

Factory Heat on Charge: Thermal Batteries as Gas Alternatives

A financing, operating and implementation framework for replacing gas-fired process heat with stored renewable electricity

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Abstract

Background. Industrial thermal batteries convert electricity into stored heat and deliver it when a factory requires steam, hot air or other process heat. Their commercial value depends on process temperature, load profile, electricity price shape, grid capacity, charging rate, storage duration, heat-delivery efficiency and retained backup. Objective. This paper develops a financing, operating and implementation framework for factories considering thermal batteries as alternatives to gas-fired heat. Method. It combines current primary and authoritative evidence with an hourly heat balance, a system map, a technology and market benchmark, capital and operating sensitivities and a stage-gated implementation roadmap. Findings. A thermal battery creates value through the combination of electrification and time shifting. Cheap charging hours, high discharge utilisation, dependable process integration and flexible demand can reduce delivered-heat cost and gas exposure. Grid upgrades, demand charges, weak price spreads, cycling losses, low utilisation and production disruption can remove the benefit. Implications. Management should value the complete heat service, contract power and performance on compatible boundaries, preserve backup during evidence gathering and size storage through hourly dispatch rather than annual averages. All numerical exhibits are hypothetical and describe no identified company or project.

JEL Classification: G31, G32, L60, Q41, Q42, Q48

Keywords: thermal batteries, thermal energy storage, industrial heat, electrification, renewable electricity, gas replacement, demand flexibility, project finance, levelised cost of heat, manufacturing

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INTRODUCTION

Factories need heat when production requires it. Renewable electricity is available when weather, generation and the power system provide it. Thermal batteries connect those time profiles by converting electricity into heat, storing the heat in a material and releasing it later as steam, hot air, hot water or direct process heat.

The International Energy Agency describes thermal storage as an enabling technology that can connect low-cost variable renewable electricity with continuous industrial demand. It notes that storage media such as sand, cement and bricks can reach high temperatures and can be materially

cheaper per unit of stored energy than electrochemical batteries, while the industrial market remains developing.[1]

The investment decision is therefore wider than the storage vessel. It includes electric charging, grid access, power procurement, controls, heat exchange, factory integration, performance guarantees and backup. This paper develops a framework for underwriting that complete service.

1. DEFINE THE HEAT SERVICE

Specify the process boundary at which useful heat is delivered. Record temperature, pressure, flow, medium, purity, ramp, availability and control tolerance. The boundary may be a steam header, hot-air duct, thermal-oil loop, dryer inlet, furnace zone or hot-water network.

Define the production consequence of interruption or deviation. A food process, chemical reactor, paper dryer, kiln and curing oven have different tolerance. The investment case should use useful heat and product requirements rather than storage capacity alone.

Set the counterfactual. The thermal battery may replace an ageing boiler, displace marginal gas use, avoid new capacity, provide resilience or enable renewable generation. Each case has different cash flow. Avoided capital belongs in the model only when the conventional asset would otherwise be purchased.

2. DRAW THE COMPLETE SYSTEM MAP

Map electricity supply, grid connection, transformer, rectifier or resistance heater, storage medium, insulation, heat exchanger, steam generator, ducting, controls, process sink and backup. Include cooling, water and treatment where required.

Assign capacity, losses, ownership and interface to every component. Storage energy capacity does not prove charging power or discharge capability. A system can hold sufficient heat while failing to deliver the required ramp or pressure.

Map physical and contractual boundaries together. The power supplier, equipment vendor, engineering contractor, factory and heat-service provider can measure performance at different points. One agreed meter boundary is required for operating control, warranty, payment and financing.

3. BUILD THE HOURLY HEAT BASELINE

Record heat demand by hour or representative operating period. Capture batches, shifts, weekends, maintenance, seasons, product mix and expansion. Annual gas consumption cannot reveal peak heat, storage duration or charging opportunity.

Reconcile fuel purchase to useful heat. Apply boiler efficiency, standby, blowdown, distribution loss, condensate return and auxiliary electricity. Separate high-temperature and low-temperature duties. The thermal battery should be compared against the portion of the system it can actually serve.

Normalise for production. A temporary volume decline should not become an efficiency assumption. Preserve the raw data, adjustment method and uncertainty. The investment model should trace every heat unit from energy purchase to production service.

4. REDUCE AVOIDABLE HEAT DEMAND FIRST

Improve insulation, steam traps, condensate recovery, leak control, process scheduling, exchanger performance and temperature set points before sizing storage. Lower demand reduces charging power, storage volume and grid capacity.

Coordinate heat recovery. Direct use of waste heat usually avoids conversion and storage losses. Thermal storage can then serve residual demand or shift recovered heat. The International Energy Agency recommends plant-level optimisation before major electrification.[2]

Recalculate the hourly profile after efficiency measures. Some measures reduce peak demand, while others change timing. Use the post-improvement baseline for procurement. Avoid locking an inefficient heat system into a long-lived electrical asset.

5. SELECT THE TEMPERATURE CLASS

Temperature determines storage material, containment, insulation, exchanger, charging method and applications. Water tanks can serve lower-temperature duties. Solid media, molten salts, phase-change systems and thermochemical approaches can support other ranges.

