

The Unified Thermal Commons

Data center waste heat recovery × residential deep well geothermal — a single closed-loop thermal economy where no joule is wasted.

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EXECUTIVE ABSTRACT

Modern data centers convert **60–80% of every watt of purchased electricity into heat** that is today rejected to the atmosphere. Homes, in parallel, spend money to *create* heat with electricity and gas, then spend money again to *remove* it — heat that discarded refrigerators, dryers, ovens, showers, and HVAC systems could otherwise bank beneath the lawn. This report unifies the two problems into one solution: **the thermal commons**.

Part 1 examines the data center as a **thermal power plant**: sand and soapstone batteries that store 400–600 °C heat at 85–95% efficiency, fourth-generation district heating (4GDH) at 45–65 °C, mandatory waste heat reuse policies across Europe and Asia, and four operating case studies. Part 2 examines the home as a **thermal battery owner**: 300–500 ft deep vertical wells storing 15–45 kWh of heat each, a low-flow water-jacketed plenum tying every appliance into one manifold, and double-wall heat exchangers that make the loop safe. Part 3 fuses the two: **data center surplus flows into neighborhood deep well fields; neighborhood wells return heat to homes** — a closed loop in which district-scale storage and residential-scale storage smooth each other's peaks, and no heat is ever thrown away.

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PART 1 OF 3

The Data Center Thermal Commons

Treating every megawatt of data center electricity as a thermal asset — captured, stored in sand, distributed through 4GDH networks, and sold to industry, agriculture, and neighborhoods instead of vented to the sky.

1.1 Executive Summary — A Two-Part Report on the Viability of Mandatory Waste Heat Capture

This is the first half of a two-part analysis. Read together with **Part 2 (Residential Deep Well Geothermal)**, it answers one question: *if data centers are required to capture and sell their waste heat, who are the paying customers — and do the economics work for everyone?* The answer developed across both parts is that the two systems are naturally complementary, and it is the **combination** — district-scale storage plus neighborhood and household-scale storage — that turns a regulatory obligation into a profitable, resilient thermal market.

85–90 MW
recoverable thermal output per 100 MW data center (liquid cooling, 55–65 °C)

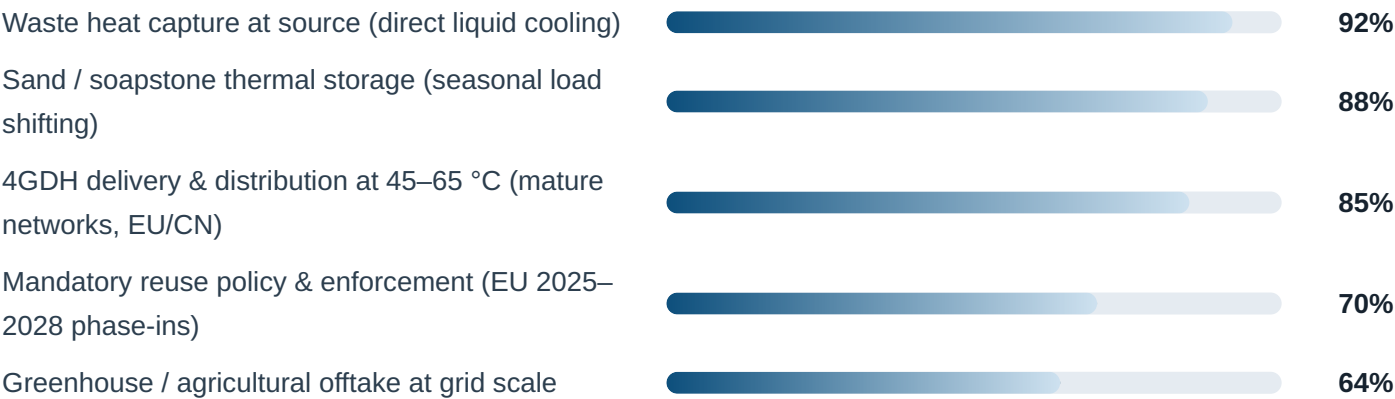
60–80%
of every MWh of IT electricity currently rejected as waste heat

400–600 °C
sand / soapstone battery operating range with 85–95% round-trip efficiency

45–65 °C
4th-generation district heating (4GDH) supply temperature — low enough for DC waste heat without booster pumps

KEY FINDING — PART 1
A 100 MW liquid-cooled data center is, thermally, a **85–90 MW baseload heat plant** running 8,760 hours per year — roughly **700 GWh/yr of heat** that a sand battery can time-shift and a 4GDH network can sell. At EU district heat prices (€45–70/MWh) this is **€30–50 million/yr in potential revenue** against recovery capex in the tens of millions — a payback of **2–6 years** before counting avoided cooling energy.

Viability Scores — Data Center Side



Industrial process heat offtake (requires heat-pump
lift >100 °C)



58%

Scores are modeled feasibility ratings combining technology maturity, demonstrated deployments, economics at 2026 prices, and policy support. Part 3 shows how coupling to residential well fields raises the aggregate viability of the DC business case.

1.2 The Problem — Data Centers Convert 60–80% of Electricity into Waste Heat

Every bit of compute is paid for twice: once as electricity and again as the energy used to remove the heat that electricity inevitably becomes. Roughly **60–80% of the electricity delivered to a data center is converted directly to heat inside the processors, memory, and power electronics** — and classically, every joule of it is rejected to the atmosphere through cooling towers, chillers, and air handlers.

The physics is unforgiving: a processor that draws 350 W emits close to 350 W of heat; a server rack that draws 30 kW emits close to 30 kW. Multiply across a 100 MW facility and the data center is a *heat source the size of a small city's district heating plant* — running flat-out, 24/7, 365 days a year.

Where the Heat Goes, and What Modern Cooling Can Recover

Cooling architecture	Typical heat rejection temperature	Recoverable fraction of IT load	Reuse compatibility
Air-cooled (legacy halls)	32–45 °C (return air)	~0–20% economically	Poor — too low-grade for most networks without large heat-pump lift
Direct liquid cooling (cold plates / immersion)	55–65 °C loop supply	85–90% (85–90 MW per 100 MW IT)	Excellent — matches 4GDH supply range natively
Hybrid (air + liquid)	35–50 °C	40–70%	Moderate — needs booster heat pumps at the plant wall
Non-recoverable losses (PSUs, UPS, grid interface)	—	10–15% of total input	Not practically recoverable

The reframing: a data center is not an electricity consumer that produces waste. It is a **baseload thermal power station with an IT side-business**. The 60–80% "loss" is the product; the compute is the by-product that funds it. Every policy, siting, and investment decision should start from that inversion.

1.3 Sand & Soapstone Battery Technology

Waste heat is only valuable if it can be *stored* and *time-shifted*. Data center heat output tracks compute load (roughly steady), while district heating demand is strongly seasonal and diurnal. Sand and soapstone thermal batteries decouple the two.

How a Sand Battery Works

Electrical resistive elements (or hot water / steam from the data center loop) heat a large mass of industrial sand or soapstone to **400–600 °C**. The mass is insulated in a silo or container; heat is extracted when needed by circulating air or water through embedded heat exchangers, or by fluidizing the sand. Charge and discharge are decoupled by hours, days, or a whole season.

Parameter	Sand battery	Soapstone battery	Notes
Operating temperature	400–600 °C	450–650 °C	Higher $\Delta T \Rightarrow$ more energy per kg of media
Round-trip efficiency	85–95%		Heat losses scale with surface area; better at utility scale
Specific heat capacity	~0.8–1.0 kJ/kg·K	~0.98–1.1 kJ/kg·K	Soapstone stores ~10–20% more energy per kg
Capital cost	\$10–25 / kWh-thermal		vs. \$150–400/kWh for lithium-ion (electrical)
Lifespan	30–50 years		No cycling degradation; media is inert
Self-discharge	Low (insulated silo, %-per-day scale)		Capable of seasonal storage
Output	Hot water / steam / hot air		Feeds district networks or industrial processes
Failure mode	Passive (insulated solid mass)		No thermal runaway, no toxic chemistry

Role at the Data Center

- **Supply smoothing:** charge during low heat demand (spring/summer nights), discharge into the district network at morning and evening peaks — converting a mandatory flat heat supply into a marketable flexible one.
- **Grid-price arbitrage:** resistive charging can run on low-price or surplus renewable electricity, storing 400–600 °C for later dispatch — effectively a low-cost grid battery with a thermal output.
- **Resilience:** the battery becomes an emergency heat source for critical buildings and, coupled with a turbine or ORC, an emergency power source.
- **Integration anchor (Part 3):** when the sand battery reaches capacity and the district network cannot absorb more, its control logic triggers the *maximum-saturation dump* into neighborhood deep well fields.

Sizing Example — 100 MW Data Center

Storage design	Capacity	Capex @ \$10–25/ kWh-th	Discharge capability
Daily buffer (12 h at 90 MW)	~1,100 MWh-th	\$11–27 M	Full network peak coverage
Weekly buffer (3 days at 80 MW)	~5,800 MWh-th	\$58–145 M	Weather-deep dips in DH demand
Seasonal shoulder (60 days at 30 MW surplus)	~43,000 MWh-th	\$430 M–1.1 B [*]	Summer surplus carried to winter — usually better shifted to residential well fields (Part 3) at far lower marginal cost

^{*} Long-duration sand storage beyond a few days is rarely economic vs. borehole thermal energy storage in deep wells, which is why Part 3 routes seasonal surplus to wells rather than bigger silos.

