting boundary converts gross captured CO₂ into net durable atmospheric removal, and which earlier claims (coolant inventory, utilisation products, campus-wide removal ratios) fail that boundary?

RQ4. What minimum measurement plan and sequential decision gates would allow the coupling to be supported or falsified before a site-specific demonstration is proposed?

2. Methods

2.1 Review scope and sources

This selective engineering review draws on published DAC, data-centre thermal-management and carbon-accounting literature, a recent related preprint, and property data for carbon dioxide. It is not a systematic review, a detailed design, a measured field study, or a techno-economic assessment with independently validated inputs. The earlier campaign-oriented DACR–HSDC deployment document contained promotional estimates, regional siting claims and a proposed coolant scheme; none is treated here as an established result. The review instead identifies the minimum balances and operating tests needed to compare a coupled plant with separately operated computing and DAC facilities. A formal model and site-specific safety case are future work.

2.2 Property data and bounding calculation

Carbon-dioxide phase feasibility (RQ1) is tested against the critical-point values in the NIST reference equation of state (NIST 2026). The heat-pump bound (RQ2) is obtained from the reversible (Carnot) heating coefficient of performance, $COP_{rev} = T_{hot} / (T_{hot} - T_{cold})$, with absolute temperatures taken at the refrigerant side after assumed heat-exchanger approaches. Source temperatures follow ASHRAE liquid-cooling facility-water classes W32, W40 and W45 (ASHRAE 2021); sink temperatures span the regeneration range reported for solid-sorbent temperature-vacuum swing processes, approximately 80–120 °C depending on material and process design (Sabatino et al. 2021; Wiegner et al. 2022). These bounds are upper limits for an ideal cycle and are used only to frame what a site model must measure.

2.3 Accounting framework

Net removal (RQ3) is defined by a period- and boundary-consistent balance following IPCC (2023) and the CRCF direct air capture protocol (Isometric 2026). The measurement plan and gates (RQ4) are derived from the quantities that appear in the balances of Sections 3.2 and 3.3; each gate states the evidence that would pass or fail it.

3. Results

3.1 RQ1 — The two-phase CO₂ compute coolant is not physically feasible

The original proposed design described pumped two-phase R-744 (carbon dioxide) boiling near 45–50 °C and returning at 55–60 °C. This is physically inconsistent for pure CO₂. NIST lists its critical temperature at 304.1282 K (30.9782 °C) and critical pressure near 7.377 MPa (NIST 2026). A 45–60 °C CO₂ stream cannot undergo ordinary saturated liquid–vapour boiling at any pressure; a cycle crossing below the critical temperature would be a different design, not validation of the original claim. The proposed reference architecture therefore removes the two-phase CO₂ compute loop altogether. Every heat-transfer, pumping, power and cost estimate derived from that loop must be recalculated rather than carried forward.

Two physically distinct research options remain. One is a subcritical R-744 loop whose evaporating temperature stays below its critical temperature; this changes the chip-to-coolant approach temperature, pumping/compression work and lift to DAC regeneration, and requires a new rack-level feasibility analysis. The other is a single-phase or supercritical CO₂ compute-cooling concept at higher temperature and pressure; it cannot claim the latent-heat benefit of two-phase boiling. Both would need pressure-containment, leak detection, serviceability and transient testing. Neither is assumed equivalent to the warm-water reference case. In particular, captured atmospheric CO₂ used as the initial working-fluid inventory in a closed cooling loop is not itself a recurring removal stream: losses and end-of-life disposition determine its net carbon accounting.

Answer to RQ1: No. The reference architecture therefore uses warm-water liquid cooling, and any R-744 variant is a separate design requiring its own feasibility analysis.

3.2 RQ2 — Thermodynamic bound and the quantities that decide energy savings

In a temperature-vacuum swing adsorption configuration, air passes through a solid sorbent and captured carbon dioxide is released by heating and/or lowering pressure. The exact useful heat temperature, heat demand per tonne, electrical demand, sorbent replacement rate and purity of the captured stream depend on the material and process design (Sabatino et al. 2021; Wiegner et al. 2022). It is misleading to assign every solid-sorbent plant one universal temperature or claim that regeneration heat is always a fixed percentage of total cost. Fans, vacuum equipment, heat pumping, compression, construction and storage remain relevant even if some regeneration heat is recovered.