Use the lowest temperature that reliably meets process and hygiene requirements. Lower delivery temperature can improve equipment choice and reduce loss. Review whether an existing steam pressure exceeds process need.

Classify each application as commercially proven, engineered or developmental at the required temperature and scale. Apply different contingency, schedule and financing. A familiar hot-water store and a high-temperature direct-process system carry different completion risk.

6. CHOOSE THE STORAGE MECHANISM

Sensible-heat storage raises the temperature of a material such as water, rock, brick, sand, concrete or molten salt. Latent-heat storage uses a phase change. Thermochemical storage uses a reversible reaction. Each differs in energy density, temperature, loss, cycling and complexity.

Compare complete systems. Include charging, containment, heat delivery, controls, foundations, safety and maintenance. High energy density can be offset by expensive media or heat exchange.

Require evidence at relevant temperature, duration and cycle frequency. Laboratory capacity does not prove factory integration. Review material degradation, corrosion, thermal expansion, insulation and end-of-life. Record which components are replaceable and which require major outage.

7. DEFINE CHARGING EQUIPMENT

Electric resistance heaters, electric boilers, heat pumps, induction, infrared and other technologies can charge or directly serve heat. Selection depends on temperature, efficiency, power quality, control, storage medium and process.

Size charging power against available low-price hours and required stored energy. A small charger can have high utilisation but fail to replenish storage. A large charger can increase connection capital and demand charges.

Model conversion performance across load. Include auxiliaries, transformer loss, standby and control. Define the test boundary. A vendor's heater efficiency can exclude grid, power electronics and storage loss. Project economics require the complete charge-to-useful-heat result.

8. DEFINE STORAGE DURATION

Storage duration is useful energy capacity divided by deliverable thermal output under stated conditions. The required duration can cover intraday price peaks, renewable variability, weekend charging, grid curtailment or backup.

Use hourly optimisation rather than a generic number. More duration adds capital and thermal loss while increasing price-shifting opportunity. Charging constraints can make nominal capacity unusable.

Test multiple operating years and extreme periods. A design optimised to average solar output may fail during a cloudy production week. Define whether backup gas, grid charging or production flexibility covers the gap. Finance should recognise the residual exposure.

9. SPECIFY DISCHARGE AND HEAT DELIVERY

Discharge must meet heat rate, temperature, pressure and response. The system may create steam through a heat exchanger, heat air directly, circulate thermal oil or feed a process vessel. Each adds pressure drop and control.

Build a discharge-performance map across state of charge and load. Temperature can decline as storage empties. Available output may be lower than nameplate near the end of discharge.

Define redundancy, bypass and safe shutdown. A continuous process can require parallel trains or retained boiler capacity. Include pumps, fans, water treatment, condensate and controls. Acceptance should measure useful heat at the process boundary.

10. MEASURE ROUND-TRIP THERMAL EFFICIENCY

Thermal efficiency is useful heat discharged divided by electricity or heat charged over the same cycle and boundary. It depends on conversion, standing loss, discharge loss, auxiliaries and unused residual heat.

Separate efficiency from utilisation. A well-insulated store can have high cycle efficiency while delivering little annual heat if price spreads or production schedules limit dispatch. Low utilisation raises the capital cost per useful unit.

Use performance guarantees for defined charge, hold and discharge profiles. Test at relevant ambient, temperature and part load. Record degradation over time. The finance model should use expected annual performance and a downside case rather than a single laboratory value.

11. SECURE GRID CAPACITY

Calculate maximum charging demand, annual electricity, ramp, harmonics, power factor and resilience. Compare with contracted capacity, transformer, switchgear, protection and utility limits. Include other planned site electrification.

Request a utility study early. Connection scope and lead time can determine feasibility. The IEA identifies grid planning and flexible-demand treatment as priorities for industrial heat electrification.[1]

Value existing spare capacity carefully. Physical transformer margin does not prove contractual capacity. Efficiency, onsite generation or production changes can create headroom, subject to confirmation. Include grid upgrade, owner works, deposits and delay.

12. MODEL THE ELECTRICITY TARIFF

Apply the hourly charging schedule to energy, network, demand, capacity, losses, taxes, levies and penalties. Wholesale prices alone are insufficient. Some tariffs reduce the value of shifting because network charges remain.

Model negative and low-price hours, peaks and seasonal structure with dated evidence. Avoid assuming historical spreads persist. Renewable growth, interconnection and tariff reform can change them.

Test fixed, indexed and dynamic procurement. A fixed price reduces volatility but can remove arbitrage. Wholesale exposure preserves opportunity and downside. Use a portfolio that aligns debt protection with operating flexibility.

13. INTEGRATE ONSITE RENEWABLE POWER

Onsite or dedicated solar and wind can supply charging, subject to generation profile, land, connection and curtailment. Direct use can reduce some network charges while increasing integration capital.

Co-optimize generation, charger and storage. Oversized generation can create cheap energy but low asset utilisation. Storage can capture output that would otherwise be curtailed. Record whether renewable attributes remain with the factory.

