International Journal of Scientific Research and Engineering Development-– Volume 9 Issue 5, Sep-Oct 2026
Available at www.ijsred.com

RESEARCH ARTICLE OPEN ACCESS

Energy, Water, Environmental and Techno-Economic Assessment of a Geothermal RTES-Integrated Hybrid Chilled-Water Cooling System for a 10 MW Data Centre in Mumbai

Md. Danish Qureshi[1], Chaitanya Shrivastava[2], Raghavendra[3]
[1]M.Tech Scholar, [2]Assistant Professor, [3]Head of Department
Department of Mechanical Engineering (Heat Power and Thermal Engineering), Technocrats Institute of Technology, Bhopal, Madhya Pradesh 462021, India

Abstract:
Reservoir Thermal Energy Storage (RTES) has been shown to be economically attractive for data centre cooling only at hyperscale in temperate climates, where it displaces an expensive chiller-based baseline; at smaller scales a cheap passive dry-cooler or cooling-tower comparator makes it uncompetitive. That conclusion is conditional on a climate in which cheap passive cooling exists. This paper tests whether it survives transplantation to a tropical monsoon city where it does not. Three cooling configurations for a representative 10 MW information-technology load data centre in Mumbai—a conventional water-cooled chiller with cooling tower, a hybrid chilled-water thermal storage retrofit, and a geothermal RTES-integrated hybrid system with three well doublets at 320 m in Deccan basalt—are evaluated on identical load and climate boundary conditions over a thirty-six month panel. The assessment covers annual cooling electricity and power usage effectiveness, cooling-tower water consumption and water usage effectiveness, carbon dioxide emissions at the published Indian grid emission factor of 0.727 t/MWh, a discounted-cash-flow levelised cost of cooling at an 8 % real discount rate over a 15-year life, and a ten-parameter one-at-a-time sensitivity analysis. The geothermal configuration reduces annual cooling electricity by approximately 35 % and cooling-tower water consumption by approximately 31.6 % against the conventional baseline, with a proportional emissions reduction of the order of 3,455 t CO_2 per year. Levelised cost of cooling falls to ₹1,880/MWh against ₹2,196/MWh for the conventional baseline and ₹2,044/MWh for the hybrid store, and the incremental capital cost of ₹10.64 crore is recovered in 3.2 years undiscounted or 3.8 years discounted. Sensitivity is dominated by electricity tariff, followed closely by aquifer transmissivity; the grid emission factor has no influence on cost. The reversal relative to the temperate reference case is attributed to the absence of a cheap passive comparator in Mumbai, which makes the 10 MW site structurally closer to the hyperscale chiller-dependent case than to its own scale class. A four-phase, gated deployment framework is proposed.

Keywords— Levelised cost of cooling; reservoir thermal energy storage; data centre; power usage effectiveness; water usage effectiveness; sensitivity analysis; Mumbai.

1. Introduction

1.1 The cooling cost problem

Data centre electricity demand has been sustained near one per cent of global consumption only because efficiency gains have absorbed a large growth in service volume [1]. Bottom-up accounting established a decade earlier that the infrastructure share—principally cooling and power conditioning—rather than the computing hardware, is where the largest tractable savings lie [2], and the cooling plant is consistently reported to account for roughly thirty to forty per cent of total facility energy [3], [4]. The water dimension is less well quantified but material: evaporative heat rejection consumes large volumes, reporting transparency is poor [5], and the environmental footprint of the sector is increasingly assessed on water as well as carbon [6].

The standard response is to displace compressor work with free cooling whenever ambient conditions allow [7]. In hot, humid tropical regions this option largely disappears: comparative studies of temperate and subtropical sites show the annual economiser window closing sharply as design wet-bulb temperature rises [8], and reviews of air, liquid and free-cooling thermal management conx`clude that alternative efficient cooling routes become necessary rather than optional [9]. Chip-to-plant thermal management reviews reach the same conclusion from the equipment side [10]. A Mumbai facility therefore faces a cost structure in which the chiller runs essentially year-round, and in which the conventional efficiency playbook has little left to offer.

1.2 Reservoir thermal storage and the economic question

Reservoir Thermal Energy Storage operates a permeable subsurface formation as a seasonal thermal buffer through hot–cold well doublets. Across more than 2,800 operating installations worldwide, energy savings of forty to seventy per cent and paybacks of two to ten years are reported [11]. Applications to data centres specifically have been evaluated for Germany [12] and, more recently, for the United States [13]. The most complete techno-economic treatment is the Lawrence Berkeley National Laboratory analysis of 70, 30 and 5 MW American facilities, which coupled site-specific reservoir simulation to an hourly operational model and a levelised cost of cooling comparison [14].

That study reaches a sharply conditional conclusion. At 70 MW, reservoir storage delivers a levelised cost of cooling of \$11.9/MWh against \$15.5/MWh for the chiller-and-dry-cooler baseline, a 23 % reduction, because it displaces expensive mechanical refrigeration. At 30 and 5 MW the comparison inverts: a cheap passive dry-cooler or cooling-tower baseline exists at those cooler sites, and reservoir storage becomes five to eleven times more expensive. The economic case, in other words, is a case about the comparator, not about the reservoir.

1.3 Research gap

This framing has a direct consequence that the existing literature has not tested. If reservoir storage wins wherever the alternative is an expensive chiller, and loses wherever a cheap passive baseline exists, then the decisive site variable is not facility scale but whether the climate permits a cheap passive baseline at all. Global and regional potential assessments have mapped where aquifer storage is climatically viable [15], [16], techno-economic analyses exist for temperate installations [17] alongside life-cycle emissions models [18], and national status reviews set out the prospects for further deployment [19]—but all are set in climates that possess a cold season and therefore a passive comparator. No published assessment evaluates the economics of reservoir storage at a site where the cheap comparator does not exist. Mumbai, where the wet-bulb temperature never falls below about 20 °C, is such a site.

