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Beyond Foundations: Energy Geostructures as Embedded Thermal Infrastructure for Building Decarbonization

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Energy geostructures (EGs) can provide embedded thermal infrastructure by connecting load-bearing structures to building energy systems. Their deployment advantage arises from sharing necessary construction, making new buildings and major structural renewal the immediate priority. That advantage is conditional: thermal demand must remain compatible with ground conditions, structural serviceability and neighboring uses throughout operation. The decisive scaling challenge is therefore to translate site-specific feasibility into accountable, financeable service. Fragmented responsibility across construction, energy operation and subsurface regulation obstructs this translation. Three linked actions are needed: performance-based certification to define acceptable service, whole-life economic assessment to establish its value, and coordinated permitting to secure its operating conditions. This framework supports selective deployment, including supplementary systems for existing buildings, while avoiding the assumption that greater heat-exchange capacity necessarily delivers lower costs or emissions.

FROM STRUCTURAL FOUNDATIONS TO EMBEDDED THERMAL INFRASTRUCTURE

Urban decarbonization creates an opportunity to extend the role of underground structures beyond load bearing. Integrating heat-exchange pipes into piles and tunnel linings connects necessary structural assets to heat pumps, enabling building heating and cooling. Building-integrated photovoltaic/thermal systems can supply electricity and, where recharge is needed, solar heat for seasonal storage in the surrounding ground. Coordinating these functions supports a transition from individual structural elements to embedded thermal infrastructure and scalable thermal batteries, as illustrated in Figure 1. Here, the battery concept denotes thermal rather than electrochemical storage; net-zero carbon remains a system-level objective requiring whole-life emissions verification.

This transition depends on sharing construction already required for structural purposes. A global database of 972 installations, test sites and simulations supports considering EGs across infrastructure types, without establishing uniform commercial performance.¹ New construction and major structural renewal should therefore receive priority, allowing thermal requirements to inform design before foundation geometry and reinforcement are fixed. Additional foundations solely for thermal capacity would weaken that advantage. The objective is to obtain sustained energy services from necessary structures and integrate them into the wider building energy system.

Existing buildings can participate through connections to suitable thermal assets without converting their buried foundations. Installing loops inside completed piles can threaten reinforcement or waterproofing, while restricted access increases costs. More credible opportunities include thermal activa-

tion during necessary underpinning, accessible wall panels, nearby energy quay walls or shared networks.² Separate boreholes remain an alternative, although they are not EGs. Selection requires access, hydraulic compatibility and connection-cost checks; minimally invasive foundation conversion remains a research priority. In either pathway, expansion from individual structures to coordinated infrastructure must respect the operating limits considered next.

MATCH THERMAL DEMAND TO A SAFE OPERATING ENVELOPE

An appropriate construction opportunity is necessary but insufficient. Its value depends on whether the available ground and structural surfaces can meet useful demand over time. Evidence concentrated in moist, cool-temperate settings¹ should therefore inform site screening rather than establish universal design assumptions. In hot-arid regions, dry ground and cooling-dominated loads can restrict heat rejection. Designers should evaluate seasonal moisture changes, initial ground temperature and long-term heat accumulation before selecting loop capacity. Heat recovery or auxiliary dry cooling may be appropriate; solar recharge is unsuitable where additional heat would worsen ground warming.

Groundwater changes this assessment but does not remove the need for it. A high-water table can favor heat transport, yet saturation alone does not demonstrate effective advection. Permeability, hydraulic gradients and seasonal fluctuations determine whether groundwater disperses heat and where thermal plumes travel. The strong influence of adjoining water on energy quay-wall performance² illustrates why favorable results cannot be transferred directly to isolated foundations. Screening should also address protected aquifers, watertight detailing and downstream receptors. Capacity should be reduced, or alternatives selected, when acceptable conditions cannot be maintained.

Within a suitable site, annual thermal balance should guide system configuration before exchanger enhancement. A coupled photovoltaic/thermal-energy-pile simulation maintained mean soil temperature near 10.4 °C over 20 simulated years in Shenyang,³ supporting recharge as a design option for heating-dominated loads. Model predictive control can then coordinate weather, demand and ground-temperature constraints.⁴ Complementary heating and cooling also improved long-term exchange in Cutter Soil Mix wall modelling.⁵ Together, these findings support a design hierarchy: balance the heat budget, optimize operation, and then refine loop geometry. Additional pipe length or conductivity cannot indefinitely compensate for persistent thermal imbalance.