Include backup and grid interaction. Onsite generation does not guarantee continuous charging. Model maintenance and extreme weather. The IEA notes that renewable power combined with thermal storage can improve heat-electrification economics in suitable markets.[1]

14. COMPARE THERMAL AND ELECTROCHEMICAL STORAGE

Thermal storage serves a heat load directly. Electrochemical batteries store electricity that can later power heating or other loads. The correct comparison depends on the service and value streams.

Compare delivered useful heat, not nameplate energy. Include power electronics, round-trip losses, duration, degradation, fire protection, replacement and grid services. Thermal systems can use abundant storage materials, while electrochemical systems can provide broader electrical flexibility.

Hybrid systems may be appropriate. A small electrical battery can manage fast power or microgrid functions while thermal storage carries bulk heat. Avoid charging both technologies with the same flexibility revenue in the model.

15. COMPARE DIRECT ELECTRIFICATION

An electric boiler or resistance heater can deliver heat without storage. A heat pump can provide more useful heat per unit of electricity in suitable temperature ranges. Thermal storage adds time shifting and capacity.

Evaluate direct electric, heat pump, storage and hybrid configurations against the same process boundary. Include grid capacity, operating hours, tariff and retained backup. The IEA finds that storage can improve electric-boiler economics under variable prices, while heat-pump results depend on equipment size and application.[3]

Choose the smallest system that meets operating and economic requirements. Storage should have a defined purpose: price shifting, grid flexibility, renewable integration, resilience or capacity deferral.

16. COMPARE THE GAS COUNTERFACTUAL

Use delivered gas cost including commodity, network, capacity, taxes, carbon and minimum charges. Apply measured boiler efficiency and residual fixed costs. A retained gas connection can continue to incur expense after displacement.

Include conventional capital, maintenance, water, emissions control and compliance. Preserve the value of proven reliability and fuel storage where relevant. Avoid comparing a complete thermal-battery system with only the gas commodity price.

Model gas and electricity scenarios together. Thermal storage changes exposure rather than removing energy risk. The value of diversification should be shown through cash-flow distribution and contract terms.

17. DEFINE THE OPERATING STRATEGY

Dispatch should satisfy heat demand at minimum risk-adjusted cost within equipment, tariff, emissions and production constraints. Controls need forecasts of demand, prices, renewable output and state of charge.

Set reserve margins and priorities. The battery may charge during low-price periods, maintain a minimum state for resilience, and discharge during peaks. Manual override and safe fallback are required.

Use rolling optimisation with approved boundaries. AI-enabled forecasting can support decisions, subject to validation and cyber controls. Preserve logs, overrides and model versions. Operators should understand why dispatch changes.

18. VALUE DEMAND FLEXIBILITY

Flexible charging can avoid peak prices, reduce renewable curtailment and support the power system. Potential revenue can include demand response, interruptible tariffs or ancillary services where market rules allow.

Separate energy savings from grid-service revenue. Confirm eligibility, metering, minimum capacity, response time, penalties and aggregator terms. Avoid assuming that a thermal load can provide every battery service.

Protect production first. A demand-response event should not exhaust heat needed by the factory. Define the available flexible envelope after reserves. Debt sizing should use contracted or demonstrated revenue and conservative availability.

19. SELECT INDUSTRIAL APPLICATIONS

Food and beverage processes can use steam, hot water, drying and clean-in-place heat. Paper uses steam and drying. Chemicals, textiles, minerals, engineering and consumer goods have distinct temperature and control needs.

Screen applications by temperature, hours, variability, product criticality, space, grid and existing equipment. Stable base load can support high utilisation, while batch processes can align with storage dispatch.

Prioritise services with clear metering and manageable integration. One site can contain several candidate duties. A portfolio should rank them rather than assuming one central battery serves every process efficiently.

20. INTEGRATE WITH STEAM SYSTEMS

Define steam pressure, quality, flow, condensate and ramp. A thermal battery can generate steam directly or through an exchanger. Existing headers, traps, treatment and condensate systems remain part of the service.

Review whether multiple pressure levels can be rationalised. Lower pressure can improve system choice while preserving process performance. Separate high-pressure duties that require another solution.

Plan tie-ins and control. Parallel operation with boilers can support commissioning and peaks. Include blowdown, water chemistry and startup. Acceptance should measure steam delivered and electricity consumed over a representative cycle.

21. INTEGRATE WITH DIRECT PROCESS HEAT

Some systems deliver hot air, radiant heat or contact heat without producing steam. Direct integration can reduce exchanger loss while increasing process-specific engineering.

Define temperature uniformity, atmosphere, contamination, response and safety. A dryer, furnace or kiln can be sensitive to heat quality and flow. Pilot representative material and product.

Preserve production isolation and rollback. Process qualification can take longer than mechanical commissioning. Include trials, inventory and contribution margin at risk. Contract remedies should address product consequence as well as heat output.

22. BUILD THE COMPLETE CAPITAL BUDGET

Include storage modules, heaters, heat exchange, steam generation, power electronics, transformer, switchgear, grid works, piping, ducting, civil works, fire and safety systems, controls, metering, engineering, permits, commissioning and contingency.

