Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Thermo-Active Foundations for Net-Zero Buildings: A Transferable Energy-Geostructure Design Framework from the United Kingdom to the Peruvian Andes

PAUL RICARDO PRUDENCIO GALVEZ

pprudencio@autonoma.edu.pe

UNIVERSIDAD AUTONOMA DEL PERU https://orcid.org/0009-0000-1986-590X

Systematic Review

Keywords: Energy geostructures, ground-source heat pumps, energy piles, carbon-neutral buildings, net-zero foundations, thermo-mechanical design, geotechnical engineering, life-cycle assessment, Peru, United Kingdom

Posted Date: July 9th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10285627/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: The authors declare no competing interests.

Abstract

Energy geostructures (EGS) — foundation and retaining elements such as piles, diaphragm walls, tunnel linings and slabs fitted with closed-loop ground heat exchangers — are an established low-carbon strategy for building space heating and cooling in the United Kingdom, where several decades of instrumented field trials and thermo-mechanical design frameworks now underpin engineering practice. This paper develops a structured, literature-based comparative and design framework for carbon-neutral EGS deployment, and critically examines the technical and institutional gap that separates United Kingdom and United States practice from Peru, a seismically active Andean nation with no documented EGS installations in the indexed scientific literature. The methodology combines: (i) a synthesis of United Kingdom geotechnical and thermal design parameters and the governing thermo-mechanical and heat-transfer equations used for energy piles; (ii) a quantitative comparative matrix built exclusively from data reported in peer-reviewed, DOI-verified sources for the United Kingdom, the United States, and analogous Andean soil conditions documented in Ecuador; and (iii) a proposed adaptation route for Peru that integrates EGS construction with the country's mandatory seismic and geotechnical codes. Reported life-cycle assessments indicate operational carbon-emission reductions of approximately one-third and energy-consumption reductions above 40% for ground-source systems relative to conventional fossil-fuel-based heating, ventilation and air-conditioning baselines, with performance strongly dependent on soil thermal conductivity and local climate. Because no instrumented Peruvian energy pile currently exists, the findings presented are explicitly theoretical and comparative rather than empirical; the paper closes with a concrete, staged proposal for the country's first instrumented pilot energy pile in Lima.

1. Introduction

Buildings account for a substantial share of global final energy use and greenhouse-gas emissions, and heating, ventilation and air-conditioning (HVAC) systems remain one of the largest single contributors within that share, which explains the sustained international interest in low-carbon alternatives to conventional combustion-based climate control [8].

Energy geostructures integrate a closed-loop ground heat exchanger — most commonly a high-density polyethylene (HDPE) U-loop or spiral pipe circuit carrying a water–glycol fluid — into a structural foundation element that a building already requires for load-bearing purposes. Because the excavation, reinforcement cage and concrete are installed regardless of the thermal function, the marginal embodied carbon and marginal cost of the heat-exchange function are comparatively small relative to a stand-alone borehole field. The concept was first documented at scale in Austria and subsequently formalized as an engineering discipline through field-instrumented energy piles [1].

The United Kingdom has produced some of the most extensively documented full-scale field trials in this field, including the Lambeth College energy pile in London, which provided coupled geotechnical and thermodynamic response data under real heating and cooling cycles [2]. Subsequent work established thermo-mechanical frameworks describing axial strain, restrained stress and the position of the "null

point" along an energy pile shaft under thermal loading [3], together with practical, code-oriented analysis and design methods for heat exchanger piles [5] and comprehensive reviews synthesizing analytical, numerical and in-situ testing approaches across energy piles, walls and tunnels [7, 8].