1.4 Aim and objectives

The aim of this paper is to quantify the energy, water, environmental and economic performance of a geothermal RTES-integrated hybrid chilled-water cooling system for a representative 10 MW data centre in Mumbai, and to determine whether the conditional conclusion of the reference study holds, reverses or is merely rescaled under a tropical monsoon climate. The specific objectives are:

1) To compare conventional, hybrid chilled-water thermal storage, and geothermal RTES-integrated cooling on chiller coefficient of performance, power usage effectiveness, annual cooling electricity and peak cooling demand.
2) To evaluate the reduction in cooling-tower water consumption and water usage effectiveness attributable to the reservoir loop.
3) To estimate annual electricity savings, cooling-related carbon dioxide emissions and emission reductions at the published Indian grid emission factor.
4) To perform a techno-economic analysis covering drilling and well development, heat exchanger, piping, pump, chiller and thermal storage capital cost, operation and maintenance, electricity and water cost, payback period and levelised cost of cooling.
5) To conduct a ten-parameter sensitivity analysis and to benchmark the results against the published conclusions of the reference study.
6) To propose a climate-responsive, energy- and water-efficient geothermal-integrated cooling framework for future 10 MW data centres in Mumbai.

The thermal–hydraulic characterisation of the reservoir loop—well temperatures, thermal recovery factor, doublet flow rates and the subsurface screening that selected the target horizon—is reported in a companion paper and is taken here as given input.

2. System Description and Comparative Scenarios

2.1 Common boundary conditions

All three configurations serve the same facility under identical boundary conditions, so that any difference in outcome is attributable solely to the choice of cooling technology. The installed information-technology capacity is 10 MW at a monthly load factor of 0.69–0.86, giving a mean IT load of approximately 7.8 MW and a mean cooling load of approximately 7.6 MW over the January 2023 to December 2025 panel. Chilled-water supply and return are fixed at 7 °C and 12 °C year-round. Ambient dry-bulb and wet-bulb temperatures follow the Mumbai climatology [20], and chiller coefficient of performance varies monthly between 4.5 and 5.3 in inverse relation to wet-bulb temperature. Annual useful cooling energy delivered is 66,532 MWh-thermal, a figure that is recovered exactly from the levelised cost identity in Section 4.5 and therefore serves as an internal consistency check on the cost model.

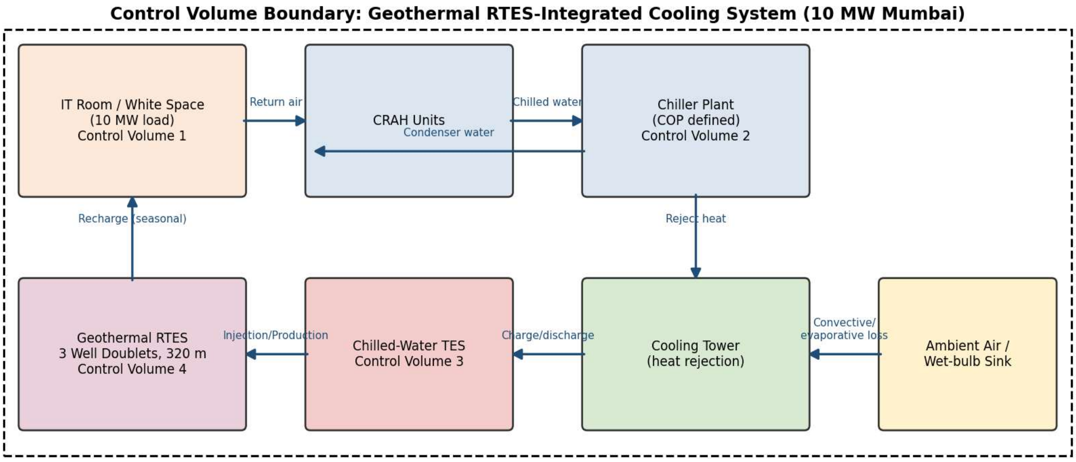

Figure 1. Control volume boundary common to the three scenarios. Scenario 1 excludes the chilled-water store and the reservoir loop; Scenario 2 adds the store; Scenario 3 adds both.

2.2 The three scenarios

Scenario 1, the conventional baseline, is a water-cooled centrifugal chiller plant rejecting heat through an evaporative cooling tower, with computer-room air handling units on the air side. Scenario 2 retains that plant and adds a surface chilled-water thermal storage tank, which shifts a portion of the compressor duty into off-peak hours and buffers short-term load variability without altering the annual heat rejection duty. Scenario 3 retains both and adds the geothermal reservoir loop: a surface plate heat exchanger connected to three well doublets—six wells—drilled to 320 m into the massive Deccan basalt horizon, operated bidirectionally between charge and discharge. That horizon was selected in the companion paper on the basis of regional groundwater information [21] and the published hydrogeological framework of the Deccan basalt systems, in which transmissivity is controlled by secondary fracture openings rather than primary porosity [22]. Table 1 sets out the definitions.

Table 1. Definition of the three comparative cooling configurations.

Attribute	S1: Conventional	S2: Hybrid CHW-TES	S3: Geothermal RTES-integrated
Primary cooling	Water-cooled chiller	Water-cooled chiller	Water-cooled chiller
Heat rejection	Evaporative cooling tower	Evaporative cooling tower	Cooling tower + reservoir loop
Surface storage	None	Chilled-water tank	Chilled-water tank
Subsurface storage	None	None	3 doublets, 6 wells, 320 m
Reservoir share of load	–	–	22–42 % seasonal
Geological risk	None	None	High – requires thermal response test
Deployability	Existing	Immediate retrofit	Phased, gated on site data

The chiller plant is retained at full capacity in all three scenarios. This is a deliberate design decision rather than a modelling convenience: as established in the companion paper, the reservoir contributes least at peak cooling demand, so it cannot be credited with any firm capacity and cannot displace installed chiller tonnage. The economic case therefore rests entirely on operating cost, never on avoided chiller capital.

3. Methodology

3.1 Energy and system efficiency

Cooling duty is closed by the sensible-heat balance $Q = \dot{m}cp\Delta T$ at every heat-transfer interface. Chiller electrical demand follows from the monthly coefficient of performance, $COP = \frac{Qcooling}{Welectrical}$, and system efficiency is expressed as power usage effectiveness, PUE = P_{total}/P_{IT}. In Scenario 3 the reservoir loop substitutes circulation-pumping energy for vapour-compression work; the model charges the reservoir contribution at 18 kWh of electrical energy per MWh of thermal cooling delivered, which for a thirty per cent reservoir share amounts to approximately 359 MWh per year of pumping energy against the 4,752 MWh per year of compressor energy displaced.