The reference integration begins with a warm-water liquid-cooled compute loop. ASHRAE's W32 and W40 classes describe facility-water supply temperatures of 32 and 40 °C, not chip temperatures or guaranteed return-water temperatures; equipment compatibility and vendor limits still control the actual choice (ASHRAE 2021). A heat exchanger delivers a measured portion of recoverable load to the evaporator of a separate industrial heat pump. The heat-pump condenser supplies a temperature appropriate to the chosen DAC sorbent cycle; neither the class designation nor the existence of server heat guarantees sufficient temperature lift, duty cycle or capacity. Remaining compute heat requires an independent rejection route, such as dry coolers where climate and design permit, whenever DAC demand is low, maintenance interrupts capture, the heat pump trips, or ambient conditions impair performance (DOE 2024). A thermal store may smooth short mismatches, but it cannot replace a quantified seasonal or outage balance. The facility must protect compute availability and isolate sorbent, refrigerant and chip-cooling circuits.

Heat-pump performance must be stated at a precise system boundary. For a simplified steady-state heat pump, delivered heat equals source heat plus heat-pump electrical work, before explicitly excluded losses. Heating COP is delivered heat divided by heat-pump electrical work at the same boundary. The source-side heat cannot exceed metered recoverable computer heat after exchanger losses and competing uses. Neither these identities nor an assumed coefficient of performance specifies annual energy use: source and sink temperatures, exchanger approach, part-load efficiency, auxiliary pumps and fans, outages and backup heat must be measured or modeled. The R-245fa refrigerant mentioned in an earlier proposal is not specified for this reference case; refrigerant selection requires separate safety, leakage, climate-impact and regulatory review.

The ideal reversible heating COP at absolute hot- and cold-side temperatures is the hot-side absolute temperature divided by the difference between hot- and cold-side absolute temperatures; it is an upper bound for an ideal cycle, not an achievable annual plant COP. Finite temperature approaches at both heat exchangers increase the lift above the difference between measured water temperatures; compressor, drive, pump and distribution losses reduce delivered performance further. A site calculation must report

simultaneous hourly heat-recovery potential, the heat pump's source and sink conditions, DAC heat demand and fallback rejection. It must compare integration with a specified conventional cooling and separately supplied DAC baseline, not count recovered heat as both cooling savings and new heat generation. No numeric COP, avoided cooling energy or carbon-removal tonnage is established by this review.

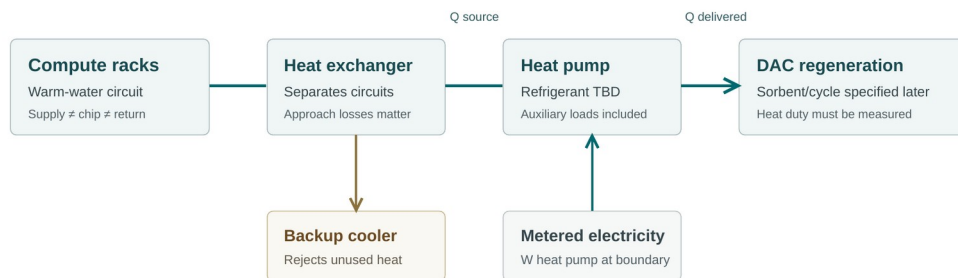
Table 1 evaluates the reversible bound for representative refrigerant-side temperatures. Evaporating temperature is taken 8 K below facility-water supply to allow for exchanger approach; condensing temperature equals the assumed regeneration set point. Achievable heat pumps deliver a fraction of these values after compressor, drive and part-load losses, and a site model must replace them with measured hourly data.

Table 1. Reversible heating COP upper bounds for representative source and sink conditions (ideal cycle; not achievable plant performance).

Facility water (ASHRAE class)	Assumed evaporating T	Assumed condensing T	$COP_{rev} = \frac{T_h}{T_h - T_c}$
32 °C (W32)	24 °C (297 K)	100 °C (373 K)	4.9
32 °C (W32)	24 °C (297 K)	120 °C (393 K)	4.1
40 °C (W40)	32 °C (305 K)	100 °C (373 K)	5.5
40 °C (W40)	32 °C (305 K)	120 °C (393 K)	4.5
45 °C (W45)	37 °C (310 K)	100 °C (373 K)	5.9
45 °C (W45)	37 °C (310 K)	120 °C (393 K)	4.7

Thermal reference case: measure at each boundary

Warm-water cooling is the reference, subject to server qualification and site design



At one defined, steady-state heat-pump boundary:

$$Q_{\text{delivered}} = Q_{\text{source}} + W_{\text{heat pump}} - \text{losses}$$

Heating $COP = Q_{\text{delivered}} / W_{\text{heat pump}}$; neither a COP nor recovered heat proves net CO_2 removal.