Add site preparation and production impact. Brownfield access, foundations and tie-ins can dominate cost. Include owner engineering, training, spare parts and inventory build.

Separate committed quotations from allowances. Record currency, escalation, tax and schedule. Use stage-appropriate contingency based on technology maturity, site data and interface. Avoid presenting equipment price as total installed cost.

23. FORECAST OPERATING COST

Operating cost includes electricity, network and capacity charges, water, treatment, auxiliaries, maintenance, inspections, software, service agreements and component replacement. Deduct gas and boiler cost only where avoided.

Model charging losses, standing losses and unused heat. Apply availability and degradation. Include periodic insulation, heater, fan, pump, valve and control work.

Define staffing and specialist support. A service contract can transfer performance risk while adding indexation and counterparty exposure. Compare ownership and heat-as-a-service on the same life-cycle boundary.

24. CALCULATE LEVELISED COST OF HEAT

Levelised cost divides present-value capital and operating cost by present-value useful heat delivered. State horizon, discount rate, tax, degradation, replacement, residual value and heat boundary.

Show electricity, network, capital, maintenance and integration separately. Compare with gas, direct electric and other alternatives. Include retained backup and fixed connection costs.

Test electricity spread, charge hours, utilisation, efficiency, storage duration, grid capital and outage. Present breakeven values. NREL's industrial heat tools use levelised heat, net present value and capital as core decision metrics.[4]

25. BUILD THE DISCOUNTED-CASH-FLOW CASE

Translate thermal performance into after-tax cash. Include capital tranches, depreciation, tax, working capital, grants, electricity, gas savings, maintenance, flexibility revenue, production effects and residual value.

Apply construction and commissioning ramp. Separate contracted, indexed and merchant value. Power savings can vary by year and hour. Demand-response revenue can require performance.

Reconcile project cash to enterprise cash and budgets. Avoid counting avoided gas in both operating savings and product margin. Preserve model versions and sources. Update valuation as metering, engineering and contracts replace assumptions.

26. STRUCTURE OWNERSHIP

The factory can own the system, lease it, form a joint venture or buy heat as a service. Each choice affects capital, control, accounting, tax, security and termination.

Direct ownership captures operating value and requires technical capability. A service model can reduce upfront capital while creating a long-term fixed payment and provider-credit risk. A lease may separate equipment from integration.

Define site access, utility supply, operation, maintenance, metering, change control, insurance and removal. The contract should survive ownership changes and protect production. Obtain accounting, tax and legal advice for the specific structure.

27. DESIGN THE HEAT-SERVICE AGREEMENT

Specify useful heat, temperature, pressure, volume, availability and measurement boundary. Set price, indexation, minimum payment, performance adjustment and payment during outages. Define who supplies electricity and bears tariff risk.

Allocate charging and dispatch authority. The provider may optimise power while the factory controls production. Preserve minimum state of charge and emergency use. Define data access and cyber requirements.

Address change in law, grid curtailment, force majeure, termination and asset removal. Termination compensation should reflect debt and unavoidable cost while encouraging mitigation. Align service tenor with financing and site life.

28. FINANCE THE ASSET

Development equity funds metering, engineering, grid studies, permits and procurement. Construction capital can combine sponsor equity, vendor support, grants, equipment finance, corporate debt or project debt.

Financing depends on technology, completion, host credit and cash-flow structure. A behind-the-meter owner project can use corporate capacity. A heat-service company may use contracted payments and equipment security. First-of-a-kind systems can require sponsor support.

Stage commitments. Early works should have caps and exit points. Full investment approval should follow grid, contracts, engineering, contingency and operating plans. Preserve liquidity for ramp.

29. SIZE DEBT

Debt capacity follows cash available for debt service after electricity, operations, maintenance, sustaining capital, tax, working capital and reserves. Use the lender definition consistently.

Build base, downside and severe cases. Test electricity price shape, utilisation, efficiency, production, gas price, flexibility revenue, outage, capital and delay. Preserve correlations. A production slowdown can reduce heat use and energy savings together.

Shape amortisation to commissioning and contracts. A grace period supports ramp while increasing later burden. Tenor should not exceed credible site, service and power-contract life without a tested renewal case.

30. PROCURE PERFORMANCE EVIDENCE

Issue a common request for proposal with heat profile, temperature, site, tariff, grid and acceptance requirements. Ask for references at comparable temperature, duration, output and application.

Require a complete schedule of energy capacity, charge power, discharge power, efficiency, loss, availability, degradation, auxiliaries, footprint, safety, maintenance and exclusions. Reconcile bids to the same installed boundary.

Evaluate vendor balance sheet, service coverage, spares and warranty security. A lower equipment price can carry greater completion and lifecycle risk. Use independent technical review.

31. ALLOCATE COMPLETION RISK

Create an interface matrix across storage vendor, electrical contractor, utility, process engineer, factory and operator. One party should own integrated performance or the contracts should define resolution.

Set acceptance tests for energy capacity, charging, discharge, temperature, pressure, efficiency, availability, controls, safety and product quality. Test representative operation over multiple cycles.