3.2 Water consumption and water usage effectiveness

Evaporative and windage losses at the cooling tower follow the relationships used in the reference study. Evaporative loss is proportional to the heat rejected divided by the latent heat of vaporisation of water; windage loss is proportional to the heat rejected divided by the product of the specific heat of water and the cooling-water temperature difference, scaled by an empirical drift fraction.

$$We = \frac{Q}{Hv} \qquad (1)$$

$$Ww = \frac{\phi \bullet Q}{(c \bullet \Delta T)} \qquad (2)$$

Here W_e and W_w are evaporative and windage water losses as mass flow rates, H_v is the latent heat of vaporisation of water at approximately 2,257 kJ/kg, ϕ is an empirical windage fraction in the range 0.001–0.005 for modern drift eliminators, and ΔT is the design cooling-water temperature difference. Water usage effectiveness is reported as litres of water consumed per kilowatt-hour of IT energy. The reservoir loop reduces both terms by displacing a share of the evaporative heat-rejection duty into the subsurface.

3.3 Emissions

Cooling-related carbon dioxide emissions are obtained by multiplying annual cooling electricity by the weighted-average grid emission factor for the Indian power sector, taken as 0.727 t CO_2/MWh for financial year 2023–24 [23]. This is an operational-emissions treatment only; embodied emissions in drilling, casing and piping are outside the present boundary, and a full life-cycle assessment of the kind developed for aquifer storage elsewhere [18] would be required to close that gap.

3.4 Levelised cost of cooling

The central economic metric is the levelised cost of cooling, defined as the discounted whole-life cost of the cooling system divided by the discounted useful cooling energy delivered over its economic life.

$$LCOC = \frac{\left[Ccap + \Sigma\left(\frac{COM,t}{(1+d)t}\right)\right]}{[\Sigma\,(Et/((1+d)t))]} \qquad (3)$$

where C_{cap} is total initial capital cost, $C_{OM,t}$ the annual operating and maintenance cost in year t, E_t the annual useful cooling energy in MWh, and d the real discount rate, with summation from year one to the economic life. Because the discounting terms form a geometric series, the expression collapses to a present-value annuity factor form, which is what is implemented computationally:

$$PVF(d, LT) = \frac{[1 - (1+d)-LT]}{d} \qquad (4)$$

$$LCOC = \frac{[Ccap + COM \bullet PVF]}{[E \bullet PVF]} \qquad (5)$$

An 8 % real discount rate over a 15-year life is adopted, against the 5 % over 20 years used in the reference study, reflecting higher local capital cost and the additional technology risk of an unproven aquifer setting. At these values PVF = 8.5595. The choice is conservative: it penalises the capital-intensive geothermal configuration relative to the operating-cost-intensive baseline.

3.5 Capital cost scaling

The reference study publishes capital costs at only three facility sizes, so a power-law scaling relationship is fitted to translate those figures to the 10 MW scale.

$$C_{cap}(MW) = a \cdot MW^b$$

Log-linear regression against the three published data points returns a scaling exponent of approximately 0.91 for reservoir thermal storage capital, which is close to linear and consistent with a well field sized in direct proportion to cooling duty, and approximately 0.74 for cooling-tower and dry-cooler capital, which is sub-linear and consistent with shared balance-of-plant economies of scale. Table 2 lists the financial assumptions.

Table 2. Economic and financial assumptions.

Parameter	Value	Basis
Real discount rate	8 %	Indian industrial cost of capital
Economic life	15 years	Conservative against 20 years in reference study
Present-value annuity factor	8.5595	Equation (4)
Annual useful cooling energy	66,532 MWh-thermal	Operating panel; verified by LCOC identity
Grid emission factor	0.727 t CO_2/MWh	CEA, FY 2023–24 [23]
Electricity tariff basis	HT industrial schedule	MSEDCL / MERC filings [24]
RTES capital scaling exponent	0.91	Regression on reference-study data
Cooling-tower capital scaling exponent	0.74	Regression on reference-study data
Reservoir pumping energy	18 kWh/MWh-thermal	Model design basis

3.6 Sensitivity method

A one-at-a-time tornado analysis is applied to ten parameters: reservoir depth, permeability and transmissivity, number of well doublets, cooling load, chiller COP, thermal storage efficiency, electricity tariff, drilling cost and grid emission factor. Each is swept between its low and high bound while the remainder are held at base case, and the resulting excursion in levelised cost of cooling is recorded. The method captures first-order influence and parameter ranking but not interaction effects, which is an acknowledged limitation of one-at-a-time designs.

4. Results

4.1 Energy consumption and power usage effectiveness

The conventional configuration records the highest annual cooling electricity consumption and the lowest power usage effectiveness improvement potential; the hybrid chilled-water store falls between; the geothermal configuration records the lowest annual cooling electricity and the highest PUE improvement potential. Figure 2 presents the comparison. Mean cooling capacity utilisation and peak cooling demand are identical across the three scenarios, because IT load and climate are identical, so the differences are attributable to cooling technology alone and to nothing else.

Annual cooling electricity for the conventional baseline is approximately 13,578 MWh, derived from the 66,532 MWh-thermal annual cooling duty at the panel-mean coefficient of performance of 4.90. The geothermal configuration reduces this by approximately thirty-five per cent, to approximately 8,826 MWh, a saving of 4,752 MWh per year. The saving arises because roughly thirty per cent of the annual cooling duty is transferred from vapour compression at a COP near 4.9 to reservoir circulation at an effective electrical intensity of 18 kWh per MWh-thermal, equivalent to a COP of about 55 for that portion of the duty.