No 45–60 °C two-phase R-744; that range exceeds pure CO_2 's 30.98 °C critical temperature.

Figure 1. Reference heat-pump boundary and warm-water cooling. All site temperatures, duties and COP require measurement.

Answer to RQ2: The reversible bound lies between roughly 4 and 6 for the stated conditions, so a real heat pump will deliver each unit of regeneration heat for a substantial fraction of a unit of electricity. Whether that beats separately operated facilities is decided by five measured quantities: hourly recoverable source heat, refrigerant-side temperature lift, part-load COP, auxiliary and fallback-rejection electricity, and the emissions intensity of the electricity actually supplied. None is established by this review.

3.3 RQ3 — The accounting boundary for net durable removal

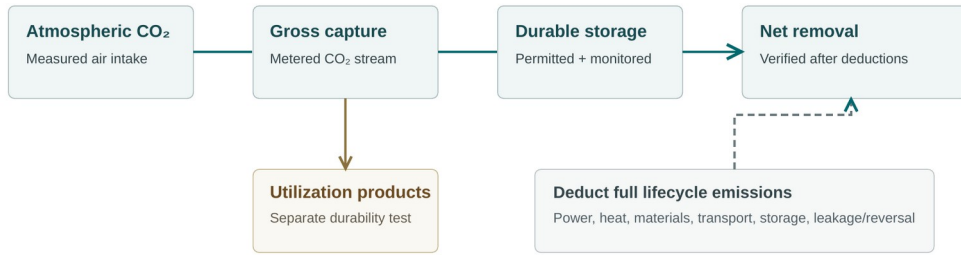
Gross carbon dioxide captured at a DAC contactor is not net atmospheric removal. For a stated period and boundary, an indicative calculation is net durable removal = atmospheric CO₂ initially injected or mineralized minus subsequent losses or reversals minus attributable lifecycle greenhouse-gas emissions expressed in CO₂-equivalent. The result must use one consistent monitoring period and avoid subtracting a loss twice if the storage measurement is already a net retained amount. The accounting method must also specify permanence, uncertainty and who may claim the removal (Isometric 2026). A defensible inventory includes manufacture and installation of DAC and incremental compute/power equipment where attributable; electricity and heat added by integration; refrigerant leakage; replacement sorbents; capture and compression; transport; storage injection and monitoring. A separate consequential comparison evaluates whether integration improves on independently operated computing and DAC and whether power or heat is diverted from better alternative uses. Do not simply assign the entire baseline compute load to DAC, nor automatically treat it as zero-emission waste heat. Dedicated power may lower operating emissions if additional and reliable, but no project-specific quantity has been measured here (IPCC 2023; Isometric 2026).

The preferred climate outcome is durable storage of atmospheric carbon dioxide with monitored permanence, such as appropriately permitted geological storage or demonstrably stable mineralization. Making a fuel or methanol from captured CO₂ usually returns carbon to the atmosphere on use. Carbonated building products can vary in storage fraction and lifetime. A polymer made using captured carbon is not thereby biodegradable, and biodegradation is not synonymous with carbon neutrality if its carbon becomes CO₂ or methane or if production emits greenhouse gases. Each proposed product requires a separate lifecycle and end-of-life assessment. The same tonne cannot simultaneously be sold as a verified durable-removal credit and counted in a short-lived product without a rigorous, non-duplicative accounting rule.

An electrical compute rating cannot be converted directly into DAC tonnage. Nearly all input electrical energy ultimately becomes heat somewhere, but the fraction recoverable at a usable temperature and time, after equipment losses and competing heat uses, has not been established for this proposal. At each time step, measured recoverable source heat must bound heat-pump uptake; condenser output equals that uptake plus heat-pump electrical work within the defined boundary; actual sorbent heat delivered is lower after distribution losses and must be matched to the process demand. Fans, vacuum, cooling, compression, backup heating, downtime and the emissions of their electricity remain additional. Fang et al. (2026) offer model scenarios, not transferable campus-wide removal or cost guarantees.

From gross capture to net removal

An accounting pathway replaces the unsupported "removal imperative" forecast



Climate context

Rapid emissions cuts remain essential; removals complement, rather than replace, mitigation.

No universal 450 ppm extinction cliff or fixed 2035 gigaton target follows from this design.

Protocol and storage jurisdiction must be specified before credits or net-negative status are claimed.

Figure 2. Gross capture, durable storage and net-removal accounting are different quantities.