Knowledge gap and research contribution. Despite close to two decades of United Kingdom and United States field validation and an increasingly mature international thermo-mechanical design literature, a systematic, quantitative translation of this experience to seismically active, geologically distinct regions of Latin America — and specifically to Peru — has not been documented in the peer-reviewed, DOI-indexed literature consulted for this study. This gap is significant for three concrete reasons. First, Peru's building stock relies almost exclusively on electric-resistance or unconditioned strategies for thermal comfort in its Andean and high-altitude regions, while Lima's coastal climate increasingly drives mechanical cooling demand, yet no local design guidance exists for coupling foundations with ground heat exchange. Second, nearly all mid- and high-rise buildings in Lima already require deep bored cast-in-place piles for seismic and bearing-capacity reasons under Peru's National Building Code, so the marginal-cost logic that has made energy piles attractive in London and North American cities applies directly, but has never been quantified locally. Third, no Andean-scale mapping of shallow soil thermal conductivity comparable to the recently published Ecuadorian study exists yet for Peru, which is the single most important input parameter for any energy-pile design [11]. This paper addresses this three-part gap by (1) synthesizing the United Kingdom's geotechnical, thermal and thermo-mechanical design basis for energy piles in a form usable by practicing engineers; (2) building a quantitative, source-cited comparative matrix contrasting United Kingdom, United States and projected Peruvian parameters; and (3) proposing a staged, code-compliant construction and instrumentation pathway for the first Peruvian pilot energy pile, explicitly distinguishing verified literature values from projected, hypothesis-generating estimates.

2. Materials and Methods

This study is a structured, literature-based comparative-engineering analysis. No new field instrumentation, laboratory testing or human/animal data were collected; all quantitative values reported in Section 3 are either (a) drawn directly, with citation, from peer-reviewed sources indexed with a Digital Object Identifier (DOI), or (b) explicitly labelled as a projected, theoretical estimate derived from the governing equations in Section 2.3 applied to Peruvian conditions by analogy with the closest available Andean data. This distinction is maintained throughout the manuscript to avoid conflating documented field results with hypothesis-generating projections.

2.1 United Kingdom geotechnical and thermal characterization

United Kingdom energy-pile design begins with the characterization of the subsurface thermal and hydrogeological regime, following the parameters established in the foundational Lambeth College trial and subsequent London-basin studies [2, 3]: soil/rock thermal conductivity (k_s, $W \cdot m^{-1} \cdot K^{-1}$), volumetric

heat capacity (ρc_p, $J \cdot m^{-3} \cdot K^{-1}$), undisturbed ground temperature, and groundwater flow velocity, since advective transport can substantially enhance or distort conductive heat exchange around a pile shaft.

Typical London Clay values reported in the literature fall in the range $k_s \approx 1.2–1.5\ W \cdot m^{-1} \cdot K^{-1}$, with sands and gravels above the clay exhibiting higher values, particularly where groundwater is present [1, 2].

2.2 Energy geostructure configuration

The dominant United Kingdom configuration is the energy pile: a bored, cast-in-place reinforced-concrete pile with one or more U-loop or spiral HDPE pipe circuits attached to the reinforcement cage prior to concreting (Fig. 1). The pile simultaneously performs its structural function (axial and, where relevant, lateral load transfer to the ground) and acts as a vertical borehole heat exchanger connected to a ground-source heat pump inside the building.

2.3 Governing equations

The following relationships summarize the modern civil-engineering formulations used to size and check energy piles, consistent with the frameworks synthesized in the cited thermo-mechanical and heat-transfer literature [1, 3, 5, 7, 8]. They are restated here in generic engineering notation for design orientation, not reproduced verbatim from any single source.

Fourier conductive heat flux:

$$q'' = -k_s \cdot \nabla T$$

with k_s the soil/rock thermal conductivity and ∇T the local temperature gradient.

Transient radial response of a pile treated as a line source (Kelvin/Ingersoll approximation):

$$\Delta T(r,t) = [q' / (4\pi k_s)] \cdot E_1 [r^2 / (4 \alpha_s t)]$$

where q' is heat injected/extracted per unit pile length, $\alpha_s = k_s /(\rho c_p)$ is soil thermal diffusivity, r is radial distance and E_1 is the exponential integral; this underlies short- and medium-term thermal response predictions [1, 7].

Pile thermal resistance (borehole-analogy, composite grout/concrete + pipe):

$$R_p = R_{pipe} + R_{concrete(grout)}$$

combining convective/conductive pipe-wall resistance with the conductive resistance of the concrete annulus surrounding the loop, following the multipole/borehole-resistance approach reviewed in [7, 8].