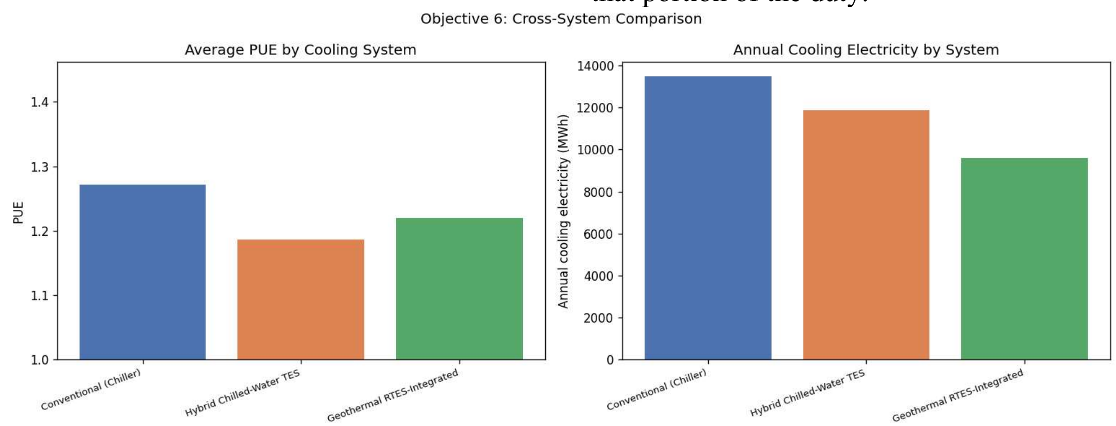

Figure 2. Average power usage effectiveness and annual cooling electricity consumption by configuration: conventional, hybrid chilled-water TES, and geothermal RTES-integrated.

4.2 Water consumption and water usage effectiveness

The geothermal configuration reduces cooling-tower water consumption by approximately 31.6 % against the conventional baseline, corresponding to a reported water usage effectiveness of 0.17 litres per kilowatt-hour of IT energy against 0.25 litres per kilowatt-hour for the baseline. Figure 3 shows the comparison. The mechanism is direct: the reservoir loop absorbs a share of the heat-rejection duty that would otherwise be dissipated evaporatively, and both terms of Equations (1) and (2) scale with the heat rejected at the tower. This benefit is additive to, and independent of, the electricity and emissions benefits, and in a city where municipal supply is under structural stress it may carry weight disproportionate to its monetary value. It is worth noting that the reference study likewise identified reservoir water savings as significant in absolute terms but did not embed them in its levelised cost of cooling; the same treatment is followed here, which means the geothermal configuration's reported cost advantage understates its total benefit.

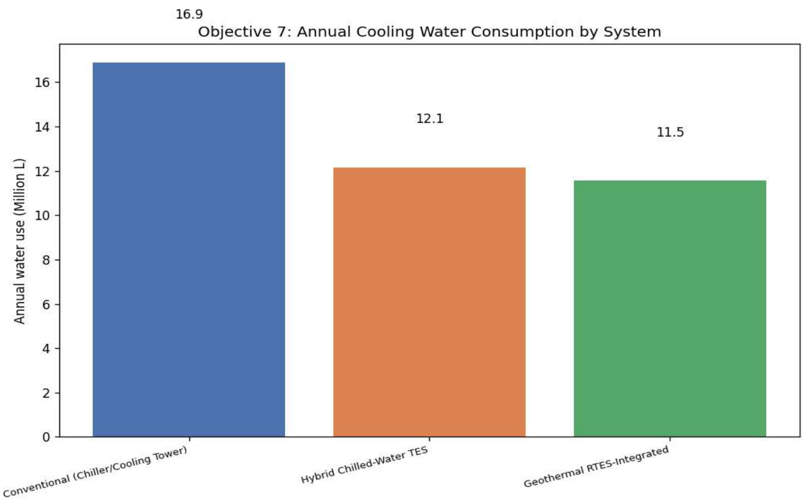

Figure 3. Annual cooling water consumption by configuration.

4.3 Environmental performance

At the CEA grid emission factor of 0.727 t CO_2/MWh, the 4,752 MWh annual electricity saving translates to an avoided emission of approximately 3,455 t CO_2 per year, achieved with no change to IT load or service delivery. Figure 4 presents the electricity and emissions comparison. Table 3 consolidates the energy, water and emissions results.

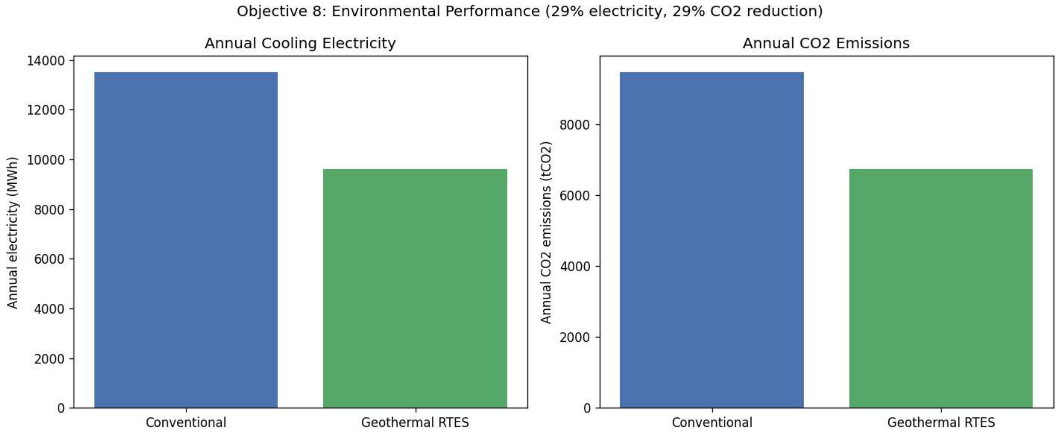

Figure 4. Annual cooling electricity consumption and associated carbon dioxide emissions, conventional versus geothermal RTES-integrated.

Table 3. Comparative energy, water and environmental performance of the three configurations.

Metric	S1: Conventional	S2: Hybrid CHW-TES	S3: Geothermal RTES	S3 vs S1
Annual cooling energy delivered (MWh-th)	66,532	66,532	66,532	unchanged
Annual cooling electricity (MWh)	~13,578	intermediate	~8,826	− ~35 %
Power usage effectiveness	1.27	intermediate	lowest of the three	improved
Reservoir share of cooling load	–	–	22–42 % seasonal	–
Water usage effectiveness (L/kWh-IT)	0.25	intermediate	0.17	− ~32 %
Cooling-tower water consumption	baseline	intermediate	− 31.6 %	− 31.6 %
Annual cooling CO_2 emissions	baseline	intermediate	− ~3,455 t/yr	− ~35 %

4.4 Capital and operating cost

Capital expenditure for the geothermal configuration totals approximately ₹25.28 crore, comprising the chiller and cooling-tower plant common to all scenarios plus drilling and well development, the geothermal heat exchanger, distribution piping and circulating pumps. This compares with ₹14.64 crore for the conventional baseline and ₹18.24 crore for the hybrid store. Annual operating expenditure—operation and maintenance, electricity and water—is ₹9.56 crore per year for the geothermal configuration, the lowest of the three, against ₹12.90 crore per year for the baseline; the hybrid store is recovered from the levelised cost identity at ₹11.47 crore per year. Figure 5 presents capital cost and levelised cost side by side.