Answer to RQ3: Net durable removal = atmospheric CO₂ durably stored – subsequent reversals – attributable lifecycle emissions, on one period and boundary. Coolant inventory, utilisation products and a heat-pump COP applied to a compute rating all fail this test and are withdrawn as removal claims.

3.4 RQ4 — Measurement plan and decision gates

At minimum, a pilot should report time-resolved server electrical load; useful heat recovered at metered inlet and outlet conditions; heat-pump source and delivery temperatures, electrical draw and part-load COP; heat delivered to the sorbent; ambient temperature and humidity; contactor capture rate; the electricity used by fans, vacuum, pumps, compression and dry coolers; downtime and curtailment; capture-stream purity; storage injection and leakage monitoring; and marginal emissions intensity of the actually supplied power. Measurement uncertainty and calibration should accompany every reported tonne. A comparison facility or defensible modeled counterfactual should establish whether co-location outperforms separately optimized cooling and capture under the same boundary.

The first gate is a corrected process-flow and property model with explicit CO₂ phase state, temperature approaches, compressor or pump maps and sensitivity to climate and server utilization. Results should be reproducible from declared inputs, with the warm-water baseline and any alternative R-744 or single-phase CO₂ cooling modeled separately. The second gate is benchtop and rack-level testing of heat recovery without compromising chip reliability or safety. A heat-pump and DAC test rig must then demonstrate performance at variable loads and realistic ambient conditions, not only a single steady design point.

The third gate is an independently audited lifecycle and consequential-power assessment, plus a storage pathway with verifiable monitoring, reporting and verification. Its output is net tonnes durably stored, not merely gross tonnes captured, coolant inventory, or revenue from carbon-containing products. The fourth gate is a site-specific demonstration with an operating budget, safety case, reliable fallback heat rejection, clear responsibility for outages and community review. Only after reproducible results should a larger campus, public enterprise arrangement or scaled removal estimate be proposed. These gates could yield a modified design or a negative result; both would be informative.

Table 2. Sequential decision gates with pass and fail evidence.

Gate	Evidence required	Passes if	Fails if
1. Validated process model	Process-flow and property model with explicit CO ₂ phase state, exchanger approaches, compressor/pump maps, climate and utilisation sensitivity; warm-water and any R-744 case modelled separately	Results reproducible from declared inputs; hourly heat balance closes; modelled COP within measured equipment maps	Balance requires unmetered heat; COP exceeds reversible bound; results not reproducible
2. Rack-level heat recovery	Benchtop and rack tests of heat recovery at ASHRAE W32/W40 without chip-reliability or safety compromise; heat-pump and DAC rig at variable load and ambient	Recovered heat at usable grade meets modelled fraction across load range; no thermal-reliability excursions	Recoverable grade or quantity below model; compute availability degraded
3. Audited lifecycle and storage pathway	Independent lifecycle and consequential-power assessment; Class VI or equivalent storage pathway with MRV	Net tonnes durably stored > 0 after all attributable emissions; storage permit pathway credible	Net removal ≤ 0 or unquantifiable; no permitted storage route
4. Site demonstration	Operating budget, safety case, independent fallback heat rejection, outage responsibility, community review	Measured net removal and cost compared against separately operated baseline on same boundary	Coupled plant does not outperform baseline; safety or community conditions unmet

Answer to RQ4: A four-gate sequence with the evidence in Table 2. Gates may return a modified design or a negative result; either outcome is informative.

3.5 Summary of answers

Table 3. Research questions, findings and status of evidence.

Question	Finding	Evidence status
RQ1 Two-phase CO ₂ coolant at 45–60 °C	Physically impossible above 30.98 °C critical temperature; withdrawn	Established (NIST property data)
RQ2 Heat-pump bound and deciding quantities	COP _{rev} $\approx$ 4–6 for stated conditions; five measured quantities decide savings	Bound established; plant values unmeasured
RQ3 Net-removal boundary	Stored – reversals – lifecycle emissions on one boundary; earlier ratio and product claims fail	Framework established; no project quantity
RQ4 Gates	Four sequential gates with pass/fail evidence	Proposed; untested