KEY FINDING

Sand/soapstone batteries are the **cheapest dispatchable storage on the thermal side of the grid:** \$10–25/kWh-th against lithium-ion's \$150–400/kWh-e, a 30–50 year life with zero cycling degradation, and 85–95% round-trip efficiency. They convert a "must-run" waste heat source into a flexible asset that can sell into peak district heating prices.

1.4 Mandatory Waste Heat Reuse Requirements

Voluntary markets have proven too slow. Beginning in 2024–2029, jurisdictions across Europe and Asia are converting waste heat capture from "nice-to-have" into a **licensing condition of data center operation**. The common design is a phased performance obligation plus an economic-out exemption.

Jurisdiction	Mandate mechanism	Threshold / trajectory	Exemption / escape valve
EU	Energy Efficiency Directive (EED) 2023/1791, Art. 26	Reporting for DCs ≥ 500 kW IT load; waste heat reuse studies mandatory; reuse where "technically and economically feasible"	Cost-feasibility demonstration; no viable offtaker within reach
Germany	Energy Industry Act (§16a EnWG)	New/refurbished DCs: $\geq 10\%$ waste heat reuse from 2026, $\geq 20\%$ from 2028; penalties for non-compliance	Economic disproportionality (heat-pump lift too expensive at site)
France	Climate & Resilience Law 2021 implementing decrees (2023–24)	DCs > 1 MW must perform heat-reuse study and valorize waste heat where feasible; new DCs must pre-allocate heat offtake	Technical/economic infeasibility review
Finland	New data center heat recovery law (adopted 2024–25)	Large DCs must make waste heat available to municipal district heating under regulated conditions; phase-in 2028–29	Municipal network not present or no agreement on commercial terms
USA	No federal mandate (as of 2026)	Voluntary: DOE Better Buildings, FEMP guidance, state clean-heat standards piloting; utility incentive programs	Not applicable — market-driven
China	National green data center mandates + provincial pilots	PUE ceilings (≤ 1.30 national, ≤ 1.25 pilot zones), dual-carbon targets 2030; Beijing and other northern cities pilot DC $\rightarrow$ district heating feed-in	Region-specific implementation

KEY FINDING

Mandates work when they are **phased, percentage-based, and paired with an economic-out** — Germany's 10% → 20% ladder and Finland's heat-handover law are the templates. The EU's "where feasible" framing recognizes that a mandate is only as good as the offtake market; **Part 3 argues the residential deep-well market is the missing offtaker that makes mandates cheap to satisfy.**

1.5 District Heating Infrastructure — 4th Generation (4GDH) at 45–65 °C

District heating is the physical marketplace for waste heat. Fourth-generation networks (4GDH) are engineered for exactly the temperatures liquid-cooled data centers produce natively — **45–65 °C supply** — eliminating the need for large central heat pumps and unlocking low-temperature renewable and waste sources.

Generation	Supply temperature	Primary heat sources	DC waste heat fit
1GDH (steam)	>120 °C	Coal/steam boilers	Poor — needs large lift
2GDH (pressurized water)	>100 °C	Fossil boilers, CHP	Poor
3GDH (conventional water)	70–90 °C	CHP, biomass, large heat pumps	Moderate — booster heat pump needed
4GDH	45–65 °C	Waste heat, solar thermal, ambient, heat pumps, storage	Native — direct coupling at the plant wall

The Data Center Connection Package

- **Plant-wall heat exchanger:** the DC's 55–65 °C server loop gives up heat into the network's 45–55 °C return/supply loop through a plate heat exchanger — zero cross-contamination of the two hydraulic systems.
- **Booster heat pumps (optional):** where the network runs 3GDH at 70–90 °C, a centralized large heat pump lifts the DC stream; COP 3–5 keeps the economics strong.
- **Bidirectional substations:** 4GDH customer substations can both take heat (winter) and reject heat (summer) — the technical hook that lets homes and well fields become *suppliers*, not just consumers (Part 3).
- **Storage integration:** sand batteries charge from the DC loop and discharge into the network; the network itself becomes a thermal buffer (pipes carry significant thermal mass).

KEY FINDING

A 100 MW liquid-cooled data center matching a 4GDH network can supply on the order of **90 MW of the network's winter peak and effectively 100% of its summer baseload** — the district network becomes the data center's heat pipeline, and the data center becomes the district's baseload plant.

1.6 Greenhouse & Agricultural Applications

Agriculture is the second-largest heat market after buildings, and its temperature needs sit almost perfectly in the DC waste heat envelope.

Application	Required temperature	Fit with 55–65 °C DC heat	Notes
Greenhouse heating (temperate crops)	25–45 °C	Direct — no lift needed	Low-temperature under-bench and root-zone systems maximize use
Vertical farm / indoor agriculture	20–35 °C + dehumidification	Direct via fan-coils	Constant 24/7 load matches DC baseload
Fish / aquaculture recirculation	24–29 °C	Direct with mixing valve	Very stable annual load
Drying & curing (grain, hay, biomass)	35–70 °C	Direct near the top of range	Seasonal, harvest-weighted demand
Soil warming / frost protection	15–30 °C	Direct	Winter-night shock load, pipe-based
CO ₂ -enriched greenhouse air from DC exhaust	ambient	Complement	Combustion-free CO ₂ boosts crop yield 15–30%

Why this matters commercially: greenhouses are the ideal *summer* offtaker. When residential heating demand collapses in June, greenhouses still need 25–45 °C heat for cooling-season crop protection, ventilation pre-heat, and night-temp floors — absorbing the data center's flat summer surplus that otherwise has no buyer. This is the first rung of the "load ladder" that Part 3 formalizes.

1.7 Industrial Process

Heat

Industry consumes roughly a quarter of final energy in Europe, and most of it as heat below 150 °C. Data center waste heat cannot reach most industrial processes directly at 55–65 °C — but it can feed the **low-temperature rungs of the industrial temperature ladder**, and industrial heat pumps (delivering COP 2.5–4 at 90–150 °C output) can lift the rest.

Process	Process temperature need	Delivery path from DC heat
Washing / rinsing / cleaning lines	60–90 °C	Direct or small lift
Space heating of plants & warehouses	18–30 °C	Direct
Pre-heating boiler feedwater / make-up water	55–85 °C	Direct (largest single saving: cuts fuel boiler input)
Drying (textiles, wood, food, sludge)	90–160 °C	Industrial heat pump lift (COP 2.5–3.5)
Pasteurization (dairy, beverage)	72–85 °C	Heat pump lift
Steam generation (batch processes)	130–180 °C	High-temperature heat pump or sand battery discharge (400–600 °C zone)
Plastics / rubber processing	150–220 °C	Sand/soapstone battery direct discharge

KEY FINDING

The battery changes the industrial story. A sand battery stores at **400–600 °C**, so it can serve *steam-grade* industrial customers directly, while the data center's live loop serves 55–65 °C customers continuously. **One DC installation can thus sell into three temperature tiers simultaneously:** live loop (district/greenhouse), battery discharge (steam/plastics), and heat-pump lift (drying/pasteurization).

1.8 Economic Analysis — Costs, Savings, Payback

The DC-side business case rests on three revenue/avoidance streams against one capex envelope. All figures are 2026 modeled estimates for a representative 100 MW liquid-cooled facility; assumptions are itemized in Appendix B.

1.8.1 Capital Investment (Recovery Package)

Component	Function	Modeled capex	Unit basis
Direct liquid-cooling conversion / retention	Raise loop to 55–65 °C recoverable grade	\$15–35 M	Incremental over air-cooled design
Plant-wall plate heat exchangers + hydraulic separation	Hand-off heat to district network, zero mixing	\$2–5 M	Per plant
Central booster heat pumps (if 3GDH)	Lift 55–65 °C → 70–90 °C network grade	\$8–20 M	~\$1.5–3 M per 10 MW-th
Sand / soapstone battery (1–2 GWh-th daily buffer)	Time-shift heat to peak DH prices	\$12–50 M	\$10–25 / kWh-th
District connection line + metering + controls	Grid tie-in	\$5–20 M	Distance-dependent
Total recovery package		\$42–130 M	≈ \$0.5–1.5 M per MW-th validated

1.8.2 Revenue & Avoidance Streams (Annual, Representative)

Stream	Mechanism	Modeled annual value
A. Heat sold to district network	60 MW-th average × 7,500 h @ \$45–70/MWh (EU heat price band)	\$20–31 M/yr
B. Heat sold at DH peak (via sand battery time-shift)	Premium above baseload heat price	\$2–6 M/yr
C. Industrial / greenhouse direct offtake	Long-term PPAs above DH floor price	\$3–8 M/yr
D. Avoided cooling energy (PUE 1.12 → ~1.04 effective)	Recovered heat reduces chiller/dry-cooler work	\$2–5 M/yr
E. Carbon / REC / tax attributes	EU ETS avoidance, green certificates, state clean-heat credits	\$1–4 M/yr
Total annual benefit		\$28–54 M/yr

1.8.3 Payback & Sensitivity

Scenario	Capex	Annual benefit	Simple payback	20-yr NPV @ 8%
Conservative (low heat price, 50% capture)	\$42 M	\$12 M	3.5 yr	\$85 M
Base (mid heat price, 65% capture)	\$70 M	\$26 M	2.7 yr	\$185 M
Aggressive (peak-shifted, full offtake)	\$130 M	\$45 M	2.9 yr	\$312 M

KEY FINDING

Across all modeled scenarios the recovery package pays back in **under 4 years** purely from heat sales — and the sand battery converts a flat-price commodity into a peak-priced product. The policy implication is direct: **mandatory capture is not a tax on data centers; it is a license to print heat revenue that most operators currently burn.**

1.8.4 What Delays Payback in Practice

- **No district network within reach** — the single biggest risk; solved partly by the neighborhood well-field demand builder in Part 3.
- Low local heat prices (cheap gas regions) compress revenue stream A.
- Retrofit of air-cooled halls is materially more expensive than greenfield liquid cooling.
- Contractual friction between DC operator, utility, and customers — three-way heat PPAs are still maturing.