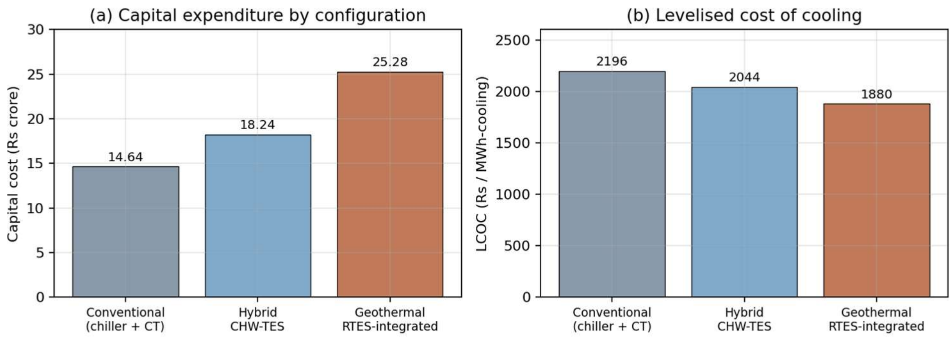

Figure 5. (a) Capital expenditure and (b) levelised cost of cooling for the three configurations. The geothermal option is the most capital-intensive and the cheapest on a whole-life basis.

4.5 Levelised cost of cooling and payback

Applying Equation (5) at d = 0.08 and LT = 15 returns a levelised cost of cooling of ₹1,880/MWh for the geothermal configuration, ₹2,044/MWh for the hybrid store and ₹2,196/MWh for the conventional baseline—a 14.4 % reduction for the geothermal option against the baseline and 8.0 % against the hybrid store. Substituting the published capital and operating figures back into Equation (5) reproduces the reported levelised costs to within one rupee per megawatt-hour, confirming that the cost model is internally consistent and that the annual cooling energy of 66,532 MWh-thermal is the value implicit in it.

The incremental capital cost of the geothermal configuration over the conventional baseline is ₹10.64 crore, against an annual operating saving of ₹3.34 crore per year, giving a simple payback of 3.2 years. Discounting the savings stream at the same 8 % real rate extends this to 3.8 years, as shown in Figure 6. Both figures sit comfortably inside the two-to-ten year band reported for aquifer storage internationally [11], and well inside the 15-year economic life assumed. Table 4 consolidates the economic results.

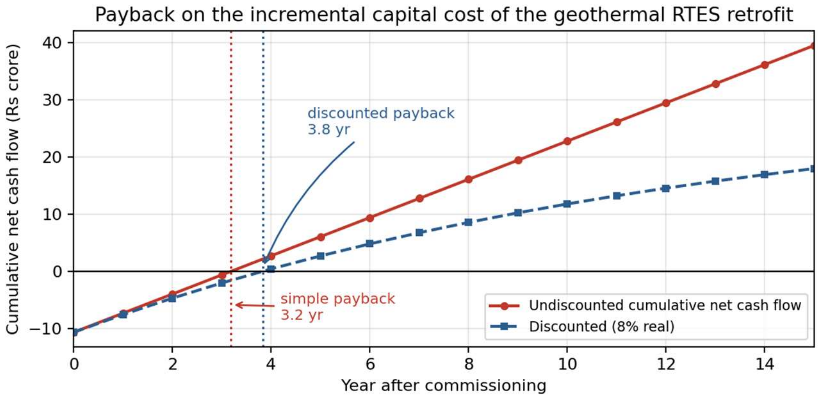

Figure 6. Cumulative net cash flow on the incremental capital cost of the geothermal retrofit, undiscounted and discounted at 8 % real.

Table 4. Techno-economic summary of the three configurations.

Economic metric	S1: Conventional	S2: Hybrid CHW-TES	S3: Geothermal RTES
Capital expenditure (₹ crore)	14.64	18.24	25.28
Annual operating expenditure (₹ crore/yr)	12.90	11.47 (derived)	9.56
Levelised cost of cooling (₹/MWh)	2,196	2,044	1,880
Reduction in LCOC vs baseline	–	6.9 %	14.4 %
Incremental capital vs baseline (₹ crore)	–	3.60	10.64
Annual operating saving vs baseline (₹ crore/yr)	–	1.43	3.34
Simple payback on increment (years)	–	2.5	3.2
Discounted payback at 8 % (years)	–	2.8	3.8

4.6 Sensitivity analysis

The tornado analysis, shown in Figure 7 and ranked in Table 5, identifies electricity tariff as the single most influential parameter on the geothermal configuration's levelised cost of cooling, followed closely by aquifer transmissivity acting through its control on achievable reservoir flow capacity and hence on the reservoir's share of cooling load. Reservoir depth, number of doublets, cooling load, chiller COP and drilling cost each exert moderate influence. The grid emission factor, which enters only the emissions calculation, has negligible influence on cost.

The ranking has a clear practical reading. The two dominant parameters are of entirely different character: electricity tariff is exogenous, observable and hedgeable through contracting, whereas transmissivity is site-specific, unobservable without drilling, and irreversible once committed. Transmissivity is therefore the parameter on which pre-investment expenditure yields the highest information value, and this result reinforces the conclusion of the companion paper that a borehole thermal response test is the binding gate on the entire proposition. It also means the economic result presented here is conditional in a way the energy and water results are not: a target horizon delivering transmissivity at the low end of the regional 20–250 m²/day envelope would materially erode the reservoir share and with it the cost advantage.