Define delay, retest, cure and damages. Vendor damages may not cover lost production. Use contingency, insurance and sponsor capacity. Lenders can require support until sustained completion is certified.

32. FUND COMMISSIONING AND RAMP

Plan energisation, heating, drying, thermal cycling, control tuning, steam or process qualification and operator training. Initial cycles can differ from steady performance.

Fund electricity, temporary heat, technical support, product trials, maintenance and lost output. Maintain reserve beyond the expected date. Grid or production delays can create fixed cost before savings.

Use milestone payments with retention. Release final amounts after integrated tests and operating evidence. Preserve data for warranty and future sites. Update portfolio assumptions from measured ramp.

33. PROTECT PRODUCTION CONTINUITY

Prepare tie-in, bypass and rollback plans. Schedule work during planned outages where possible. Retain boiler or temporary heat during commissioning and evidence gathering.

Model lost contribution margin and customer impact. A short outage can exceed annual energy savings in a high-value process. Apply probability supported by engineering and construction plans.

Integrate the system into business continuity. Define response to power outage, control failure, depleted storage, grid curtailment, fire, water issue and cyber incident. Test manual fallback.

34. MANAGE SAFETY AND PERMITTING

Thermal batteries contain high-temperature materials and substantial stored energy. Hazards can include burns, pressure, fire, electrical fault, thermal expansion, material release and confined spaces.

Complete hazard analysis, zoning, fire protection, isolation, relief, ventilation and emergency planning. Apply relevant electrical, pressure, building, environmental and occupational requirements. Obtain specialist advice.

Design inspection and maintenance access. Train operators and emergency services. Record residual risks and insurance conditions. Safety systems belong in the capital, schedule and acceptance plan.

35. BUILD THE DATA AND CONTROLS LAYER

Meter electricity, charge energy, state of charge, thermal loss, discharge, useful heat, backup fuel and production. Capture temperature, pressure, flow and availability. Reconcile to invoices and the financial model.

Define ownership, cybersecurity, retention, calibration and audit. A service provider and factory can need different access. Preserve raw data and control history.

Use forecasting and optimisation within safe bounds. Detect degradation and anomalies. Human operators should understand recommendations and override. Data quality should support warranty, payment, carbon reporting and continuous improvement.

36. MEASURE EMISSIONS

Calculate displaced gas and incremental electricity using stated factors and boundaries. Distinguish location-based, market-based and marginal electricity methods where relevant. Include backup and losses.

Avoid describing contracted renewable attributes as physical zero-emissions supply without the accounting method. Customer and regulatory claims should follow applicable standards and assurance.

Run future-grid and dispatch scenarios. Charging during low-price hours can coincide with low or high marginal emissions depending on the system. Preserve cash and emissions cases separately. A project may deliver energy security or flexibility before it delivers the claimed emissions outcome.

37. APPLY MARKET BENCHMARKS CAREFULLY

Benchmark temperature, capacity, duration, charge power, efficiency, utilisation, installed cost and service model. Compare like boundaries. Vendor announcements can exclude grid, integration or operating evidence.

The IEA identifies emerging projects across food, beverages and other industries, including multi-megawatt-hour thermal-storage systems.[3] The United States Department of Energy supports demonstrations that combine thermal batteries, electric boilers and renewable power.[5] Selection or demonstration status is not proof of general commercial economics.

Use benchmarks to challenge assumptions, then rely on site engineering, tariffs and contracts. Label project announcements and estimates according to their evidence status.

38. APPLY SCENARIO ANALYSIS

Create central, downside and severe cases. Change electricity spreads, network charges, charge hours, utilisation, efficiency, duration, grid capital, gas price, production, flexibility revenue, schedule and support.

Calculate breakeven average charging price, minimum utilisation, maximum grid capital and required gas displacement. Present annual liquidity, debt coverage and covenant headroom. A project can have positive present value and weak early cash.

Use reverse stress testing. Identify the combination that exhausts contingency or reserves. Define management actions and lead time, including hybrid operation, revised dispatch, temporary gas or additional capital. Avoid assuming every action is available at once.

39. ESTABLISH GOVERNANCE

Assign owners for heat data, production, electrical, grid, procurement, finance, safety, controls and reporting. Define authority over dispatch, reserve, contingency, contracts and shutdown.

Maintain an assumption register with source, date, owner and range. Link the model to meter data, tariffs, studies and quotations. Preserve prior versions.

Require reapproval after material changes in heat load, temperature, electricity, grid, capital, duration, efficiency, production, support or financing. Record conflicts between energy optimisation and production authority.

40. USE STAGED INVESTMENT GATES

Gate one should establish the measured heat profile, counterfactual and initial technology screen. Gate two should complete concept design, grid assessment, tariff modelling, site layout and supplier engagement. Gate three should deliver front-end engineering, permits, binding bids, contracts and finance.

Final approval should require committed funding, cost and schedule confidence, completion tests, production-continuity plan, contingency and governance. Early works should be capped.

Post-commissioning gates should require measured heat, electricity, availability, product and cash. Release retention and approve replication only after evidence. Each gate should state decision owner and maximum new capital at risk.