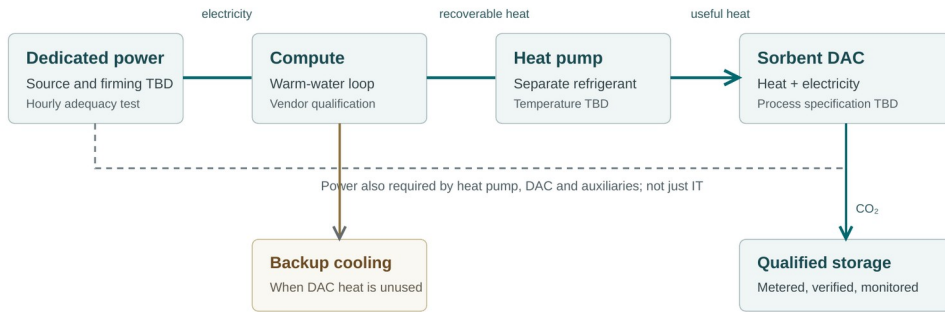
4. Discussion

4.1 Architecture implications

Figure 3 replaces the prior fixed removal trajectory, model-specific heat-pump schematic and quantitatively asserted campus architecture. They do not report a working facility or predict annual removal.

Proposed campus: independent circuits

Conceptual only - no capacity, COP, removal rate or operating agreement established



Separate option: A licensed high-temperature generator may study an sCO₂ power cycle.

That circuit is neither the warm-water compute coolant nor the heat-pump refrigerant.

Electrical arrows show required loads, not a validated distribution design. Heat-exchanger interfaces omitted for clarity.

Figure 3. Proposed campus architecture: distinct heat, coolant and power systems with backup cooling and qualified storage.

4.1.1 Power conversion is a different loop

The earlier concept also contemplated a dedicated, fully islanded campus power system using wind, solar, storage, enhanced geothermal and possibly licensed small modular reactors. A sealed supercritical-CO₂ Brayton power-conversion loop was suggested for a compatible high-temperature heat source and dry heat rejection. That is physically separate from both a compute coolant and the DAC heat-pump refrigerant, even if each uses a carbon-dioxide working fluid. Availability of an appropriate reactor outlet temperature, heat exchanger, turbine, precooler, licensed safety design, backup supply and firm reserve cannot be assumed. A proposed dry-cooling advantage must be evaluated against hot-weather derating, fan power, capital cost and plant safety. Neither an islanded label nor an sCO₂ cycle proves zero water use or zero emissions across construction, fuel supply and operation.

4.2 Economic and infrastructure tests

The proposed commercial structure combines a private compute anchor customer with a separate capture project, dedicated generation and verified storage offtake. Its potential advantage is shared use of thermal interfaces, land planning and selected infrastructure; its liabilities include complex contracts, operational interdependence and competition for capital and electricity. A cost comparison must annualize equipment and financing under common assumptions, value heat against its next-best use, count the cost of capacity kept available for outages, and separate revenue for permanent removal from revenue for CO₂ utilization. The earlier assertion that feedstock sales automatically eliminate dependence on tax credits or voluntary-market premiums is not established by the engineering concept.

The proposed Colorado public-enterprise and private-capital arrangements are governance options, not existing permits, statutory exemptions or guaranteed long-term contracts. Site selection requires independent evidence on geology and pore-space rights, grid interaction, land and water, transmission and distribution, geothermal resource quality, nuclear licensing if relevant, environmental justice and community consent. A “fully islanded” design additionally needs a tested black-start strategy, reserves, fuel and storage duration, protection coordination and a transparent definition of emergency imports or exports. Commercial feasibility and physical feasibility are separate gates.

Shared thermal interfaces, power planning and storage access might create value, but heat pumps and backup cooling add capital and electricity costs. The financially relevant comparison includes annualized

capture equipment, dedicated generation and storage, uptime, alternative heat value, sorbent replacement, qualified storage fees, financing, contracts, and realistic markets for each product. A quoted voluntary-credit price is not a guaranteed floor. A market for short-lived CO₂ products cannot automatically support permanent-removal credits. Section 45Q eligibility and economics must be examined under current law and actual contract terms, not presumed unnecessary.

The four multipliers proposed in the earlier document for dedicated power, per-site DAC expansion, multi-state replication and utilization demand were not derived from an integrated deployment model. They cannot be multiplied into a credible gigaton-per-year result. Larger DAC capacity beyond recoverable compute heat would need additional heat and power, and multiplying sites raises further land, materials, storage, workforce and finance constraints. A gigaton-scale objective can remain a campaign aspiration, but it is not a forecast or a result independently established by Fang et al.

4.3 Worked application of the gates: constraints for a Colorado site

The following applies the gates of Section 3.4 to the siting conditions assumed in the earlier document. It is an application of the framework, not a validated deployment plan.