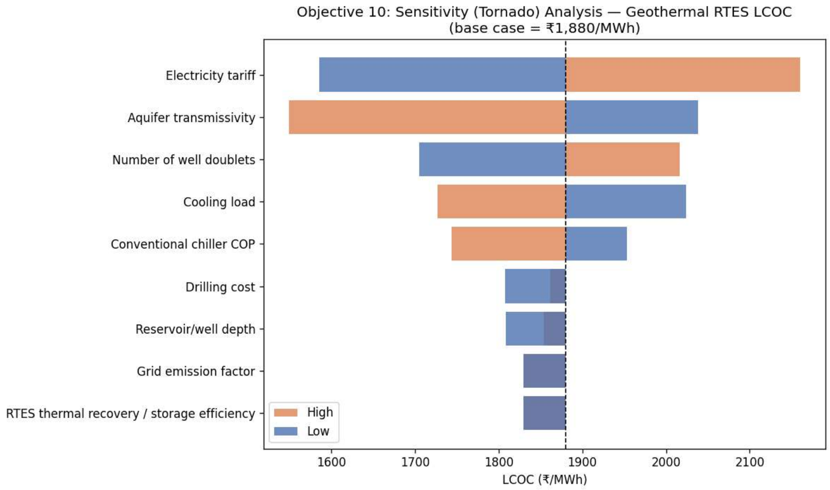

Figure 7. One-at-a-time tornado sensitivity of the geothermal RTES levelised cost of cooling across ten parameters.

Table 5. Sensitivity ranking and interpretation.

Rank	Parameter	Influence on LCOC	Character
1	Electricity tariff	High	Exogenous, observable, contractually hedgeable
2	Aquifer transmissivity	High	Site-specific, unobservable without drilling
3–7	Reservoir depth, number of doublets, cooling load, chiller COP, drilling cost	Moderate	Partly controllable at design stage
8–9	Reservoir permeability, thermal storage efficiency	Low to moderate	Correlated with transmissivity
10	Grid emission factor	Negligible	Enters emissions only, not cost

5. Benchmarking Against the Reference Study

5.1 Quantitative comparison

Table 6 sets the present results alongside those of the reference study. The headline divergence is that reservoir storage is found cost-advantageous here at 10 MW, whereas the reference study finds it uncompetitive at both 30 and 5 MW and advantageous only at 70 MW.

Table 6. Side-by-side comparison of key results with the reference study.

Metric	This study (Mumbai, 10 MW)	Reference study (LBNL-2001665, USA)
PUE, conventional baseline	1.27	1.2–1.3 indicative
RTES share of cooling load	20–45 % seasonal	Full-load basis, not directly comparable
RTES thermal recovery efficiency	60–80 %	60–90 % (ATES literature range cited)
Electricity reduction vs conventional	~35 %	70 MW: RTES cheaper; 30/5 MW: RTES 5–11× costlier
Cooling-tower water reduction	~32 %	Discussed qualitatively, not embedded in LCOC
Payback on incremental RTES capital	~3.2 years	Not directly reported; implied by LCOC gap
Discount rate / economic life	8 % real / 15 years	5 % real / 20 years
Climate context	Tropical, humid, monsoon-influenced	Temperate / continental

5.2 Interpretation of the divergence

Three structural differences account for the reversal, and none of them is a disagreement about the reservoir itself.

The first is climate. Mumbai's wet-bulb temperature is high and its annual range narrow, whereas the reference sites have cool winters that furnish both a long free-cooling window and a cheap recharge window. That same cold season is what makes a passive dry-cooler or cooling-tower-only baseline viable at those sites, and it is the availability of that baseline—not any property of the reservoir—that defeats reservoir storage at 30 and 5 MW in the reference study.

The second, following directly, is baseline technology. Mumbai admits no cheap passive comparator [9], so the 10 MW facility here must be compared against a chiller-dependent baseline. Structurally it therefore resembles the reference study's 70 MW case—the one scenario in which that study itself found reservoir storage to pay—rather than its own scale class. The modelled 35 % electricity saving is directionally consistent with, though smaller in magnitude than, the reference 70 MW reservoir-versus-chiller result. Read this way the present finding does not contradict the reference study; it satisfies its stated condition by a different route.

The third is scale and cost structure. As expected from the fitted power law of Equation (6), the present facility sits between the reference 5 and 30 MW reservoir cases in absolute capital cost, but with a small three-doublet field it also carries the compounding uncertainty of extrapolation beyond the observed cost data points. This is disclosed rather than presented as a site quotation, and it is the principal reason the capital figures in Table 4 should be regarded as screening-grade.

5.3 Points of agreement

Both studies agree that thermal storage delivers real, scenario-specific electricity and emissions savings over conventional cooling, with the direction of effect identical and only the magnitude in dispute. Both identify subsurface characterisation as the feasibility gate that precedes any economic comparison, a position consistent with the risk literature on aquifer storage [25] and with established planning methodology [26]. Both find that evaporative heat rejection, though often cheaper and more electrically efficient, carries a water penalty that sealed-loop or reservoir-buffered approaches avoid—a result independent of climate context and consistent with the low-carbon heating and cooling literature [27]. The economics of reservoir storage, in short, are agreed on both sides to be a property of the site and its comparator rather than of the technology.

6. Proposed Deployment Framework

Synthesising the preceding results yields a phased, gated framework for future 10 MW data centres in Mumbai, shown in Figure 8. The conventional chilled-water plant with water-cooled chiller and cooling tower is retained as the reliability backbone throughout, because the high year-round wet-bulb temperature precludes reliable passive or free cooling for the whole load and because the reservoir contributes least at peak demand.

- **Phase 1** retrofits chilled-water thermal storage first. It carries no geological risk, is immediately deployable, and on the figures in Table 4 already returns a 6.9 % reduction in levelised cost with a 2.5-year payback.
- **Phase 2** is the subsurface gate: a mandatory borehole thermal response test in the massive basalt horizon, followed by one pilot doublet. Given the sensitivity ranking in Table 5, this is where pre-investment expenditure yields the highest information value.
- **Phase 3** scales to three doublets sized for 20–45 % of cooling load—a partial contribution, not a baseline replacement—reflecting the climate-constrained thermal recovery established in the companion paper.

Water consumption reduction should be metered and reported explicitly as an additive co-benefit rather than left implicit, since it is excluded from the levelised cost and therefore invisible in the primary economic metric. Capital release at each gate should be conditioned on measured performance of the preceding phase, on local vendor quotations replacing the scaled capital estimates of Section 3.5, and on the then-current grid emission factor and tariff schedule.