41. BUILD THE IMPLEMENTATION ROADMAP

Start with metering and efficiency. Select one heat service with clear data and manageable production risk. Complete grid, tariff, technology and site work before procurement.

Use a pilot or first site to validate integration, controls, dispatch and commercial terms. Preserve backup and measure full-year performance where season matters. Standardise data and contracts for replication.

Sequence portfolio sites by heat fit, price spread, grid readiness, gas exposure and operating evidence. Avoid deploying identical capacity where profiles differ. Update the roadmap after each gate.

42. DECIDE WHEN THERMAL BATTERIES BEAT GAS

Thermal batteries are attractive where usable low-cost electricity can be captured, heat demand is predictable, charging and discharge fit the process, grid access is available and capital is utilised. They can also provide resilience, emissions reduction and gas-risk diversification.

Gas can remain competitive where it is inexpensive, grid capacity is constrained, electricity spreads are weak, heat is highly variable or required temperature and reliability are not supported. Hybrid operation can manage transition and peaks.

The decision should follow hourly delivered-heat economics and production risk. Management should show the counterfactual, system boundary, contract terms, downside and evidence. That converts a technology proposal into an investable factory-heat decision.

43. PREPARE PORTFOLIO REPLICATION

A successful first installation should create evidence that can be reused without assuming that every site is identical. Record the heat-demand profile, electricity prices, grid conditions, civil design, control logic, commissioning sequence, operating interventions and measured performance. Separate features that can be standardised from those that remain process-specific.

Create a common screening model for additional sites. Inputs should include heat temperature, annual and peak demand, interval load, gas and electricity tariffs, grid capacity, renewable access, footprint, production criticality, asset age and planned shutdowns. Use the model to identify sites that justify detailed engineering. A portfolio ranking should preserve the underlying values rather than reduce every decision to one score.

Standardise procurement where it supports value. Common technical schedules, metering, cybersecurity, warranties, spare parts and service arrangements can reduce cost and operating complexity. Retain site-specific heat exchangers, civil works, permits and qualification. Volume purchasing should follow verified demand and should not force equipment into unsuitable processes.

Coordinate deployment with energy procurement and grid planning. A portfolio can aggregate electricity demand and negotiate supply, while simultaneous charging can create new peaks. Model correlated production and renewable conditions across sites. The network or utility may require staged connections.

Govern replication through measured thresholds. Approve the next tranche only after the first site demonstrates useful heat, availability, efficiency, dispatch value, product quality and cash performance over a representative period. Update capital, schedule and operating assumptions using actual results. Preserve a stop, redesign or alternative-technology decision at every tranche.

Plan portfolio funding as a series of evidence-linked commitments. The first site may require more equity, contingency and vendor support because technology and integration evidence remain limited. Later sites can use standard contracts, measured performance and established operating procedures to support longer tenor or lower financing cost, subject to site-specific diligence. Keep project cash flows and security identifiable where lenders finance individual assets.

Aggregate procurement and financing only after checking concentration. A common vendor, control platform or electricity supplier can reduce cost and accelerate training, while exposing every site to the same defect, cyber event or counterparty failure. Preserve alternative supply, spare strategy and contractual step-in where the consequence is material. Portfolio governance should compare scale benefit with correlated risk before approving a framework agreement.

Use the portfolio to improve market evidence. Consolidated heat demand can support renewable-power procurement or grid discussions, and measured flexibility can support demand-response negotiation. Recognise revenue only when market eligibility and contracts are documented. Continue reporting useful heat, production and cash at site level so underperformance is visible rather than hidden by portfolio averages.

CONCLUSION

Industrial thermal batteries combine electrification, storage and process integration. Their value comes from converting electricity at favourable times into reliable heat at the factory's required time and quality. Storage capacity alone cannot establish the case.

Management should begin with measured heat, reduce avoidable demand, secure grid and power terms, compare full alternatives and retain backup during ramp. Contracts should align power, performance, heat service and debt. The financial model should use hourly dispatch and complete installed cost.

A staged programme can produce operating evidence before portfolio scale. The resulting framework allows owners, investors and lenders to identify where stored renewable heat can replace gas while protecting production, liquidity and long-term value.

DECISION EXHIBITS

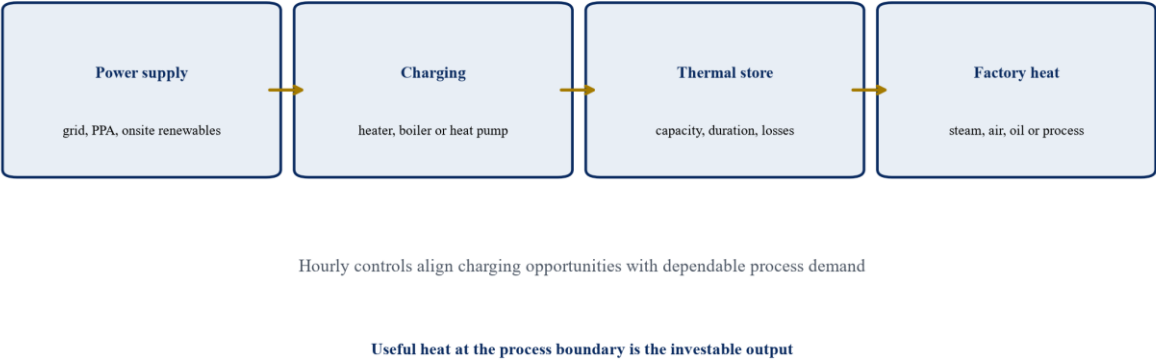


Figure 1. Industrial thermal-battery system map
Proposed decision architecture based on the sources and analysis in this paper.