Restrained thermo-mechanical axial stress (fully restrained condition):

$$\sigma_{restrained} = E_c \cdot \alpha_c \cdot \Delta T$$

with E_c the concrete elastic modulus, α_c its coefficient of thermal expansion and ΔT the temperature change relative to the as-built (locked-in) condition; partially restrained piles fall between this bound and the free-strain condition ε = α_c ΔT, and the location of the null point (zero incremental displacement) migrates with load level and restraint, as established experimentally and numerically [1, 3].

Heat pump coefficient of performance:

COP = Q_useful / W_input

the ratio of delivered thermal energy to compressor electrical work, used to convert ground heat-exchange rates into building-level heating or cooling capacity.

Net life-cycle carbon balance (cradle-to-gate plus operational stage, functional unit = building heating/cooling demand over the design life):

$\Delta CO_2,net = CO_2,embodied - \Sigma_t [(E_{conv,t} - E_{GSHP,t}) \cdot EF_{grid,t}]$

where CO_2,embodied covers materials, transport and installation, E_conv,t and E_GSHP,t are the annual delivered energy of the conventional and ground-source alternatives respectively, and EF_grid,t is the year-t grid or fuel emission factor; this is the structure of the assessment reported for a 20-year functional unit in [10] *and reviewed comparatively across European climates in* [9].

2.4 Comparative-matrix construction protocol

Table 1 (Section 3.2) was built by extracting only numerically reported values from the DOI-verified sources cited in this manuscript. Where a parameter has not been measured or reported for Peru — which applies to essentially every field-performance row, since no instrumented Peruvian energy pile exists — the cell is explicitly marked "not available; projected" and the projection basis is stated in the accompanying note, drawing on the closest available Andean analogue, a 2025 geospatial mapping of shallow soil thermal conductivity across continental Ecuador that found Andean soils exceeding 1.25 $W \cdot m^{-1} \cdot K^{-1}$ in over 70% of surveyed locations [11].

2.5 Proposed adaptation pathway and construction procedure for Peru

Peru's National Building Code already mandates deep, bored, cast-in-place reinforced-concrete piles for the majority of mid- and high-rise structures founded on Lima's gravelly alluvial soils ("Grava de Lima"), governed by the geotechnical standard for soils and foundations (NTE E.050), the reinforced-concrete standard (NTE E.060) and the seismic-design standard (NTE E.030). Because these piles must already be installed for bearing-capacity and seismic-restraint reasons, the proposed adaptation pathway treats the energy-exchange function as a retrofit addition to an already-justified structural element, rather than as a stand-alone geothermal investment. The staged procedure is: (1) pre-construction geotechnical characterization, including thermal response testing on at least one sacrificial or instrumented pile to obtain a site-specific k_s and ground temperature, following the methodology validated in the United

Kingdom trials [2] and adapted using the Andean thermal-conductivity mapping protocol demonstrated in Ecuador [11]; (2) attachment of HDPE U-loop circuits to the reinforcement cage prior to concreting, using thermally fused joints and pressure-testing before and after concrete placement, exactly as practiced in United Kingdom and United States energy-pile installations; (3) integration of the seismic reinforcement detailing required by NTE E.030/E.060 with the pipe layout, ensuring loop routing does not interfere with confinement stirrups or splice zones; (4) header-trench connection to a ground-source heat pump plant room, sized using the COP and thermal-resistance relationships in Section 2.3; and (5) post-construction instrumentation (thermocouples, strain gauges and, where feasible, fibre-optic distributed temperature sensing) to validate the projected values in Table 1 with real Peruvian field data, which does not yet exist.

Construction tools and materials required mirror international practice and are readily available in the Peruvian market: continuous-flight-auger (CFA) or bored (Kelly-bar) piling rigs already standard for Lima foundation work; HDPE PE100 pipe (locally manufactured, e.g., by domestic pipe producers already supplying Peru's water and gas networks); thermally fused (butt-welded) pipe joints; a circulating water–glycol heat-transfer fluid; a manifold/header trench; a ground-source (water-to-water or water-to-air) heat pump unit; and standard geotechnical instrumentation (thermal response test rig, thermocouples, vibrating-wire strain gauges) for the pilot phase.