4.3.1 Dedicated power

The proposal retains a dedicated, fully separated normal-operation campus microgrid to avoid relying on public utilities for routine compute and DAC electricity. Wind, solar, storage and potentially characterized enhanced geothermal form the intended backbone; a licensed SMR is a possible firm addition if alternatives prove insufficient. “Behind the meter” does not itself resolve hour-by-hour capacity, reserve margins, maintenance, grid interconnection or emergency import/export. An islanded site must demonstrate seasonal adequacy, protection, black start, stability and a transparent rule for any standby connection and its cost. A nuclear module is not an assumed day-one solution. Safety and emergency planning are design- and site-specific; a small module has no automatic site-boundary emergency zone or guaranteed accident-free behavior (NRC final rule).

Dry cooling might reduce evaporative use but requires its own heat-rejection, fan-energy and hot-weather performance assessment. A no-evaporative-tower objective is narrower than a zero-water campus. Fire protection, domestic uses, reactor selection, DAC process needs and maintenance require a permitted site-wide water balance. The earlier 0.00 gal/day and blanket water-independence claims are withdrawn.

4.3.2 Siting and storage

The Eastern Plains and other Colorado regions may be evaluated against verified resource quality, fiber, land title, environmental justice, geology, pore-space ownership, water rights, power reliability and community support. An elevated site is not inherently a lower-energy DAC site: lower air density changes volumetric airflow, fan performance and capture contactor sizing, and any net advantage must be modeled. Neither the Denver-Julesburg nor Piceance basin is automatically a permitted storage site. Class VI wells require site characterization, plume and pressure modeling, corrective action, monitoring, emergency response and financial assurance to protect underground drinking-water sources (US EPA Class VI requirements).

The CCDA would be a proposed public coordination and contracting body, subject to legislation and legal review. It cannot grant itself existing pore-space ownership, Class VI injection permits, nuclear licensing, TABOR exemption, automatic private equity, or a guaranteed state offtake market. A proposed financing model should disclose who provides capital, who assumes construction and long-term storage liabilities, what public guarantees exist, how labor and community benefits are enforced, and whether any ratepayer or taxpayer exposure remains.

4.4 Limitations

This is a selective, not systematic, review. The reversible-COP table is a bounding calculation with assumed approaches, not a design. No sorbent, heat pump, cooling equipment or storage site is specified, so no removal tonnage, cost or emissions figure is reported. The only closely comparable modelling study (Fang et al. 2026) is itself a preprint. The author's advocacy roles are disclosed below and may be perceived as relevant to the framing.

5. Conclusions

Integrating data-centre waste heat with solid-sorbent DAC is a testable way to improve a capture plant's thermal supply, not an intrinsic property of every compute campus. The heat-pump, capture and power systems must be evaluated on common hourly, lifecycle and counterfactual boundaries. A physical inconsistency in the earlier two-phase R-744 proposal has been identified and removed from the reference architecture. The conservative starting point is warm-water compute cooling with a separately specified heat pump and an independently designed heat-rejection fallback.

The proposal's scientific claim is limited: measured heat at an appropriate grade may reduce some DAC regeneration energy when the additional electricity and durable storage are supplied and counted correctly. Commercial net-negative operation, economy without subsidies, water independence, Colorado siting and large-scale deployment remain to be demonstrated. Independent pilot data should determine whether this design improves on other uses of clean energy and waste heat.

Author contributions

Christian Komor: Conceptualization; Investigation; Writing - original draft; Writing - review and editing, with AI assistance as disclosed above.

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Conflict of interest

The author is associated with Climate Deadline Alliance, is conducting a Colorado gubernatorial campaign and has advanced the DACR-HSDC concept as a policy proposal. These nonfinancial roles and advocacy interests could be perceived as relevant to the evaluation and are disclosed for reader assessment. The author reports no related ownership, patents, contracts, grants, prospective commercial interest or other financial interest.

Data availability

No original experiment, site dataset or validated numerical system model is presented. Cited public sources are identified below; future pilot datasets and model inputs should be archived independently.

Relation to earlier documents

The author's earlier DACR-HSDC Fusion and engineering documents proposed a two-phase R-744 compute-cooling loop at 45–60 °C; this review withdraws that physical claim, substitutes a warm-water reference case and makes unsupported savings, deployment-scale and net-negative estimates conditional on the gates in Section 3.4. The author's EarthArXiv preprint Inside the Extinction Envelope (Komor

2026) places DACR–HSDC within a broader climate-response portfolio; the context figure from that work is reproduced in Appendix A.