Table 1. Industrial thermal-storage market benchmark

System	Typical service	Principal strength	Principal constraint
Hot-water storage	low-temperature water and cleaning	mature, simple and efficient	low temperature and large volume
Solid sensible heat	steam, hot air and higher-temperature duties	abundant media and long duration	heat exchange and footprint
Molten-salt storage	medium- to high-temperature heat	proven thermal practice in adjacent uses	freezing, corrosion and materials handling
Phase-change storage	narrow temperature applications	higher energy density and stable temperature	media cost and cycling evidence
Thermochemical storage	specialised high-density or long-duration service	low standing loss potential	maturity and process complexity

Proposed qualitative benchmark; site engineering and supplier evidence control.

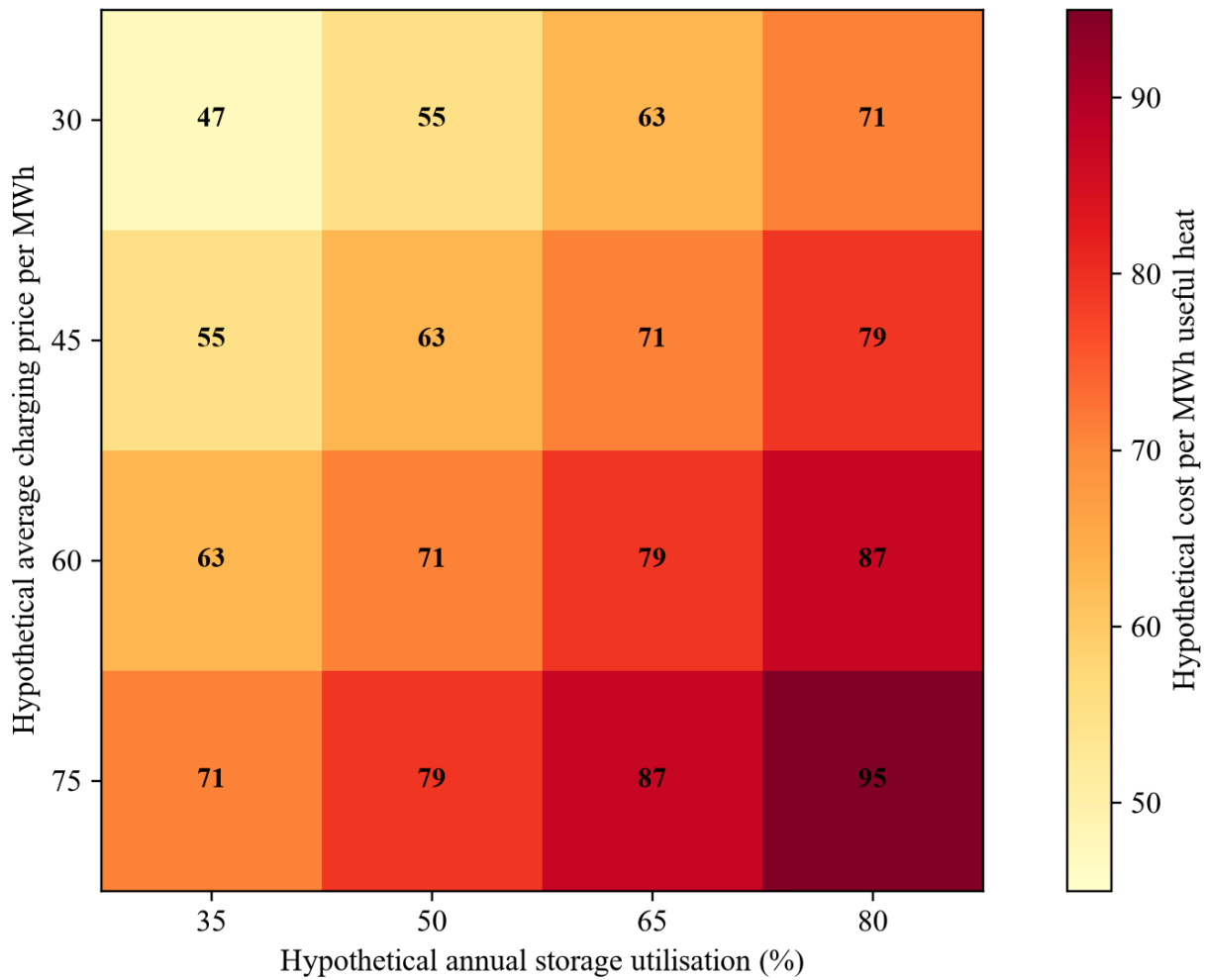


Figure 2. Hypothetical delivered-heat cost sensitivity
Wholly hypothetical; the values describe no identified company or project.