Maintaining thermal balance, however, does not establish structural reliability. Cyclic operation also changes pile strains, interface movement and load transfer. Field testing recorded irreversible strains and settlements with-

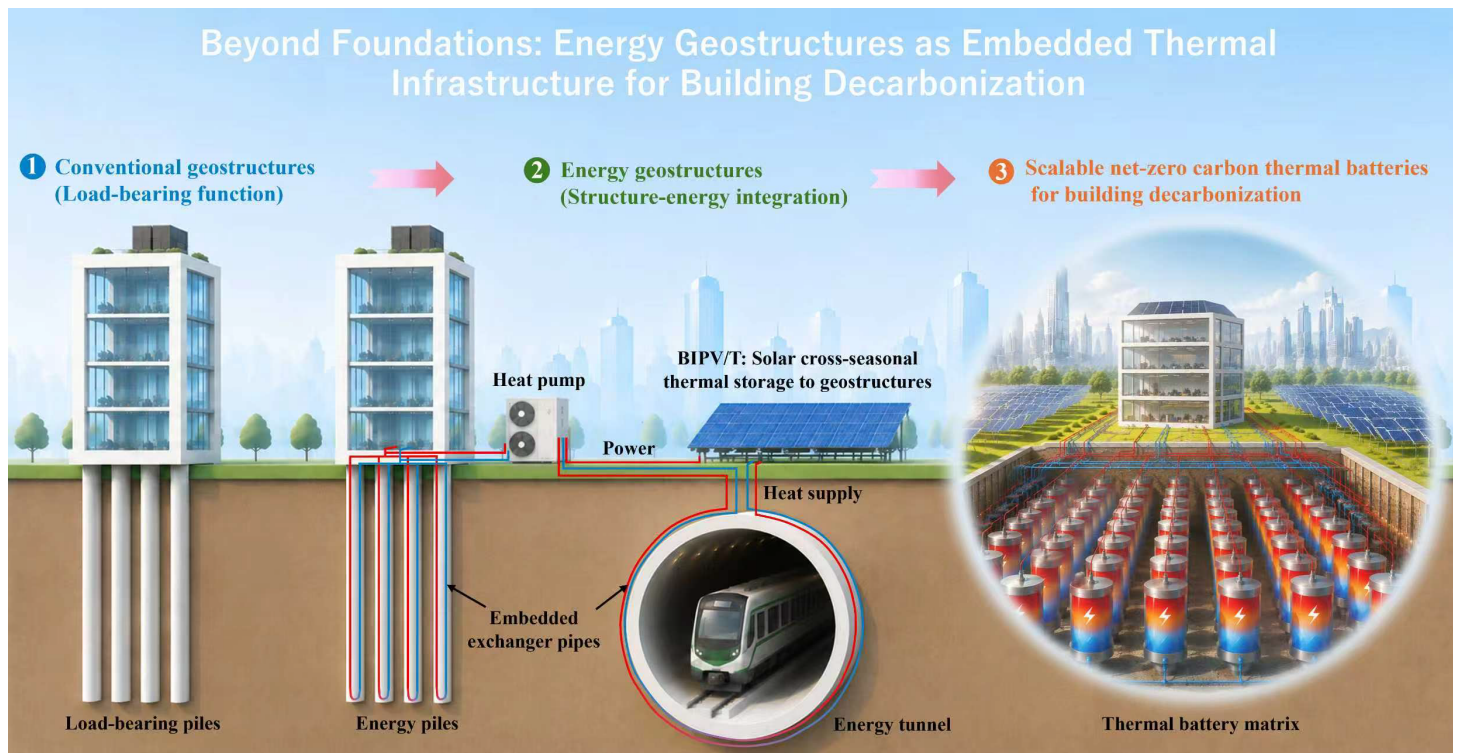


Figure 1. Energy geostructures as embedded thermal infrastructure and scalable net-zero carbon thermal batteries for urban decarbonization.

out a measured bearing-capacity reduction in that particular test,⁶ showing why serviceability and ultimate resistance require separate assessment. Evaluation should cover differential settlement, cumulative interface displacement, concrete cracking and potential fatigue of pipes and connections. Short monitoring campaigns cannot determine lifetime behavior. These uncertainties make an enforceable operating envelope essential: temperature, deformation and environmental limits must constrain energy extraction throughout service, rather than only at design approval.