References

- ASHRAE (2021). Thermal Guidelines for Data Processing Environments, 5th ed., equipment reference card, Table 3.1 (liquid-cooling facility-water supply classes).
<https://www.ashrae.org/file%20library/technical%20resources/bookstore/supplemental%20files/therm-gdlns-5th-r-e-refcard.pdf>
- DOE (2024). Best Practices Guide for Energy-Efficient Data Center Design. U.S. Department of Energy.
https://www.energy.gov/sites/default/files/2024-07/best-practice-guide-data-center-design_0.pdf
- Ebrahimi, K., Jones, G. F., and Fleischer, A. S. (2014). A review of data center cooling technology, operating conditions and the corresponding low-grade waste heat recovery opportunities. *Renewable and Sustainable Energy Reviews*, 31, 622–638. <https://doi.org/10.1016/j.rser.2013.12.007>
- Fang, Z., Zhang, B., Shang, J., and Ma, J. (2026). Recasting AI Data Centers as Engines for Carbon Removal. arXiv preprint, 2605.13114. <https://arxiv.org/abs/2605.13114>
- Isometric (2026). CRCF Direct Air Capture Protocol, version 1.0: quantification of net CO₂-equivalent removal and associated emissions. <https://registry.isometric.com/protocol/direct-air-capture-crcf/1.0>
- IPCC (2023). Climate Change 2023: Synthesis Report. Intergovernmental Panel on Climate Change.
<https://doi.org/10.59327/IPCC/AR6-9789291691647>
- Komor, C. (2026). Inside the Extinction Envelope: A Systemic Review and Meta-Analysis of Paleoclimate Extinction Markers with Comments on the Necessary Array of Last-Threshold Interventions. Non-peer-reviewed EarthArXiv preprint; original title reproduced for identification, not endorsed as a formal meta-analysis. <https://doi.org/10.31223/X5H214>
- NIST (2026). Alternative Fundamental Equation of State for Fluid Carbon Dioxide, NIST IR 8608, Table 1.
<https://nvlpubs.nist.gov/nistpubs/ir/2026/NIST.IR.8608.pdf>
- Sabatino, F., et al. (2021). A comparative energy and costs assessment and optimization for direct air capture technologies. *Joule*, 5, 2047–2076. <https://doi.org/10.1016/j.joule.2021.05.023>
- Wiegner, J. F., et al. (2022). Optimal design and operation of solid sorbent direct air capture processes at varying ambient conditions. *Industrial & Engineering Chemistry Research*, 61, 12649–12667.
<https://doi.org/10.1021/acs.iecr.2c00681>
- U.S. Nuclear Regulatory Commission. Emergency Preparedness for Small Modular Reactors and Other New Technologies, final rule. <https://www.nrc.gov/docs/ML2322/ML23226A023.pdf>
- U.S. Environmental Protection Agency. Class VI wells used for geologic sequestration of carbon dioxide.
<https://www.epa.gov/uic/class-vi-wells-used-geologic-sequestration-carbon-dioxide>

Appendix A. Context figure

Figure A1 summarises, from the author's companion preprint, indicators shared across major past extinctions, known feedbacks and the proposed intervention portfolio within which DACR–HSDC is one element. It is provided for context and is not part of the results of this review.

The Extinction Envelope at a Glance

Shared indicators across the five major extinctions, known feedbacks then and now, and the response portfolio viewed from a 2035–2040 vantage point

OBS Observed (instrumental) **REC** Reconstructed (proxy, with uncertainty) **INF** Inferred / hypothesized **PROP** Proposed by the author

1 Indicators shared by the five major extinctions — crisis levels then, observations now

Indicator	Paleo crisis level (reconstructed)	Present level (observed)	Shared tipping level?
Carbon release rate	PETM onset: ≤ 1.1 PgC/yr sustained (Zeebe et al. 2016)	~ 10 PgC/yr from fossil fuels and industry (Zeebe et al. 2016)	None. No precedent in 66 Myr
Atmospheric CO₂	Latest Permian 426 ppmv $\rightarrow$ $\sim 2,507$ ppmv at extinction (Wu et al. 2021; wide uncertainty)	425.6 ppm global mean, 2025; +2.83 ppm/yr (NOAA GML)	None. 450 ppm is a planning marker, not a paleo threshold
Global warming	End-Permian tropical SST 36–40 °C (Sun et al. 2012); PETM ~ 5 °C	~ 1.4 °C above 1850–1900; 2023–2025 averaged > 1.5 °C (Copernicus)	None. Risk rises with each increment
Ocean acidification	Carbonate crisis and calcifier loss: End-Permian, End-Triassic, PETM (Hönisch et al. 2012)	Surface pH 8.2 $\rightarrow$ 8.1, $\sim 30\%$ more acidic (IPCC AR6 WG2)	None shared. Thresholds are organism-specific
Ocean oxygen	Widespread deep-ocean anoxia, End-Permian and End-Triassic (Bond & Grasby 2017)	$\sim 2\%$ of O₂ inventory lost since 1960; dead zones expanding (Schmidtke et al. 2017)	None. Different metrics then and now
Reefs and calcifiers	Reefs absent ~ 5 – 15 Myr after each event (reef-gap record)	84% of reef area heat-stressed 2023–2025 (NOAA CRW); coral cover 30.2% $\rightarrow$ 27.3% (GCRMN)	None. Exposure is not mortality
Volcanic marker (Hg)	Mercury spikes at boundaries with large igneous provinces	Industrial mercury in lake and peat archives	Not comparable archives