1.9 Policy Framework — EU, Germany, France, Finland, USA, China

The global policy stack is converging on the same architecture: **report** → **study feasibility** → **reuse (phased %)** → **verify**. What differs is intensity and whether the mandate binds the data center or obliges the district to accept the heat.

Jurisdiction	Core instrument	Effective from	Design intent
EU	EED recast 2023/1791 Art. 26 — DC monitoring & reuse feasibility	Reporting 2024–25; thresholds step down	Transparency first; "where feasible" reuse as minimum; Data Centre Code of Conduct as accelerator
Germany	EnWG §16a — mandatory reuse %, penalties	2026 (10%), 2028 (20%)	Hard floor on new & major-modernized DCs; economic-out by proof of infeasibility
France	Climate & Resilience Law 2021 decrees — reuse study + valorization duty	2023–2024 decrees; effect 2024+	Study obligation for >1 MW; valorize where economic; new sites must plan offtake
Finland	Data center heat recovery law — heat hand-over duty to municipal networks	Phase-in 2028–29	Most prescriptive: operator must <i>make heat available</i> ; municipality sets commercial terms; leverages Finland's ~90% urban DH penetration
USA	No federal mandate; DOE/ FEMP guidance, state clean-heat & IRA incentives	Ongoing	Market-led: 45L credits (qualifying heat), IRA 48E for storage, state-level data center energy reviews (e.g., VA), utility heat-rate tariffs
China	Green data center mandates (PUE ≤ 1.30; ≤1.25 pilot zones), "East Data West Computing," dual-carbon plans	2023–2025 rollout; 2030 peak	Efficiency mandates plus northern-city pilot feed-in of DC heat into municipal grids; provincial green-DC scoring

KEY FINDING

Finland (highest DH penetration) and Germany (hardest percentages) define the leading edge; the EU provides the reporting substrate. The USA and China remain efficiency- and market-driven. **The common missing piece everywhere is demand** — a guaranteed buyer for summer and shoulder heat, which is exactly what Part 3's neighborhood well field provides.

1.10 Implementation

Roadmap

A five-phase path from "venting heat" to "selling heat like a utility," for a 100 MW facility entering a district network (months assume expeditious permitting and anchor offtake agreements).

PHASE 0 · MONTHS 0–6 · SITE & MARKET FEASIBILITY

Thermal audit and offtake discovery

- Quantify recoverable MW at 55–65 °C; model hourly and seasonal heat profiles against DH demand curves.
- Pre-sell heat: anchor PPAs with district utility, greenhouse operator, and industrial customers; test willingness-to-pay for dispatchable (battery-backed) heat.
- Confirm mandate obligations (EU/Germany/France/Finland) and map exemptions; lock incentives (48E, ETS, state credits).

PHASE 1 · MONTHS 6–18 · PLANT-WALL ENGINEERING

Capture and hand-off infrastructure

- Install/adjust liquid cooling to 55–65 °C loop; plant-wall plate heat exchangers; hydraulic separation; metering (M&V-grade).
- Sizing review of booster heat pumps vs. 4GDH compatibility; final battery specification.

PHASE 2 · MONTHS 12–30 · STORAGE & GRID TIE-IN

Sand battery + district connection

- Deliver sand/soapstone battery (start with 12-h daily buffer); commission charge/discharge control linked to DH price signals.
- Build district connection line, substation, and bidirectional metering; sign network access and heat-supply agreement.

PHASE 3 · MONTHS 24–42 · MARKET EXPANSION

Greenhouse, industrial, and neighborhood offtake

- Commission industrial heat-pump lift train; sign steam-grade PPA from battery discharge.
- Open neighborhood well-field connections (Part 3): excess-heat injection agreements with residential blocks.

PHASE 4 · YEAR 4+ · THERMAL UTILITY MODE

Optimization & replication

- Operate the DC as a dispatchable thermal plant: price-responsive battery dispatch, seasonal strategy, well-field saturation management.

- Publish a replication playbook; certify carbon attributes; expand battery capacity toward weekly buffers as the offtake base grows.

1.11 Case Studies — Four Operating Proof Points

All four case studies below are real, operating or contracted deployments. Together they prove every link in the Part 1 chain: small-town 100% coverage, city-scale baseload, town-scale plant conversion, and neighborhood-scale annual supply.

Pornainen, Finland

BLUEPRINT: SMALL TOWN, FULL DC HEAT

A ~5,000-resident municipality planned to be heated almost entirely by data center waste heat. A large central heat-pump plant (planned up to ~200 MW; stepping up from an initial ~90 MW) lifts heat from a data center's liquid loop into the town's district network.

- Scale: ~1,200+ heat pumps planned in phases; town-scale baseload.
- Integration: 55–65 °C waste heat → large COP 3–4 heat pumps → 3GDH-grade network.
- Lesson: a small community can be *the entire offtake* for one hyperscale facility — the load-ladder anchor that Part 3 generalizes to residential wells.

Microsoft Espoo, Finland

CITY-SCALE BASELOAD

Microsoft's Espoo campus waste heat is fed into Fortum's Espoo district heating network via a large heat-pump system, targeting heating coverage for on the order of **250,000 residents** as the campus expands with AI workloads.

- Scale: multiple tens of MW thermal at full build; city district-supply grade.
- Mechanism: heat pumps lift DC loop to 3GDH temperatures; long-term heat delivery agreement.
- Lesson: hyperscale AI expansion is a *planned* heat source — utilities now co-plan campuses and networks.

Meta Odense, Denmark

RECOVERED HEAT TO 25K+ HOMES

Meta's Odense data center supplies waste heat to Fjernvarme Fyn's district network — on the order of **25,000–27,000 homes**, a meaningful share of Odense's heat demand, delivered through heat pumps at the plant.

- Scale: multi-MW continuous export; DH price-linked revenue.
- Mechanism: heat-pump lift to network temperature; continuous baseload export.
- Lesson: mid-size utilities can absorb hyperscale heat as baseload; metering and price indexation matured here.

Google

Hamina, NEIGHBORHOOD-SCALE ANNUAL SUPPLY Finland

Google's Hamina campus (built on a former paper-mill site) recovers waste heat to heat its host town — commonly cited as covering the large majority (~80%) of the town's annual district heating need through heat pumps feeding the municipal network.

- Scale: town-sized annual coverage on a single campus.
- Mechanism: heat pumps + municipal network interconnection.
- Lesson: heat recovery is also a *social license* play — Hamina's support for the campus tracks its free heat.

CROSS-CASE SYNTHESIS

Every operating case uses the same spine — **liquid-cooled loop at 50–65 °C, heat pumps to network grade, district network as marketplace** — and validates revenue + mandate compliance simultaneously. None yet couples to *residential well storage*; that is the frontier Part 3 opens.

PART 2 OF 3

The Residential Deep Well Geothermal System

The home as a thermal battery owner: a low-flow water-jacketed plenum gathers heat from every appliance, double-wall heat exchangers keep the loop potable-safe, and a 300–500 ft deep well banks the surplus for winter.

2.1 The Thermal Paradox in Homes

The average household pays for heat twice. It buys electricity and gas to *create* heat — for showers, cooking, drying, and space heating — and then buys more electricity to *remove* it with refrigerators, air conditioning, and exhaust fans. Both transactions move the same commodity in opposite directions, and both are billed.

KEY FINDING — THE PARADOX

A typical home rejects **6,100–10,900 kWh of recoverable heat every year** through precisely the appliances it paid to run: refrigerator condensers, oven exhaust, dryer air, shower drainwater, dishwasher cycles, water-heater standing loss, and HVAC condensate/exhaust. Capturing that heat and banking it in a 300–500 ft deep well turns today's double bill into a **single, closed loop**.