CONVERT SITE FEASIBILITY INTO ACCOUNTABLE DEPLOYMENT

Site dependence explains why technical improvement alone cannot secure widespread adoption. Structural designers carry safety obligations, developers fund installation, and operators inherit energy performance and maintenance. Separate regulatory remits further divide oversight of foundations, groundwater and heat supply. Under these arrangements, no single party necessarily owns the combined lifetime outcome, while incomplete operating evidence makes approval difficult. Fragmented accountability is therefore the central scaling bottleneck for otherwise suitable projects. Three linked actions should connect technical limits to investment decisions and operating rights.

First, performance-based certification should turn the operating envelope into verifiable obligations. Before construction, the design team should submit coupled thermal-mechanical predictions, uncertainty bounds and project-specific limits for temperatures, settlement, stress, strain, circuit pressure loss and off-site thermal change. Applicable structural requirements and environmental assessment should determine acceptance criteria; existing safeguards should remain until equivalent protection is demonstrated. A lead integrator should coordinate the submission, with contractual responsibility assigned for commissioning, monitoring and corrective action.

Commissioning should verify circuit integrity, flow balance and metering. Provisional approval should be followed by independent review after a complete heating-cooling cycle and annual reporting thereafter. Reports should distinguish delivered heating and cooling, total electricity including auxiliaries, seasonal performance, availability, ground-temperature drift and deformation. A digital twin should update predictions from these observations and trigger predefined curtailment or backup operation. Data-driven assessment of steel-pipe exchangers⁷ suggests a route to faster prediction, but field validation, calibration ranges and model-error reporting remain

necessary. Operators should own alarm response, while independent assessors verify compliance. Monitoring obligations and funding should survive asset handover.

Second, the service established by certification should provide the basis for economic comparison. Clients and funders should require life-cycle cost and levelized cost of useful heat assessments against air-source heat pumps, separate boreholes and available district heat. Comparisons need identical demand, service temperatures, reliability, study periods and discount assumptions. Costs should include incremental EG installation, heat pumps, electricity, recharge, monitoring, maintenance, replacement and connections. Shared structural costs should be disclosed separately, with consistent allocation where cooling or electricity is co-produced. The reported incremental tunnel LCOH of 0.38 CNY/kWh⁸ is conditional on greenfield assumptions and cannot substitute for this whole-system comparison.

A simple break-even calculation makes the investment criterion explicit. For an illustrative additional investment of 100,000 currency units, annual useful heat of 100,000 kWh, a 20-year life and a 5% real discount rate, the capital recovery factor is 0.0802. Net annual operating savings must therefore exceed 8,024 units, equivalent to 0.0802 per delivered kWh, before replacements or residual value are considered. These assumptions are illustrative rather than measured costs. Project bids should disclose sensitivities to tariffs, utilization and component life, allowing support to target verified whole-life value rather than nominal exchange capacity.

Third, project-level certification and economics require stable subsurface operating conditions. Municipalities should integrate EG screening into planning and infrastructure renewal, using a coordinated register of utilities, metro protection zones, thermal systems and proposed connections. Permitting should establish installation rights, maintenance access and liability for cross-boundary interference. A designated coordinator should reconcile structural, groundwater and energy reviews before designs are fixed. District assessment should address cumulative plumes and effects on neighboring foundations, groundwater and aquatic ecosystems. Shared networks may improve load complementarity, but connection agreements must establish metering, tariffs and responsibility for thermal balance. Otherwise, neighboring development can undermine the assumptions on which project approval and investment depend.

BUILD INFRASTRUCTURE AROUND SUSTAINED SERVICE

EGs merit priority where necessary construction, suitable ground and building demand coincide. New-build integration offers the clearest immediate opportunity, while supplementary systems can extend benefits to existing buildings. Scaling should proceed through a connected sequence: establish a safe operating envelope, certify the resulting service, compare its whole-life value and protect its subsurface operating conditions. Publicly monitored projects can supply evidence for subsequent approvals. This approach gives embedded thermal infrastructure a practical meaning beyond the foundation itself: structural assets become managed components of building energy systems. Success should be measured through useful service, structural stability and emissions reductions that include electricity, auxiliaries and incremental embodied impacts.

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DECLARATION OF INTERESTS

The authors declare no competing interests.