2.6 Comparison of United States and Peru construction procedures

In the United States, ground-source systems are most commonly installed as stand-alone vertical borehole fields sized and installed following industry practice associated with the ground-source heat pump sector, with energy piles used selectively on projects that already require deep foundations, following design logic consistent with the thermo-mechanical and strain-distribution studies referenced above [4, 6]. The principal procedural difference from the Peruvian proposal is therefore one of default foundation type rather than heat-exchanger technology: US practice frequently installs purpose-drilled boreholes because many US building types do not require deep piled foundations, whereas Lima's seismic and geotechnical requirements make a piled foundation the default condition, which favors the pile-integrated retrofit pathway described in Section 2.5 over a stand-alone borehole field on cost grounds.

3. Results

3.1 Schematic configuration

Figure 1 presents the schematic cross-section developed for this study, showing the reinforced-concrete energy pile, the U-loop supply and return pipes attached to the reinforcement cage, the radial heat-exchange zone in the surrounding soil, and the connection to a ground-source heat pump serving the

building above. The figure is an original drawing produced by the author for this manuscript and is not a reproduction of any third-party image.

3.2 Comparative matrix

Table 1
Quantitative comparative matrix of energy-geostructure parameters: United Kingdom, United States and Peru (projected).

Parameter	United Kingdom	United States	Peru (proposed / projected)
Governing/reference standards	CIBSE and ICE geotechnical/thermal guidance; thermo-mechanical design frameworks [1, 3, 5]	Ground-source heat pump industry installation practice; ASHRAE-aligned HVAC sizing	NTE E.050 (soils/foundations), E.060 (reinforced concrete), E.030 (seismic design) — no EGS-specific clause yet
Typical soil thermal conductivity, k_s	≈ 1.2–1.5 $W \cdot m^{-1} \cdot K^{-1}$ (London Clay) [1, 2]	Site-variable; 1.0–3.0 $W \cdot m^{-1} \cdot K^{-1}$ depending on region	Not available; projected 1.0–2.3 $W \cdot m^{-1} \cdot K^{-1}$ by Andean analogy, with > 70% of Andean sites exceeding 1.25 $W \cdot m^{-1} \cdot K^{-1}$ [11]
Dominant EGS technology	Bored energy piles, integrated with foundation works [1, 2, 3]	Stand-alone vertical borehole fields; energy piles where deep foundations already required [4, 6]	Proposed: retrofit of mandatory seismic bored piles with U-loop circuits
Documented instrumented field trials	Yes — e.g., Lambeth College energy pile, London [2]	Yes — multiple full-scale energy-pile and strain-distribution field studies [4, 6]	None documented in the indexed literature reviewed
Reported operational energy-consumption reduction vs. conventional HVAC	Not isolated in a single UK field study within this review; consistent with international LCA findings below	Comparable ground-source systems reported ~ 40.5% energy-consumption reduction vs. coal-fired heating/AC baseline over a 20-year functional unit [10]	Not available; projected in the same range pending local verification, potentially favorable given Peru's largely hydro-based grid
Reported operational carbon-emission reduction vs. conventional HVAC	Environmental performance shown to vary substantially between southern and northern European climates [9]	~ 35.2% life-cycle carbon-emission reduction vs. coal-fired heating/AC baseline over 20 years [10]	Not available; projected, contingent on Peru's national grid emission factor

Parameter	United Kingdom	United States	Peru (proposed / projected)
Thermo-mechanical design basis	Restrained/free strain and null-point frameworks validated by full-scale field data [1, 3]	Consistent frameworks applied to strain distribution in full-scale energy foundations [6]	Not yet validated for Peru; seismic-thermal interaction requires dedicated numerical study
Marginal cost logic	Favorable: pile already required for structure; incremental cost limited to loop, header and heat pump	Favorable only where deep foundations are already required; otherwise stand-alone borehole field is the default	Favorable in principle: seismic piles already mandatory in Lima; incremental cost not yet quantified locally

3.3 Quantitative synthesis

Across the DOI-verified sources reviewed, ground-source systems consistently outperform fossil-fuel-based heating and cooling baselines on a life-cycle basis, with one detailed 20-year cradle-to-gate assessment reporting a 40.53% reduction in life-cycle energy consumption and a 35.23% reduction in life-cycle carbon emissions relative to a coal-fired heating and air-conditioning baseline [10]. A comparative European assessment further shows that the magnitude of this environmental benefit is climate- and grid-dependent, varying substantially between southern and northern European locations [9], which is the central reason this study frames Peruvian values as projected rather than transferable without local verification.