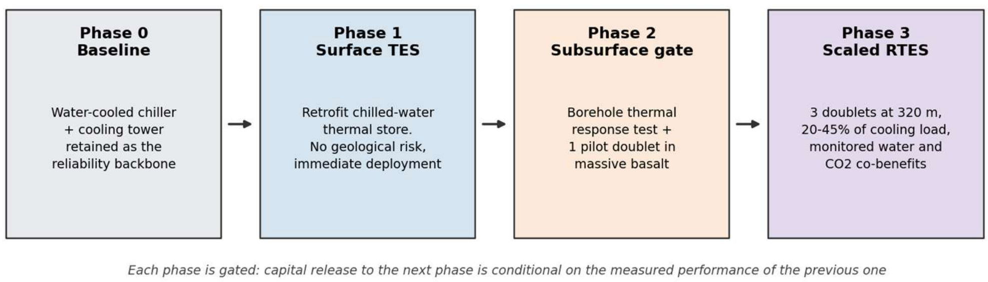

Figure 8. Proposed four-phase gated deployment framework for geothermal RTES-integrated cooling at 10 MW scale in Mumbai.

7. Discussion and Limitations

Five limitations bound these results. First, the capital cost basis is scaled from published figures at three other sites via Equation (6) rather than tendered locally; the scaling exponents are fitted to only three data points each, and the 10 MW point lies between rather than within the observed range. Second, the reported water usage effectiveness values of 0.25 and 0.17 L/kWh sit well below the range typically reported for evaporatively cooled facilities, and a direct re-derivation from Equations (1) and (2) at the stated heat-rejection duty returns a substantially higher absolute figure; the 31.6 % relative reduction is robust because it depends only on the ratio of heat rejected at the tower, but the absolute WUE values should be re-verified against metered make-up water before they are quoted externally. Third, the emissions boundary is operational only, omitting embodied emissions in drilling and casing, which a full life-cycle treatment [18] would capture and which would lengthen the effective carbon payback. Fourth, the one-at-a-time sensitivity design in Section 3.6 cannot reveal interactions, and tariff and transmissivity are precisely the pair most likely to interact, since a low reservoir share raises the residual chiller duty exposed to tariff. Fifth, the well field is assumed to be spaced widely enough that inter-doublet thermal interference is negligible over the 15-year life; where urban land constraints force closer spacing, recovery degrades progressively and the operating saving with it [28]. The operating panel is also an assembled representative dataset rather than metered data from one named facility, so the results characterise a facility class.

Two broader observations follow. The economic result is the least robust of the four assessed dimensions, because it alone depends on a parameter—transmissivity—that cannot be observed without capital expenditure; the energy, water and emissions results depend only on the reservoir share, which is bounded by thermodynamics rather than by geology. And the finding that a 10 MW tropical facility behaves economically like a 70 MW temperate one suggests that facility scale is a poor proxy for reservoir storage viability, and that the presence or absence of a cheap passive comparator is the better screening variable. Extending this reasoning across other tropical data centre markets, in the manner of published regional potential assessments [16], would be a productive direction for further work.

8. Conclusions

A geothermal RTES-integrated hybrid chilled-water cooling system for a representative 10 MW data centre in Mumbai has been assessed against conventional and hybrid thermal storage baselines on energy, water, environmental and economic criteria. The principal findings are:

- Annual cooling electricity falls by approximately 35 %, from about 13,578 MWh to about 8,826 MWh, by transferring roughly thirty per cent of the cooling duty from vapour compression at a COP near 4.9 to reservoir circulation at an effective electrical intensity of 18 kWh/MWh-thermal.
- Cooling-tower water consumption falls by approximately 31.6 %, with reported water usage effectiveness improving from 0.25 to 0.17 L/kWh-IT. This co-benefit is excluded from the levelised cost and therefore understates the total benefit of the configuration.
- Carbon dioxide emissions fall by approximately 3,455 t/yr at the published grid emission factor of 0.727 t CO_2/MWh, with no change to IT load or service delivery.
- Levelised cost of cooling falls to ₹1,880/MWh against ₹2,196/MWh conventional and ₹2,044/MWh hybrid, a 14.4 % reduction, with the ₹10.64 crore incremental capital recovered in 3.2 years undiscounted or 3.8 years discounted at 8 % real.
- Sensitivity is dominated by electricity tariff and aquifer transmissivity; the grid emission factor has no influence on cost. Transmissivity is the parameter on which pre-investment information has the highest value.

The reference study's conclusion that reservoir storage pays only where it displaces an expensive chiller baseline is confirmed rather than contradicted. What changes in Mumbai is the comparator: the tropical monsoon climate removes the cheap passive baseline that defeats reservoir storage at comparable scale in temperate settings, so a 10 MW facility here is economically closer to a 70 MW facility there. The practical recommendation is a phased, gated deployment in which the reservoir is sized as a partial contributor at 20–45 % of cooling load rather than a baseline replacement, capital is released against measured performance at each gate, and a borehole thermal response test precedes any well-field commitment. Future work should replace the scaled capital basis with tendered local costs, re-verify the absolute water usage effectiveness figures against metered make-up water, and extend the comparator-based screening logic to other tropical data centre markets.

Acknowledgment

The authors thank the Department of Mechanical Engineering, Technocrats Institute of Technology, Bhopal, for institutional support, and acknowledge the Central Electricity Authority, the Central Ground Water Board and the India Meteorological Department for the public data used in this study.

References

[1] E. Masanet, A. Shehabi, N. Lei, S. Smith, and J. Koomey, "Recalibrating global data center energy-use estimates," *Science*, vol. 367, no. 6481, pp. 984–986, 2020, doi: 10.1126/science.aba3758
[2] J. G. Koomey, "Worldwide electricity used in data centers," *Environmental Research Letters*, vol. 3, no. 3, art. 034008, 2008, doi: 10.1088/1748-9326/3/3/034008
[3] K. Ebrahimi, G. F. Jones, and A. S. Fleischer, "A review of data center cooling technology, operating conditions and the corresponding low-grade waste