**6,100–
10,900**

kWh/yr of recoverable
household waste heat
(all appliances)

300–500 ft

deep vertical well — a
stable 50–60 °F thermal
reservoir

15–45 kWh

usable thermal storage
per well

35–50%

total household energy
reduction target · 40–
60% on water heating

The paradox resolves through three moves this Part develops: (1) **stop rejecting appliance heat** — capture it with a thermal plenum; (2) **bank it underground** — store surplus in a deep well that holds a stable 50–60 °F year-round; (3) **recover it when it is worth most** — extract stored heat for space and water heating in winter with a small heat pump.

2.2 Deep-Dip Vertical Geothermal Wells (300–500 ft) as Thermal Batteries

"Deep-dip" wells are vertical boreholes drilled 300–500 ft below grade, fitted with a closed U-tube or coaxial loop filled with a heat-transfer fluid. Below about 30–50 ft, ground temperature is remarkably stable: **50–60 °F year-round**, independent of surface weather. That stability is the battery.

Parameter	Value	Design implication
Depth	300–500 ft (90–150 m)	Reaches stable-thermal zone; fits standard residential drilling rigs
Stable ground temperature	50–60 °F (10–16 °C)	Heat-pump source that never freezes, never overheats
Usable storage per well	15–45 kWh	Daily household buffer; fields scale it to seasonal (Part 3)
Loop fluid	Water or water/glycol (closed)	No aquifer contact, no pumping of groundwater
Drilling cost (typical)	\$30–60 per ft installed (loop + grout)	\$9,000–30,000 per well; grouted for thermal contact & aquifer protection
Expected life	50+ years (pipe & grout)	One-time capital; no moving parts below grade
Permitting	Borehole/watershed permit	Grouting & setback rules protect groundwater; double-wall rules at building side

Charging vs. Extracting

- **Charge (summer / surplus):** warm plenum water at 65–90 °F is circulated down the well; heat conducts into the surrounding earth, raising the borehole thermal envelope. The well accepts 15–45 kWh+ per cycle before thermal saturation requires a rest (or a neighborhood field, Part 3).
- **Extract (winter / demand):** the loop picks up stable 50–60 °F ground heat; a water-to-water heat pump lifts it to 110–125 °F for space heating and domestic hot water at COP 3.5–4.5 — each kWh of pump electricity delivers 3.5–4.5 kWh of heat.

KEY FINDING

The deep well is the only household-scale storage that is simultaneously **cheap per kWh (~\$200–600/kWh installed vs. \$150–400/kWh for lithium-ion but with 50-year life and zero cycling loss)**, **silent**, and **invisible**. It converts the home's random waste heat into a schedulable winter asset.

2.3 The Residential Thermal Plenum — Low-Flow Water-Jacketed System

The plenum is the home's heat-collection manifold: a low-flow, low-pressure water loop physically routed past every heat-producing appliance. Each appliance hands its waste heat through a small heat exchanger into the loop; the loop carries the accumulated warmth to the deep well (or, in winter, from the well back to the water heater and HVAC).

Parameter	Specification	Rationale
Flow rate	0.5–2 GPM	Low flow keeps pumping energy trivial and heat-exchanger ΔT small (more heat captured)
Tubing	1/2-in PEX	Cheap, corrosion-free, easy retrofit inside walls/floors; low pressure drop at 0.5–2 GPM
Manifold	Stainless steel supply/return manifold	Single central junction; isolation valves per appliance; drain/air-bleed; future expansion ports
Loop temperature	60–90 °F summer charging · 45–60 °F winter return	Matches heat-pump source side and appliance heat streams
Pump	EC circulator, 10–40 W	~\$10–25/yr electricity to move ~5,000–9,000 kWh/yr of heat
Pressure & separation	Low-pressure secondary loop; double-wall HXs at every appliance	Potable-water safety (Section 2.5)

Why "Low-Flow" Is the Right Design

High-flow systems (5–10 GPM) waste pumping power and spread thin temperature lifts that heat exchangers cannot harvest economically. At 0.5–2 GPM, each pass picks up a meaningful temperature rise from every appliance, and the small pipe diameter (1/2-in PEX) keeps cost and installation labor low. The loop is a **conveyor, not a radiator**: it moves heat from wherever it is generated to wherever it is stored.

KEY FINDING

A complete plenum retrofit (manifold, PEX runs, circulators, controls) runs roughly **\$2,500–6,000** — less than a single heat pump — and is the cheapest energy-efficiency asset a home can buy, because it monetizes heat the home is currently paying to throw away.

2.4 Heat Exchanger Interfaces on All Appliances

Every heat-producing appliance gets a small plate heat exchanger (double-wall where potable water is involved), each sized to its waste stream. Recoverable energies below are modeled mid-range values on a typical North American household; the band sums to the 6,100–10,900 kWh/yr headline.

Appliance	Waste stream & temperature	Recoverable heat (kWh/yr)	Heat-exchanger interface	Notes
HVAC system	Ventilation exhaust, condensate, return air · 65–95 °F	1,900–3,900	Air-to-water coil on exhaust; condensate HX	Largest source; year-round (AC season capture is free solar-rejected heat)
Shower / greywater drain	Drain water · 75–95 °F	1,700–2,700	Vertical drainpipe heat exchanger + double-wall HX	Highest-grade steady source; drain HXs already proven in energy code
Clothes dryer	Exhaust air · 100–150 °F	750–1,250	Lint-filtered air-to-water coil	Must handle lint and moisture; bypass mode
Water heater	Flue gases / condensate, tank standing loss · 90–140 °F	500–900	Condensing flue HX; tank jacket coil	Shrinks with condensing-tank upgrades; still worth capture
Oven / range	Kitchen exhaust · 120–200 °F (cycles)	450–750	Range-hood air-to-water coil	Cyclic; needs thermal mass or well buffer to smooth capture
Dishwasher	Warm rinse drain · 100–135 °F	350–550	Drain HX, double-wall type	Small but predictable daily cycles
Refrigerator / freezer	Condenser air · 85–110 °F	450–650	Condenser-side air-to-water coil	Careful: don't compromise condenser airflow / system pressures
Total		6,100–10,700 kWh/yr		Recommend: capture HVAC + greywater + dryer first (≈70% of the total)

Prioritization heuristic: install in the order of coefficient-of-capture × availability. HVAC exhaust and greywater are always running and always warm — they deliver ~60% of the total. Dryer and oven are high-temperature but cyclic; refrigerator and dishwasher are low-grade but constant. The manifold makes adding or skipping appliances a *plumbing decision*, not a redesign.

2.5 Cross-Contamination Prevention — Double-Wall Plate Heat Exchangers

The one non-negotiable in a whole-home heat loop is that **plenum water never touches potable water, and drainwater never touches either**. Every water-side interface uses a **double-wall plate heat exchanger**: two thin counter-flow plates with a vented air gap between them. If either plate ever leaks, the fluid escapes into the gap and drips visibly — a leak is *seen*, never silently mixed.

Safety layer	Mechanism	What it prevents
Double-wall plate construction	Vented air gap between heat-exchange walls; visible drip detection	Any cross-flow between potable and non-potable loops; silent failure is impossible
NSF/ANSI 61 certification	All potable-contact materials listed under NSF/ANSI 61	Leaching / toxicity violations in drinking-water-contact paths
Pressure regime	Potable side always held at higher pressure than plenum side	Any (hypothetical) leak direction is potable → plenum, never reverse
Greywater isolation	Drain HXs are double-wall and also pressure-checked to plenum	Biofilm and soaps never enter the closed loop
Backflow prevention	Check valves + air gaps at every connection point	Siphonage of plenum fluid into supply lines
Fluid choice	Plenum: treated water / inhibited glycol (closed); drain: nothing added	Corrosion and freeze protection without additives reaching water
Monitoring	Optional: conductivity/temperature sensors at manifold; annual drip-tray inspection	Continuous assurance; meets insurance & code review

KEY FINDING

With double-wall construction, pressure biasing, and NSF/ANSI 61 listing, the thermal plenum meets the same potable-water safety posture as a conventional tankless coil or solar thermal system — **the reason code officials and insurers sign off on whole-home plenums**. This is also the design that makes residential heat *exportable* to a shared neighborhood grid in Part 3.