The end-Cretaceous extinction was primarily impact-driven; the shared pattern above describes carbon-cycle crises, not five identical causes.

2 Known feedbacks — role in past extinctions versus present status

Feedback	Then (paleo record)	Now (present status)	
Permafrost and soil carbon	Inferred amplifier of End-Permian warming	Arctic warming $\sim 4\times$ global rate; thaw observed, $\sim 1,500$ GtC at risk	OBS
Methane release	Hypothesized at End-Permian and PETM	CH₄ at record levels; large hydrate release not detected	OBS
Ocean circulation slowdown	Reduced ventilation preceded End-Permian anoxia	AMOC weakening indicated; tipping timing contested	INF
Ocean deoxygenation	Primary proximal kill mechanism at sea	Loss measured; most committed loss still to come (Oschlies et al. 2021)	OBS
Vegetation collapse and wildfire	Land collapse fed nutrients to oceans, worsening anoxia	Fire regimes intensifying; Amazon dieback a modeled risk	INF
Ice-albedo loss	Largely inactive in ice-free hothouses	Active: sea-ice and ice-sheet loss reducing reflectivity	OBS
Weakening carbon sinks	Carbonate collapse limited ocean uptake	Sinks take $\sim$half of emissions but weaken in hot, dry years	OBS
Water vapor and clouds	Implicit in reconstructed hothouses	Well-quantified fast feedback in all climate models	OBS

3 Response portfolio from a 2035–2040 vantage point

ESSENTIAL FOR RECOVERY	MAY BE NECESSARY
Measures the author treats as required under any pathway	Contingent on how far and fast the essential measures deliver
Rapid fossil-CO₂ emissions reduction First-order lever; sets the release rate that has no paleo precedent.	Nuclear power (incl. SMRs) Firm augmentation only if geothermal, renewables and storage fall short.
Methane suppression at source Fastest forcing response; mature technology, uneven coverage.	Ocean alkalinity enhancement Targets surface acidification; scale and ecology still experimental.
Durable atmospheric carbon removal (DACR) Draws down legacy CO ₂ ; energy, cost and storage must be proven at scale. Waste-heat integration is an option to test.	Solar radiation modification Research and governance first; no effect on CO ₂ or acidification.
Clean firm power backbone Geothermal, wind, solar and storage to run removal without new emissions.	Coral assisted evolution at scale Trial-stage; may sustain reef function through a long drawdown.
Marine and reef protection 30 $\times$ 30 protected areas and fewer local stressors as forcing declines.	Limited BECCS and land-based removal Only within land, water and biodiversity safeguards.
Governance, finance and monitoring Emergency-scale institutions tracking the Panel 1 indicators.	CO₂-derived products and storage markets Only where lifecycle accounting shows net removal.

Sources: Zeebe et al. 2016 Nat. Geosci.; Wu et al. 2021 Nat. Commun.; Sun et al. 2012 Science; Hönisch et al. 2012 Science; Bond & Grasby 2017; Schmidtke et al. 2017 Nature; Oschlies et al. 2021; Fielding et al. 2019; Rantanen et al. 2022; IPCC AR6; NOAA GML; Copernicus C3S 2025; NOAA Coral Reef Watch; GCRMN 2026. No single numeric tipping level is shared by all five events. Paleo values carry large proxy uncertainties; present values (bold) are instrumental. Panel 3 is the author's proposal, not a validated deployment schedule. — Komor, C. (2026), Inside the Extinction Envelope / DACR-HSDC engineering paper.

Figure A1. Prior extinctions, known feedbacks and response portfolio (Komor 2026).