Table 2. Capital and operating sensitivity matrix

Exposure	Valuation effect	Evidence	Response
Electricity price shape	determines charging cost and dispatch	interval tariff, PPA and market history	portfolio procurement and control
Grid and charging power	determines capital, delay and refill rate	utility study and site electrical audit	secure capacity before final commitment
Storage utilisation	spreads fixed capital across delivered heat	hourly heat profile and production plan	size base service and stage modules
Thermal efficiency and loss	changes electricity per useful heat	guaranteed cycle and annual performance	meter boundary, retention and remedies
Production integration	creates completion and lost-margin risk	tie-in, bypass and qualification plan	retain backup and test representative cycles
Gas counterfactual	determines avoided cost and resilience value	delivered tariff and measured boiler performance	transparent scenarios and residual costs

Proposed framework; transaction-specific technical and commercial evidence is required.

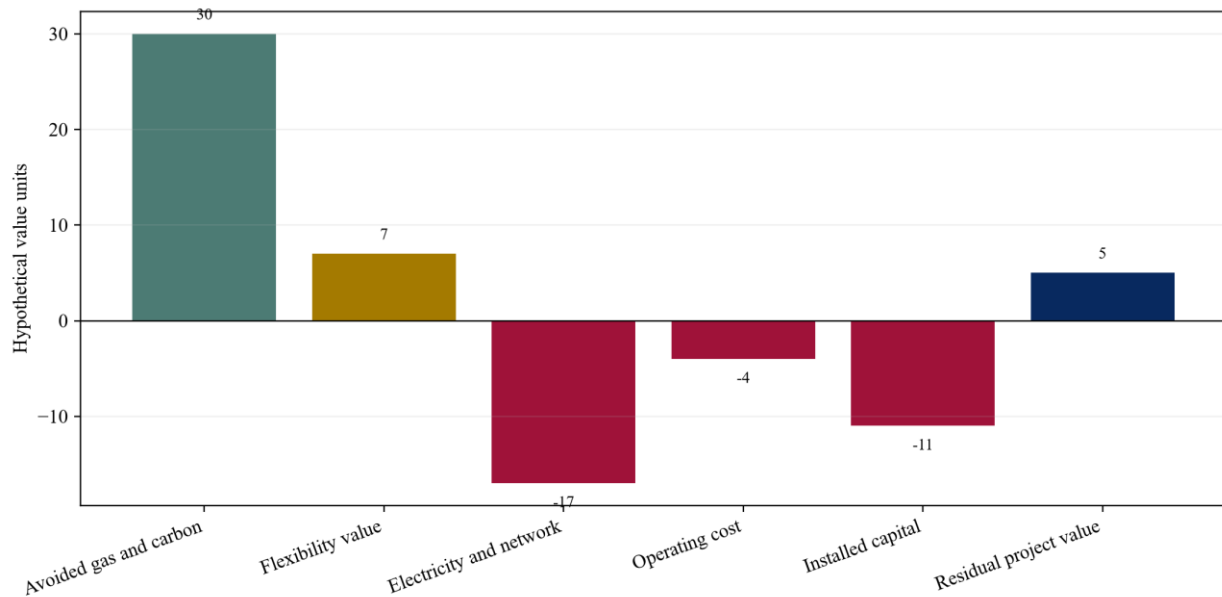


Figure 3. Hypothetical implementation value bridge
Wholly hypothetical; values describe no identified company or project.

Table 3. Implementation roadmap and investment gates

Gate	Minimum evidence	Maximum cumulative capital at risk	Decision
Heat baseline	reconciled hourly heat, counterfactual and production boundary	0.2%	select candidate service
Integrated concept	technology, grid, tariff, site and dispatch model	1.5%	approve front-end work
Bankable definition	engineering, permits, bids, contracts and finance model	5%	approve conditional commitments
Final investment	funding, grid, contingency, completion and continuity plan	100%	issue notice to proceed
Acceptance	measured heat, electricity, availability and product quality	retained capital	release support or require cure
Portfolio scale	operating history and updated site economics	next programme budget	replicate, redesign or stop

Proposed governance framework; percentages are hypothetical caps on cumulative capital at risk.

APPENDIX A QUESTIONS FOR THE INVESTMENT COMMITTEE

1. Which useful heat service and process boundary are being valued?
2. Which hourly heat profile supports energy, charge-power and duration sizing?
3. Which electricity prices, network charges and contract terms support charging?
4. Which grid capacity and connection schedule are confirmed?
5. Which storage mechanism has evidence at the required temperature, duration and scale?

6. How do charge, hold and discharge losses affect annual useful heat?
7. Which backup remains, and which fixed gas costs continue?
8. How are production continuity, qualification and lost margin protected?
9. Which flexibility revenues are contracted and compatible with heat reserves?
10. What minimum utilisation and maximum charging price protect debt service?
11. Which party controls dispatch, performance data and remedies?
12. What evidence triggers each capital commitment and reapproval?

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