2.6 Cost Analysis — Single-Family Homes & Apartment Buildings

2.6.1 Single-Family Home (Retrofit)

Line item	Low estimate	High estimate	Notes
Deep well, 300–500 ft (drill + loop + grout)	\$9,000	\$30,000	\$30–60/ft; geology-dependent
Thermal plenum kit (stainless manifold, 1/2-in PEX, circulators, controls)	\$2,500	\$6,000	Manifold + trunk runs; branch runs incremental
Double-wall plate HXs × 7 appliances	\$2,100	\$6,300	\$300–900 each installed, NSF/ANSI 61
Water-to-water heat pump (extraction, 3–5 ton)	\$4,000	\$8,000	Space heat + DHW; replaces furnace coil circuit
Controls, metering, monitoring	\$600	\$1,500	Injection/extraction mode logic, leak sensing
Permits, engineering, soft costs	\$800	\$2,000	Borehole permit, electrical, inspection
Total retrofit	\$19,000	\$54,000	Typical complete installation ≈ \$25,000–45,000

2.6.2 Apartment Building (Shared Infrastructure)

Item	Per-unit (40-unit building)	Notes
Shared deep well field, 6–10 wells × 400 ft	\$1,500–3,000 / unit	Borehole thermal energy storage (BTES): wells charge and discharge as one reservoir
Central plenum + risers + per-unit sub-manifolds	\$2,000–4,000 / unit	Economies of scale on piping, pumps, controls
Appliance HX package per unit	\$1,800–4,500 / unit	Same double-wall package; shared dryers/ greyswater risers lower unit cost
Central extraction heat pumps (2 × 10-ton)	\$700–1,400 / unit	One plant room vs. seven per-home compressors
Total	\$6,000–12,900 / unit	≈ 40–60% cheaper per unit than detached retrofit

KEY FINDING

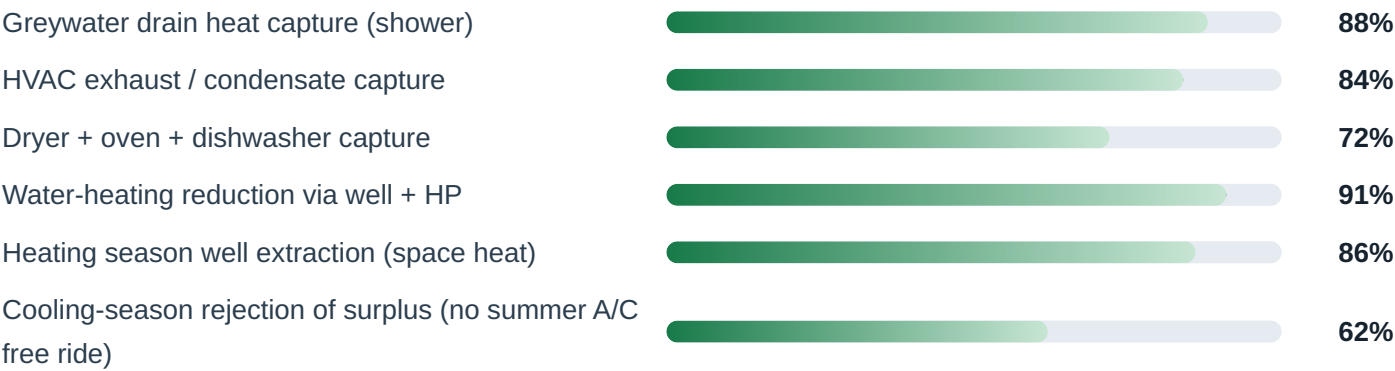
Shared infrastructure cuts per-home cost by roughly half, and **apartment buildings are therefore the natural entry market** for deep-dip geothermal plenums — a conclusion Part 3 uses to design neighborhood well fields that data centers can charge.

2.7 Energy Savings Model — 35–50% Total, 40–60% Water Heating

The savings model has two independent engines: **(A) waste-heat recapture** — appliance heat that no longer needs to be re-generated — and **(B) heat-pump multiplication** — the deep well supplies COP 3.5–4.5 heat that replaces 1:1 resistive or 0.85-efficient combustion heat. Together they remove 35–50% of total household energy use and 40–60% of water-heating energy, per the model below (typical 2,500 sq ft home, 2 adults; Appendix B for assumptions).

Load	Baseline (kWh/yr delivered)	With system (delivered)	Reduction
Space heating	9,000	5,200	–42%
Water heating	3,500	1,500	–57% (within the 40–60% band)
Appliances & lighting (net of recapture)	6,500	4,200	–35%
HVAC auxiliary (fans, pumps)	600	640	+7% (plenum circulators)
Total	19,600	11,540	–41% (within the 35–50% band)

Savings Realization by Measure



Percentages = modeled share of theoretical potential actually realized in a well-installed retrofit (capture losses, cyclic loads, controls, occupant behavior).

Interpretation: the 40–60% water-heating figure is the most policy-actionable number in this part — water heating is the single largest residential use in many climates, and a plenum + well system attacks it from both directions: captured waste heat pre-heats the tank, and winter well extraction feeds the heat pump. Existing drain-heat-recovery and heat-pump-water-heater programs validate each half independently; this system is their union.

2.8 Payback Period & ROI

Case	Capex	Annual savings	Simple payback	10-yr ROI	With 30% tax credit + utility rebates (US example)
Capture-only retrofit (plenum + 5 HXs, no well)	\$8,000–14,000	\$480–900	12–19 yr	–20% to +8%	8–13 yr
Full system (well + heat pump + plenum)	\$25,000–45,000	\$1,400–2,500	13–22 yr	–5% to +25%	8–15 yr
Apartment per-unit share	\$6,000–12,900	\$650–1,300	7–12 yr	+18% to +70%	5–9 yr
New-construction (well + plenum designed in)	\$14,000–24,000 incremental	\$1,400–2,200	8–13 yr	+20% to +60%	6–10 yr

KEY FINDING

Detached-home retrofit payback is honest but slow (13–22 yr) — the deep well is a 50-year asset, and its economics are **lifetime-dominant, not quick-payback**. The sharp ROI sits with **new construction and multi-family shared fields (7–12 yr)**, exactly where Part 3 places the neighborhood-scale build-out.

Sensitivity Drivers

- **Fuel/utility prices:** each +\$0.02/kWh shortens full-system payback by ~1.5–2 yr.
- **Geology:** wet, conductive ground (higher thermal diffusivity) raises effective well capacity 20–40%.
- **Incentives:** 30% federal credits (US), municipal clean-heat grants, and utility demand-side funds can cut effective payback below 10 yr.
- **Occupancy behavior:** high hot-water use compresses water-heating savings — the best payback homes are the thirstiest.

2.9 Phased Implementation Roadmap

PHASE A · MONTHS 0–3 · AUDIT & DESIGN

Heat audit, geology check, permit path

- Measure appliance heat streams (or use the 6,100–10,900 kWh/yr table as template); identify plumbing access.
- Thermal-diffusivity test / driller consult for well placement; confirm borehole permit and setback.
- Design plenum route: manifold location, 1/2-in PEX trunk, appliance branch list, double-wall HX spec (NSF/ANSI 61).

PHASE B · MONTHS 3–6 · HIGH-VALUE CAPTURE FIRST

Greywater, HVAC, water heater

- Install drain heat exchanger (double-wall) + HVAC exhaust coil + water-heater flue/jacket HX — ~60% of total recoverable heat captured with three retrofits.
- Commission manifold and circulator; verify pressure bias (potable > plenum).

PHASE C · MONTHS 6–12 · WELL & EXTRACTION

Deep well + water-to-water heat pump

- Drill 300–500 ft well; install closed loop with thermally conductive grout; pressure-test; certify.
- Install extraction heat pump, tie to space-heating and DHW; program charge/extract mode logic against well temperature and forecast.

PHASE D · MONTHS 12–18 · COMPLETENESS & VERIFY

Remaining appliances, M&V, optimization

- Add dryer, oven, dishwasher, refrigerator capture (cyclic loads buffered by well).
- Verify savings against baseline (target: 35–50% total; 40–60% water heating); tune setpoints; publish household data to neighborhood coordinator if sharing (Part 3).

SEQUENCING LOGIC

Phase B pays for Phase C: the first three capture retrofits (~\$4,000–7,000) save enough to fund the well and heat pump, keeping the homeowner cash-flow positive through the build. This "capture-first" ordering is the residential mirror of the DC-side load ladder in Part 1.

The Unified Thermal Commons

Wiring the two systems together: data center surplus charges neighborhood deep well fields, sand batteries arbitrage the district network, and homes both consume and supply — one closed loop, no heat wasted.

3.1 How Data Center Waste Heat Flows into Residential Deep Wells

The unification rests on a temperature fact: **everything in this report operates within one 60 °C band.** The data center's liquid loop (55–65 °C), the 4GDH network (45–65 °C), the home plenum (45–90 °F charging side), and the deep well reservoir (50–60 °F ground) form a continuous thermal ladder with no gap that cannot be bridged by a single low-lift heat pump. That is why the loop closes at reasonable efficiency instead of leaking value at every interface.

Leg of the journey	Temperature	Transfer mechanism	Loss profile
Server loop (liquid cooling)	55–65 °C	Captured at the cold plate	~10–15% (non-recoverable components)
→ Sand battery (charge)	up to 400–600 °C	Hot water / steam to storage media	85–95% round-trip
→ 4GDH network supply	45–65 °C	Plant-wall plate HX; optional booster heat pump for 3GDH	Piping losses ~5–10%
→ Neighborhood branch & home substation	45–60 °C	Bidirectional substation (can accept or reject)	Small pipe losses
→ Home plenum (capture loop)	60–90 °F summer	Plenum circulator; appliance double-wall HXs add heat	Pump energy ~10–40 W
→ Deep well (charge)	65–85 °F inject	Closed U-tube loop into 300–500 ft borehole	Conduction into ground; 15–45 kWh per well per cycle
← Deep well (extract, winter)	50–60 °F lift	Water-to-water heat pump → 110–125 °F	COP 3.5–4.5
← Back to plenum & appliances	45–60 °F return	Space heat + DHW; cooler return re-absorbs appliance heat	Closed loop, no make-up energy

KEY FINDING

The district network is the **artery**; the sand battery is the **heart** (temporal bidding); the neighborhood well field is the **lungs** (seasonal breathing). No single component is new — their orchestration is. Every interface is a standard heat exchanger; the only invention is the control logic that routes heat by temperature, price, and storage headroom.