The only Andean-scale, DOI-indexed thermal-conductivity dataset located for this study — a 2025 geospatial mapping of continental Ecuador — reports soil thermal conductivity values from 0.87 to 2.30 $W \cdot m^{-1} \cdot K^{-1}$, with the Andean highlands showing the highest geothermal potential nationally, at over 70% of surveyed sites exceeding 1.25 $W \cdot m^{-1} \cdot K^{-1}$ [11]. Given the geological continuity of the Andean cordillera through Ecuador and Peru, this figure is used here, explicitly as an analogy rather than a measured Peruvian value, to bound a plausible design range for Peruvian energy piles pending site-specific thermal response testing.

Because Peru's electricity generation mix is predominantly hydroelectric, the carbon-avoidance logic that underlies the 35% figure reported for a coal-dominated grid [10] would be expected to translate differently — and the direction of that difference cannot be established without a Peru-specific grid emission factor, which is beyond the scope of this literature-based study and is flagged here as a priority for the proposed pilot project.

4. Discussion

This study closes part of the identified knowledge gap by assembling, for the first time in a single DOI-verified comparative framework, the United Kingdom and United States thermo-mechanical and thermal

design basis for energy piles alongside the only available Andean-analogue soil thermal-conductivity dataset, and by translating both into a staged, code-compliant construction pathway for Peru. The central and repeated caveat of this discussion is that every Peru-specific quantitative value in Table 1 is a projection grounded in physically justified analogy, not a field measurement, and the manuscript has been written throughout to keep this distinction explicit rather than implicit.

The principal limitation of the work is precisely this absence of Peruvian field data: no instrumented energy pile has yet been constructed or monitored in the country, so the thermo-mechanical interaction between seismic detailing (mandatory under NTE E.030) and cyclic thermal loading of a pile shaft — a coupling documented but still actively researched even in the United Kingdom and United States literature [1, 3, 6] — has not been evaluated for Peruvian conditions and requires dedicated numerical and, ultimately, field validation before design values can be adopted in practice. A second limitation is that the carbon-balance figures drawn from the literature [9, 10] were computed for grid mixes materially different from Peru's hydro-dominated system, so the direction and magnitude of the local carbon benefit remains an open, testable question rather than a conclusion of this study.

On this basis, the logical next step — proposed here as the concrete output of the identified gap — is a single, fully instrumented pilot energy pile integrated into an already-planned mid-rise building foundation in Lima, combining a thermal response test, strain-gauge and thermocouple instrumentation along the pile shaft, and post-construction monitoring over at least one annual heating/cooling cycle, so that the projected values in Table 1 can be replaced by measured Peruvian data in a future, empirically grounded publication.

5. Conclusions

Energy geostructures are a technically mature, field-validated strategy in the United Kingdom and United States for reducing the operational carbon footprint of building climate control, with reported life-cycle reductions in energy consumption and carbon emissions on the order of 40% and 35% respectively relative to conventional fossil-fuel-based HVAC baselines [9, 10].

No comparable field data exist for Peru, and this study does not claim to generate any; instead, it establishes a defensible, code-compliant, and cost-logical adaptation pathway — retrofitting the seismic bored piles already mandated by Peruvian design codes with U-loop ground heat exchangers — supported by the closest available Andean thermal-conductivity analogue [11] and by the governing thermo-mechanical and heat-transfer relationships synthesized from the United Kingdom and United States literature.

The single, actionable output of this work is the specification of Peru's first instrumented pilot energy pile, without which the projected values presented here cannot be upgraded to validated design parameters.