heat recovery opportunities," *Renewable and Sustainable Energy Reviews*, vol. 31, pp. 622–638, 2014, doi: 10.1016/j.rser.2013.12.007
[4] G. I. Meijer, "Cooling energy-hungry data centers," *Science*, vol. 328, no. 5976, pp. 318–319, 2010, doi: 10.1126/science.1182769
[5] D. Mytton, "Data centre water consumption," *npj Clean Water*, vol. 4, art. 11, 2021, doi: 10.1038/s41545-021-00101-w
[6] M. A. B. Siddik, A. Shehabi, and L. Marston, "The environmental footprint of data centers in the United States," *Environmental Research Letters*, vol. 16, no. 6, art. 064017, 2021, doi: 10.1088/1748-9326/abfba1
[7] H. Zhang, S. Shao, H. Xu, H. Zou, and C. Tian, "Free cooling of data centers: A review," *Renewable and Sustainable Energy Reviews*, vol. 35, pp. 171–182, 2014, doi: 10.1016/j.rser.2014.04.017
[8] J. Cho, T. Lim, and B. S. Kim, "Viability of datacenter cooling systems for energy efficiency in temperate or subtropical regions: Case study," *Energy and Buildings*, vol. 55, pp. 189–197, 2012, doi: 10.1016/j.enbuild.2012.08.012
[9] S. Xu, H. Zhang, and Z. Wang, "Thermal management and energy consumption in air, liquid, and free cooling systems for data centers: A review," *Energies*, vol. 16, no. 3, art. 1279, 2023, doi: 10.3390/en16031279
[10] A. Habibi Khalaj and S. K. Halgamuge, "A review on efficient thermal management of air- and liquid-cooled data centers: From chip to the cooling system," *Applied Energy*, vol. 205, pp. 1165–1188, 2017, doi: 10.1016/j.apenergy.2017.08.037
[11] P. Fleuchaus, B. Godschalk, I. Stober, and P. Blum, "Worldwide application of aquifer thermal energy storage – A review," *Renewable and Sustainable Energy Reviews*, vol. 94, pp. 861–876, 2018, doi: 10.1016/j.rser.2018.06.057
[12] G. Drenkelfort, S. Kieseler, A. Pasemann, and F. Behrendt, "Aquifer thermal energy storages as a cooling option for German data centers," *Energy Efficiency*, vol. 8, no. 2, pp. 385–402, 2015, doi: 10.1007/s12053-014-9295-1
[13] S. Pandey et al., "Aquifer thermal energy storage: Groundwater for efficient data center cooling in the United States," *Groundwater*, 2026, doi: 10.1111/gwat.70084
[14] Y. Zhang et al., "Data centers and subsurface thermal energy storage — Matching data center cooling needs with recharging of subsurface thermal energy storage," Lawrence Berkeley National Laboratory, Berkeley, CA, USA, Final Tech. Rep. LBNL-2001665, Aug. 2024. [Online]. Available: escholarship.org/uc/item/8sn8s7pm
[15] M. Bloemendal, T. Olsthoorn, and F. van de Ven, "Combining climatic and geo-hydrological preconditions as a method to determine world potential for aquifer thermal energy storage," *Science of the Total Environment*, vol. 538, pp. 621–633, 2015, doi: 10.1016/j.scitotenv.2015.07.084
[16] A. Ramos-Escudero and M. Bloemendal, "Assessment of potential for aquifer thermal energy storage systems for Spain," *Sustainable Cities and Society*, vol. 81, art. 103849, 2022, doi: 10.1016/j.scs.2022.103849
[17] S. Schüppler, P. Fleuchaus, and P. Blum, "Techno-economic and environmental analysis of an aquifer thermal energy storage (ATES) in Germany," *Geothermal Energy*, vol. 7, no. 1, art. 11, 2019, doi: 10.1186/s40517-019-0127-6
[18] R. Stemmle, P. Blum, S. Schüppler, P. Fleuchaus, M. Limoges, P. Bayer, and K. Menberg, "Environmental impacts of aquifer thermal energy storage (ATES)," *Renewable and Sustainable Energy Reviews*, vol. 151, art. 111560, 2021, doi: 10.1016/j.rser.2021.111560
[19] M. D. Jackson, G. Regnier, and I. Staffell, "Aquifer thermal energy storage for low carbon heating and cooling in the United Kingdom: Current status and future prospects," *Applied Energy*, vol. 376, art. 124096, 2024, doi: 10.1016/j.apenergy.2024.124096
[20] India Meteorological Department, *Climatological Tables of Observatories in India, 1991–2020*. Pune, India: IMD, 2021. [Online]. Available: imdpune.gov.in
[21] Central Ground Water Board, Ministry of Jal Shakti, Government of India, *Ground Water Information Booklet, Greater Mumbai District, Maharashtra*. Faridabad, India: CGWB. [Online]. Available: cgwb.gov.in
[22] H. Kulkarni, S. B. Deolankar, A. Lalwani, B. Joseph, and S. Pawar, "Hydrogeological framework of the Deccan basalt groundwater systems, west-central India," *Hydrogeology Journal*, vol. 8, no. 4, pp. 368–378, 2000, doi: 10.1007/s100400000079
[23] Central Electricity Authority, Government of India, *CO_2 Baseline Database for the Indian Power Sector*, User Guide Version 19–20, weighted average grid emission factor for FY 2023–24. New Delhi, India: CEA. [Online]. Available: cea.nic.in
[24] Maharashtra State Electricity Distribution Company Limited, *High-Tension Industrial and Commercial Tariff Schedules*, as filed with the Maharashtra Electricity Regulatory Commission. Mumbai, India: MSEDCL.
[25] P. Fleuchaus, S. Schüppler, M. Bloemendal, L. Guglielmetti, O. Opel, and P. Blum, "Risk analysis of high-temperature aquifer thermal energy storage (HT-ATES)," *Renewable and Sustainable Energy Reviews*, vol. 133, art. 110153, 2020, doi: 10.1016/j.rser.2020.110153

[26] M. Bloemendal, M. Jaxa-Rozen, and T. Olsthoorn, "Methods for planning of ATES systems," *Applied Energy*, vol. 216, pp. 534–557, 2018, doi: 10.1016/j.apenergy.2018.02.068
[27] M. Pellegrini, M. Bloemendal, N. Hoekstra, G. Spaak, A. Andreu Gallego, J. Rodriguez Comins, et al., "Low carbon heating and cooling by combining various technologies with aquifer thermal energy storage," *Science of the Total Environment*, vol. 665, pp. 1–10, 2019, doi: 10.1016/j.scitotenv.2019.01.135
[28] S. Duijff, M. Bloemendal, and N. Hartog, "Interaction effects between aquifer thermal energy storage systems," *Groundwater*, vol. 61, no. 2, pp. 173–182, 2023, doi: 10.1111/gwat.13163