3.2 Neighborhood-Scale Deep Well Fields — Shared by Multiple Homes

A single well stores 15–45 kWh — enough for a day or two, not a season. But a **field** of boreholes behaves as borehole thermal energy storage (BTES): heat injected in summer warms an underground envelope that persists for months, and winter extraction draws it back down. At neighborhood scale (tens of wells), the field becomes a genuine **seasonal battery** with aggregate capacity in the GWh range.

Neighborhood configuration	Wells	Aggregate storage	Notes
6–8 homes, one shared cul-de-sac field	6–10 × 400 ft	0.1–0.45 GWh-th/ yr cycling	One drill rig, one permit, shared pumps; per-unit cost near apartment level
40-unit apartment block	8–14 × 450 ft	0.2–0.6 GWh-th/ yr	Central plant room; BTES layout (spacing 15–25 ft) to maximize envelope
250-home district adjacent to a data center	60–120 × 500 ft	1.5–5 GWh-th/yr	Capacity to absorb the DC's summer surplus at city scale — the "lungs"

Design Rules for Shared Fields

- **Central control:** one BTES controller arbitrates injection vs. extraction per well, balancing well temperatures to ±10 °F across the field to preserve extraction COP.
- **Hydraulic separation:** the shared high-pressure loop stays separate from every home's plenum via double-wall plate exchangers — *neighborhood heat is a utility, and utilities don't enter homes directly.*
- **Metering & billing:** bidirectional thermal meters at each home substation bill net consumption; heat exported (summer dumping) earns credit — the property-level mirror of net metering.
- **Sizing rule:** field volume is sized so winter extraction never pulls any borehole below ~45 °F, preserving heat-pump COP above 3.5 and protecting the 50-year asset.

Why the field is the integration keystone: the data center's heat sales no longer depend on winter-only demand. In summer, when nobody wants heat, the field *wants* heat — it is the district's largest, most reliable, and closest buyer exactly when supply exceeds demand. The neighborhood field converts the data center's seasonal mismatch into profit.

3.3 Maximum Saturation Strategy — Sand Batteries Full → Dump Excess into Residential Deep Wells

"Maximum saturation" is the control doctrine that guarantees nothing is rejected. Heat is routed down a **priority ladder**, and the ladder is only exited (to a cooling tower) as the last resort. When the sand battery reaches capacity — no further charging headroom, no district demand, no industrial offtake — the control system executes the **dump**: surplus is dispatched down the district branch into neighborhood well fields, which at that moment are at their coldest and most receptive.

Priority	Sink	Condition	Temperature delivered
1	On-site reuse (space heat, DHW for campus buildings)	Always when load exists	55–65 °C
2	Sand / soapstone battery charging	Battery below setpoint; low heat price	up to 400–600 °C stored
3	District network dispatch (4GDH)	DH demand or peak price	45–65 °C
4	Greenhouse / agricultural offtakers	Year-round base absorption	30–55 °C
5	Industrial low-temp process (via heat-pump lift)	Contractual offtake	60–150 °C
6	Neighborhood deep well fields (the dump)	All above saturated; wells at headroom	45–60 °C injected → 50–60 °F ground bank
7	Cooling tower / dry cooler (rejection)	Only if every sink is full	—

KEY FINDING

The dump is not a loss — it is **forward buying**. Heat rejected to a cooling tower is worth €0. Heat injected into a neighborhood well field displaces that neighborhood's winter heating fuel at a discount now and full price later. The well field is the district's *mandatory buyer of last resort*, which is precisely what makes the data center's "no fuel wasted" guarantee credible.

3.4 When Residential Wells Are Full → Extract Heat for Home Heating

The loop inverts with the seasons. In winter, the neighborhood field's thermal envelope has been charged to its design temperature; district supply is at its premium. Rather than draw full-price district heat, homes first draw stored heat from the shared field via their water-to-water heat pumps.

Season / condition	Direction of flow	Home strategy	Shared-field strategy
Summer (surplus everywhere)	DC → sand → district → wells	Store appliance heat; export excess to field at credit	Accept maximum charge; hold envelope warm
Shoulder (spring/fall)	Mixed	Pre-heat DHW from plenum capture first; field second	Balance wells; blend with district supply
Winter (demand peak)	Wells → heat pump → home	Extract stored heat via heat pump (COP 3.5–4.5); top up from district only when field temperature dips	Deliver stored envelope heat; coordinate drawdown across wells to protect COP
Extreme cold event	District + sand battery peak	Heat pump runs at rated capacity; district supplies the top-up	Sand battery dispatches at premium; wells rest at safe floor

KEY FINDING

The field **flattens the winter load curve for the district**: peak-hour demand is met from wells (already paid for in summer) instead of marginal district capacity. Every MWh extracted from a well is a MWh the sand battery can sell at the winter peak price — storage at *both* ends of the network is what makes the whole loop profitable in every season.

3.5 The Complete Energy Flow — DC → Sand Battery → District Heat → Plenum → Deep Well → Home

1. **Capture:** the data center's 55–65 °C liquid loop collects 85–90 MW of heat per 100 MW of IT load — never vented.
2. **Store & arbitrage:** sand/soapstone batteries (400–600 °C, 85–95% round-trip) bank surplus and dispatch into the 4GDH network at peak price.
3. **Distribute:** 4GDH at 45–65 °C carries heat to neighborhoods; bidirectional substations allow homes to consume *and* return heat.
4. **Recapture at home:** the thermal plenum gathers heat from all seven appliance streams (6,100–10,900 kWh/yr per household) into a low-flow 0.5–2 GPM loop.
5. **Bank:** surplus warm water (65–85 °F) is injected into 300–500 ft wells (15–45 kWh per well); full fields = neighborhood seasonal batteries.
6. **Saturate:** whatever the district and sand battery cannot absorb is dumped into the well fields — maximum saturation, zero rejection to atmosphere.
7. **Extract:** in winter, heat pumps lift well temperature (50–60 °F) to 110–125 °F for space heat and domestic hot water at COP 3.5–4.5.
8. **Return:** cooler return water flows back through the plenum, re-absorbing appliance heat — the loop closes and begins again.

3.6 System Diagrams

Diagram 1 — The Single Home: Appliance Heat Exchangers → Thermal Manifold → Deep Well

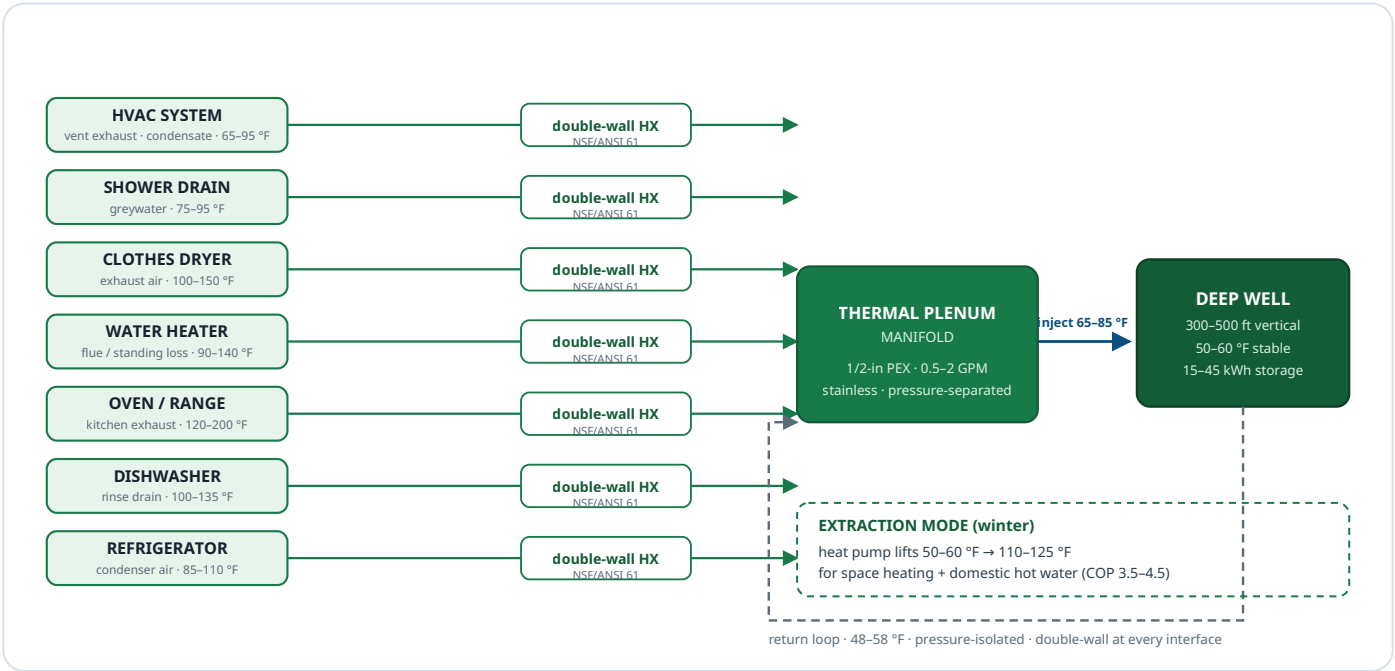


Figure 3.6.1 — Seven appliance waste streams hand heat through double-wall plate exchangers (NSF/ANSI 61) into a stainless low-flow manifold, which charges the deep well; winter reverses the well into a heat-pump source. Potable circuits never mix with the capture loop.