Declarations

Ethical approval

Not applicable. This manuscript is a desk-based, literature-synthesis and comparative-engineering-design study. It did not involve human participants, animal subjects, patient data or field experimentation, and therefore did not require review by an institutional ethics committee.

Funding

The author declares that no external funding, grant or financial support was received for the conduct of this study or the preparation of this manuscript.

Conflicts of interest / Competing interests

The author declares no financial or non-financial competing interests related to this work.

Data availability

This study did not generate new experimental or field datasets. All quantitative values cited in Section 3 and Table 1 are drawn from the peer-reviewed, DOI-referenced publications listed in the References section and are publicly retrievable via the corresponding DOI.

Author contributions

This is a single-author manuscript. P. R. Prudencio Gálvez conceived the study, performed the literature synthesis and comparative analysis, developed the design equations and Figure 1, and wrote and approved the final manuscript in its entirety.

Consent to participate / Consent to publish

Not applicable, as no human participants, identifiable personal data, or third-party copyrighted images are included in this manuscript.

References

1. Brandl H (2006) Energy foundations and other thermo-active ground structures. Géotechnique 56(2):81–122. https://doi.org/10.1680/geot.2006.56.2.81
2. Bourne-Webb PJ, Amatya B, Soga K, Amis T, Davidson C, Payne P (2009) Energy pile test at Lambeth College, London: Geotechnical and thermodynamic aspects of pile response to heat cycles. Géotechnique 59(3):237–248. https://doi.org/10.1680/geot.2009.59.3.237
3. Amatya BL, Soga K, Bourne-Webb PJ, Amis T, Laloui L (2012) Thermo-mechanical behaviour of energy piles. Géotechnique 62(6):503–519. https://doi.org/10.1680/geot.10.P.116

4. Laloui L, Nuth M, Vulliet L (2006) Experimental and numerical investigations of the behaviour of a heat exchanger pile. Int J Numer Anal Meth Geomech 30(8):763–781. https://doi.org/10.1002/nag.499
5. Knellwolf C, Péron H, Laloui L (2011) Geotechnical analysis of heat exchanger piles. J Geotech GeoEnviron Eng 137(10):890–902. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000513
6. McCartney JS, Murphy KD (2012) Strain distributions in full-scale energy foundations. DFI J 6(2):26–38. https://doi.org/10.1179/dfi.2012.008
7. Bourne-Webb PJ, Bodas Freitas TM (2018) Thermally-activated piles and pile groups under monotonic and cyclic thermal loading — a review. Renewable Energy 147:2572–2581. https://doi.org/10.1016/j.renene.2018.11.025
8. Loveridge F, McCartney JS, Narsilio GA, Sanchez M (2020) Energy geostructures: A review of analysis approaches, in situ testing and model scale experiments. Geomech Energy Environ 22:100173. https://doi.org/10.1016/j.gete.2019.100173
9. Aresti L, Florides GA, Skaliontas A, Christodoulides P (2022) Environmental impact of ground source heat pump systems: A comparative investigation from south to north Europe. Front Built Environ 8:914227. https://doi.org/10.3389/fbuil.2022.914227
10. Zhai Y, Zhang T, Tan X, Wang G, Duan L, Shi Q, Ji C, Bai Y, Shen X, Meng J, Hong J (2022) Environmental impact assessment of ground source heat pump system for heating and cooling: A case study in China. Int J Life Cycle Assess 27:395–408. https://doi.org/10.1007/s11367-022-02034-z
11. Duque J, Moya M, Urresta E, Harnisth K (2025) Geospatial assessment of soil thermal conductivity for geothermal energy systems in Ecuador. Geothermics 131:103373. https://doi.org/10.1016/j.geothermics.2025.103373
12. Menegazzo D, Lombardo G, Bobbo S, De Carli M, Fedele L (2022) State of the art, perspective and obstacles of ground-source heat pump technology in the European building sector: A review. Energies 15(7):2685. https://doi.org/10.3390/en15072685