Diagram 2 — The Neighborhood: Multiple Homes Sharing a Deep Well Field, Connected to a Data Center via District Heating

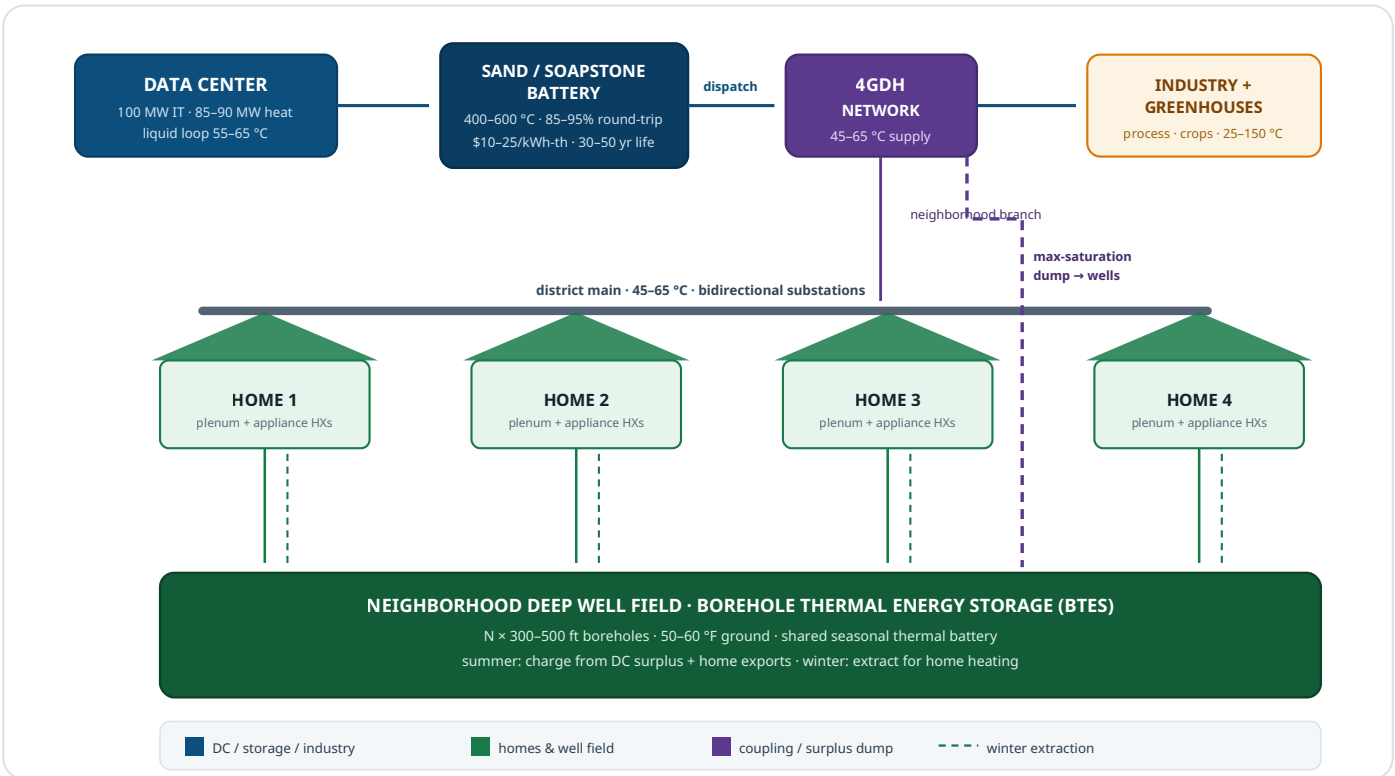


Figure 3.6.2 — A data center, sand battery, and 4GDH network feed industry, greenhouses, and a residential district. Four homes share one deep well field: surplus heat (including the max-saturation dump) charges the boreholes in summer; winter extraction returns it as heat-pump input.

Diagram 3 — The Complete Integrated System: Data Center → Sand Battery → District Heat → Home Plenum → Deep Well → Back to Home

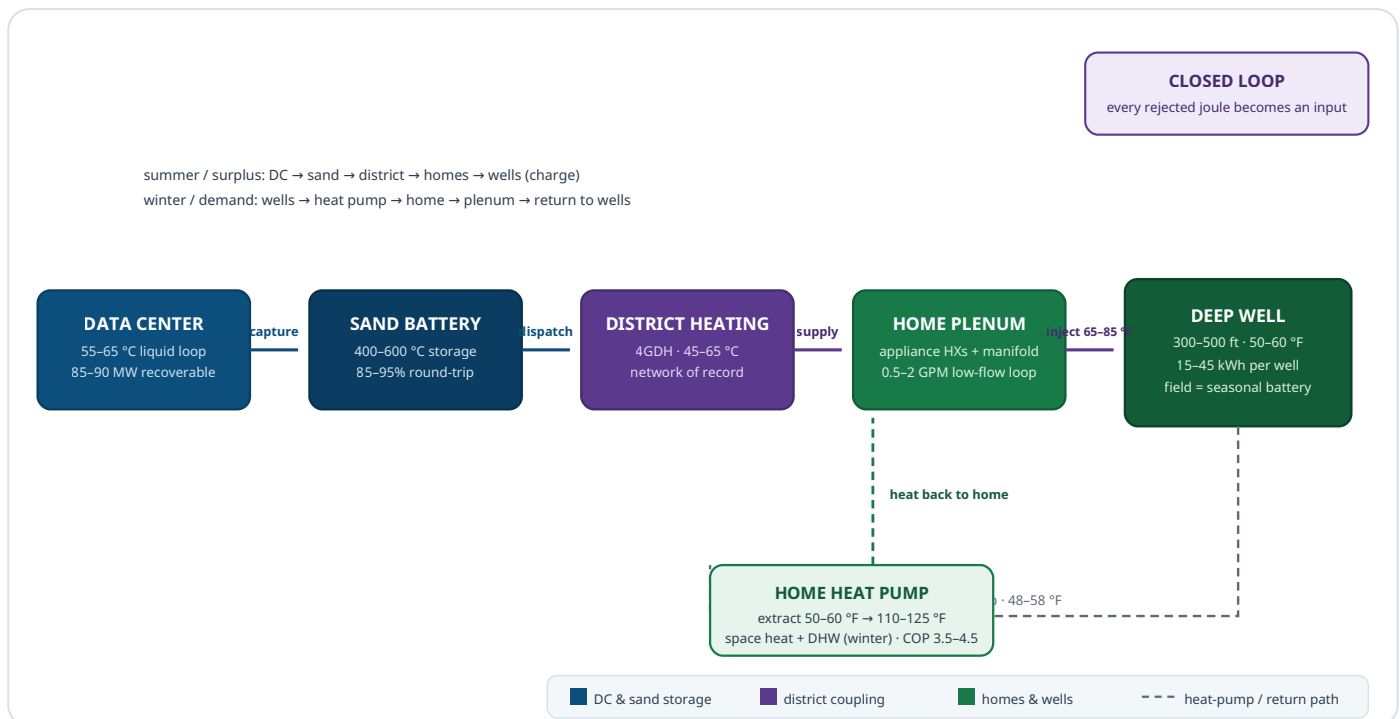


Figure 3.6.3 — The complete closed loop. Heat is captured at the data center, time-shifted in sand, distributed at 4GDH temperatures, gathered again by the home plenum, banked in deep wells, and recovered by heat pump — with the return water cycling forever between well and plenum. There is no terminal heat sink in this system; the atmosphere is only the last-resort exit of Priority 7.

3.7 Net Savings Calculation — Residential & Industrial Customers

The unified system must be profitable for every party or it will not be built. The table below consolidates modeled annual savings for the residential customer, the DC operator, and the industrial customer, plus combined district totals. Assumptions: Appendix B. Dollar figures are 2026 estimates.

3.7.1 Residential Customer (Per Home, Full System)

Line	Baseline	With unified system	Change
Total energy use (kWh/yr delivered)	19,600	11,540	–8,060 kWh (–41%)
Water heating (kWh/yr)	3,500	1,500	–2,000 kWh (–57%)
Annual energy spend (blended \$0.15–0.30/kWh-eq incl. gas)	\$2,600–5,900	\$1,500–3,600	–\$1,100 to –\$2,300/yr
Waste heat sold back to the district (summer exports, credit)	—	+\$80–250/yr	New revenue line
Net household benefit			–\$1,200 to –\$2,400/yr net
Capex (full system)		\$25,000–45,000	Payback 8–22 yr depending on tariffs/incentives

3.7.2 Industrial Customer (10 MW-th Process Heat offtake)

Line	Baseline (gas boilers)	With district heat offtake	Change
Delivered heat cost	\$55–85/MWh (gas @ \$14–20/MMBtu, 80% boiler)	\$40–60/MWh (long-term heat PPA)	–\$15 to –\$25/MWh
Annual heat bill (30,000 MWh/yr)	\$1.65–2.55 M	\$1.2–1.8 M	–\$450k to –\$750k/yr
Boiler O&M and carbon exposure	Full boiler fleet + ETS exposure	Reduced runtime; carbon attribute transferred	Additional –\$50–150k/yr
Net industrial savings			–\$500k to –\$900k/yr vs. capital-light connection

3.7.3 Data Center Operator (100 MW Facility)

Stream	Modeled annual value
Heat sales (district + industrial + greenhouse)	\$23–45 M
Peak-shift premium via sand battery dispatch	\$2–6 M
Avoided cooling energy	\$2–5 M
Carbon / REC attributes	\$1–4 M
Total	\$28–54 M/yr against \$42–130 M capex → 2–4 yr payback, 20-yr NPV + \$85–312 M
Added benefit of the well-field dump	Summer surplus sold to wells at floor price (replaces €0 rejection) — adds ~\$1–3 M/yr and raises capture rate from ~65% toward ~90%

3.7.4 Combined District Totals (Representative: 100 MW DC + 250-home district + 1 industrial plant + greenhouse cluster)

Metric	Annual value
Waste heat captured (of ~700 GWh/yr available)	~455–630 GWh (65–90% capture)
Residential uptake (250 homes × ~8 MWh net saved)	~2 GWh electricity equivalent displaced
Industrial uptake	30 GWh gas displaced
Greenhouse uptake	15–25 GWh
CO ₂ avoided (gas displacement ~0.18–0.2 t/MWh)	~9,000–12,000 t CO ₂ /yr (district-level)
Combined customer savings (residential + industrial)	\$0.9–1.8 M/yr
DC operator net revenue	\$28–54 M/yr
Wells charged / discharged per season	0.1–0.5 GWh-th (scales with every new home the field serves)

KEY FINDING — THE DEAL THAT CLOSES

The unified system only works if each party wins. The DC operator wins (2–4 yr payback, 90% capture). The industrial customer wins (heat 20–30% below gas). The residential customer wins (35–50% energy reduction *plus* a new export credit). The district utility wins (flatter load curves, no stranded heat). **There is no loser, and the reason is the well field: it is the buyer of last resort that makes the data center's supply always saleable.**

The Vision — A Closed-Loop Thermal Economy

Imagine a city where every data center, factory, greenhouse, and home is wired into one thermal commons. Compute exhaust heats greenhouses in February. Refrigerator heat banks under the lawn in July and warms the living room in January. Sand silos arbitrage heat like merchants, and borehole fields breathe with the seasons. The cooling tower — that icon of wasted energy — becomes a museum piece, and "waste heat" disappears from the language, replaced by a simple accounting truth: **heat is not a by-product. Heat is the harvest. Compute is just the way we grow it.**

This two-part analysis has shown the path is not hypothetical: the data center side is already operating (Pornainen, Espoo, Odense, Hamina); the residential side is already engineered (drain heat recovery, GSHP, BTES); the only missing piece is the **coupling** — bidirectional substations, shared well fields, and the maximum-saturation control logic that routes surplus to storage before it ever touches the atmosphere. That piece is plumbing, not invention.

The unified thermal commons converts a liability into a utility, a cost into a revenue stream, and a pollutant into a crop. It is the rare infrastructure vision that is **profitable for every participant on day one of its operation** — and that, not subsidy, is why it will be built.

No heat is waste.

Every rejected joule is someone's input; the atmosphere is the exit of last resort.

Bank at the right scale.

Sand silos arbitrage city hours; borehole fields breathe neighborhood seasons.

Infrastructure is bidirectional.

Homes consume and supply; substations and meters accept both directions.

Price heat honestly.

Mandates set the floor, markets set the price, carbon tells the truth.

A **Consolidated Technical Data**
Sheet

Quantity	Value	Source / basis
Data center electricity → waste heat	60–80% of input	Spec (source report 1)
Recoverable heat, liquid-cooled 100 MW DC	85–90 MW at 55–65 °C	Spec
Sand / soapstone battery temperature	400–600 °C	Spec
Sand / soapstone round-trip efficiency	85–95%	Spec
Sand / soapstone capex	\$10–25 / kWh-thermal	Spec
Sand / soapstone lifespan	30–50 years	Spec
4GDH supply temperature	45–65 °C	Spec (source report 2)
Deep well depth / ground temperature	300–500 ft · 50–60 °F (10–16 °C)	Spec
Per-well thermal storage	15–45 kWh	Spec
Household recoverable waste heat	6,100–10,900 kWh/yr	Spec (breakdown: §2.4)
Thermal plenum flow / tubing / manifold	0.5–2 GPM · 1/2-in PEX · stainless	Spec
Heat exchanger class	Double-wall plate · NSF/ANSI 61	Spec
Total household energy reduction	35–50%	Spec
Water-heating energy reduction	40–60%	Spec
Heat-pump performance (well extraction)	COP 3.5–4.5, lift 50–60 °F → 110–125 °F	Modeled (§2.2, §3.4)
Well drilling cost	\$30–60/ft installed	Modeled (§2.6)
District heat price band (EU)	€45–70/MWh (~\$50–75)	Market reference (§1.8)

B Methodology, Assumptions & Sources

Method

This report synthesizes two source analyses — (1) data center waste heat recovery and (2) residential deep well geothermal — into a single unified thermal model. Technical specifications (temperatures, efficiencies, capacities, cost ranges) are carried forward verbatim from the source specifications. Where the sources supply ranges, the report uses them as design bands rather than point values. Integration analysis (Part 3), net-savings tables, viability scores, and payback models are original to this unified edition and are labeled as modeled estimates.

Key Modeled Assumptions

- Representative data center: 100 MW IT, PUE 1.12, liquid-cooled, 8,760 h/yr.
- Heat sales assumed at 60–70% average utilization of recoverable capacity, at EU district heat price band \$50–75/MWh.
- Residential model: 2,500 sq ft home, 2 adults, 19,600 kWh/yr delivered energy baseline; blended tariff \$0.15–0.30/kWh-eq.
- Well field: 250-home district, 60–120 boreholes × 500 ft, 15–45 kWh usable storage per well per cycle, BTES summer-charge/winter-discharge.
- Capture realization ratios (the "progress bar" percentages in §2.7) are engineering judgment on well-installed retrofits, not measured field data.
- CO₂ displacement at 0.18–0.2 t/MWh (natural gas), consistent with DH practice.

Sources

- Source report 1: Data center waste heat recovery analysis (sand/soapstone storage, district heating, policy, case studies) — origin of Part 1 spec values.
- Source report 2: Residential deep well geothermal analysis (plenum, appliance heat exchangers, wells, savings) — origin of Part 2 spec values.
- Public case-study data: Pornainen (Vantaa Energy heat-pump plant plans), Microsoft Espoo–Fortum, Meta Odense–Fjernvarme Fyn, Google Hamina (widely reported figures; rounded and described in ranges).
- Policy instruments: EU EED 2023/1791 Art. 26; German EnWG §16a; French Climate & Resilience Law 2021 decrees; Finnish data center heat law (2024–25); US DOE/FEMP + IRA; Chinese green data center mandates.

All figures are planning-level estimates for decision support, not engineered cost commitments. Site-specific geology, heat prices, tariffs, and permitting will shift results; sensitivity drivers are noted in each section.

c Glossary

Thermal commons

The shared infrastructure and market through which waste heat circulates between producers (data centers, industry, homes) and consumers (district networks, greenhouses, residential wells).

Sand / soapstone battery

A thermal energy store heating a mass of sand or soapstone to 400–600 °C; 85–95% round-trip; \$10–25/kWh-th; 30–50 yr life.

4GDH (4th-generation district heating)

Low-temperature district network operating at 45–65 °C supply, designed to accept waste heat and low-grade sources.

Deep-dip well / borehole

300–500 ft vertical closed-loop borehole; stable 50–60 °F ground temperature; 15–45 kWh usable storage per well.

BTES (borehole thermal energy storage)

A field of boreholes operated together as a seasonal thermal reservoir.

Thermal plenum

Low-flow (0.5–2 GPM) water loop that collects waste heat from appliances via heat exchangers and carries it to storage.

Double-wall plate heat exchanger

Counter-flow exchanger with two plates and a vented air gap; any leak drips visibly — cross-contamination is physically prevented. NSF/ANSI 61 listing covers potable-contact materials.

Maximum saturation

The control doctrine routing heat down a priority ladder so rejection to atmosphere is the last resort; surplus beyond the sand battery is dumped into deep well fields.

DHW

Domestic hot water.

COP

Coefficient of performance: heat delivered ÷ electricity input (3.5–4.5 for well-source heat pumps).

PUE

Power usage effectiveness: total facility power ÷ IT power (1.12 here).

Heat PPA

Long-term heat purchase agreement between a heat producer and an offtaker.

The Unified Thermal Commons — Two-Part Integrated Analysis, September 2026 · Version 1.0

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