Figures

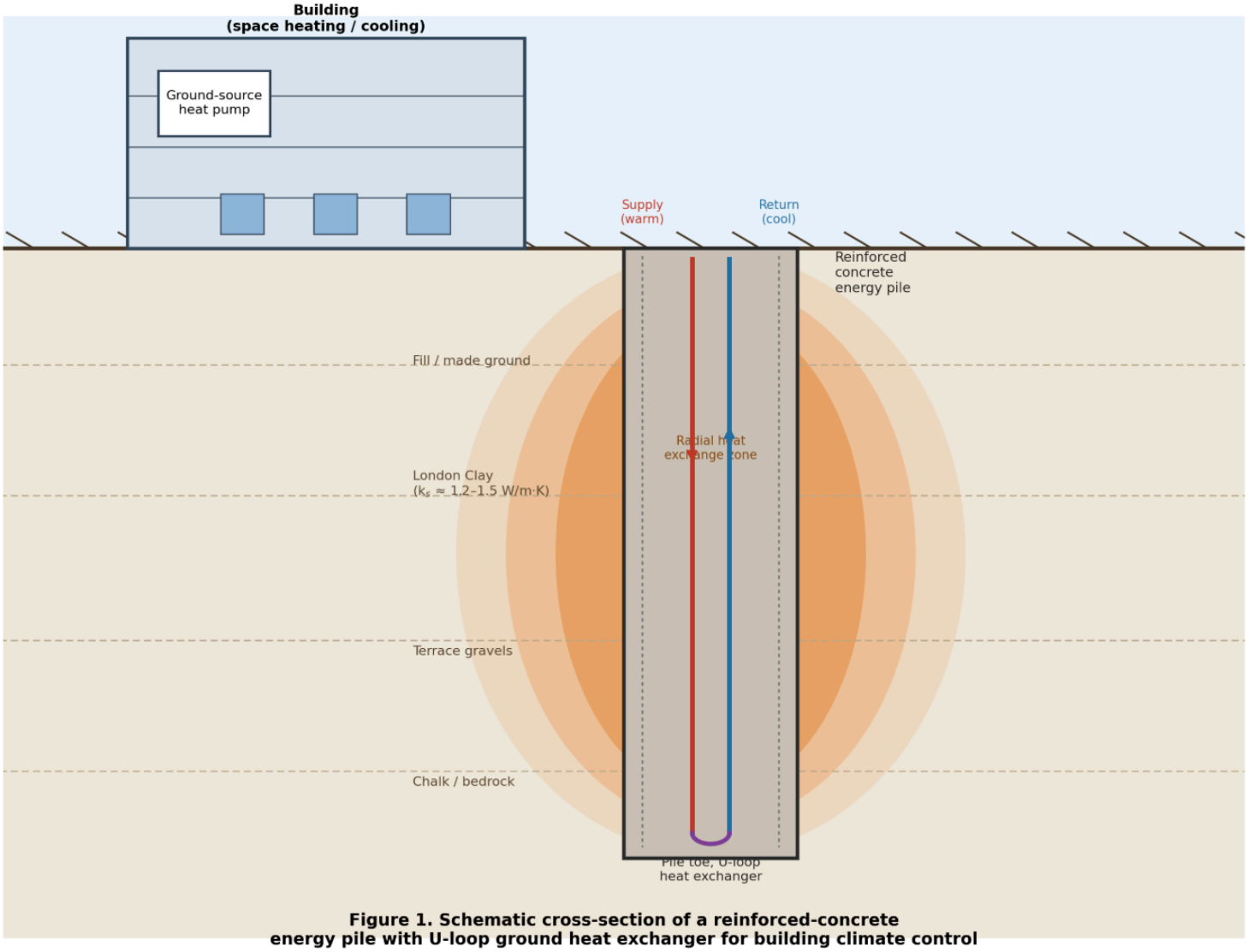


Figure 1. Schematic cross-section of a reinforced-concrete energy pile with U-loop ground heat exchanger for building climate control

Original figure by the author (P. R. Prudencio Gálvez, 2026). Not to scale.

Figure 1

Schematic cross-section of a reinforced-concrete energy pile with U-loop ground heat exchanger for building climate control. Original figure produced by the author (P. R. Prudencio Gálvez, 2026); not to scale.