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TC 308: Honour Lecture on Energy Geotechnics

Subsurface energy solutions: Where geotechnics meets innovation

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ABSTRACT: The urban subsurface is a valuable yet underexploited resource for meeting the rising energy and infrastructure demands of modern cities. Energy geostructures, structural elements equipped with geothermal heat exchangers, offer an innovative, sustainable, and cost-effective means to simultaneously provide structural support and renewable heating and cooling for buildings and infrastructure. Over the past decades, substantial research has advanced the understanding, design, and implementation of different types of energy geostructures, including energy piles, barrettes, walls, and slabs, thereby enabling the transition from theoretical concepts to practical engineering solutions. This work synthesizes these developments while extending the discussion to their application in complex underground settings. Brief insights from recent projects on geothermally activated facilities, such as complex foundation systems, underground data centers, and metro stations, demonstrate how energy geostructures are now being engineered not only for simple ground heat exchange, but also to interact with and adapt to the thermal conditions of complex underground environments where internal aerothermal conditions can influence the performance and design considerations of these structures. By bridging fundamental principles, advanced modelling strategies, and real-world applications, this paper highlights the role of energy geostructures in reducing fossil fuel dependency and contributing to decarbonization and thermal resilience of the built environment.

KEYWORDS: Energy geostructures, real-world installations, thermo-active foundations, geothermal energy

1 INTRODUCTION

The continuous rise in greenhouse gas emissions and the depletion of natural resources are intensifying climate change. Therefore, there is a need to transition to a more sustainable and low-carbon energy system. For buildings specifically, nearly half of the total energy consumed worldwide was devoted to space and water heating in 2022, and this number has not changed significantly from previous years. While cleaner and more efficient heating solutions are being developed, fossil fuels still provide over 60% of the energy used for heating our buildings. Looking specifically at cooling our buildings, the demand has surged to more than three times its 1990 level, contributing to increased electricity grid stress, higher greenhouse gas emissions, and the exacerbation of urban heat islands (IEA, 2023).

On the interface between geotechnical, structural and energy engineering, energy geostructures have emerged as a promising solution to these challenges. The geostructures harness the largely untapped shallow thermal energy of the urban subsurface by integrating geothermal heat exchangers into the reinforced concrete of structures that are in contact with the ground (Figure 1). Thus, no additional soil excavation is needed for their construction, and embedding the heat exchangers within the concrete reduces the risks of groundwater contamination or pipe damage.

Figure 1. Heat exchanger tubes on reinforcement cages of various foundation structures before pouring concrete (image sources: GEOEG (www.geoeg.net))

Initially, the technology focused on pile foundations, and since then, the technology has been extended to other types of earth-contact structures, including walls, slabs and barrettes. Energy geostructures can provide renewable heating and cooling for buildings, support domestic hot water production, offer seasonal thermal storage, prevent ice formation on pavements, bridges and runways, and can reduce ventilation requirements in underground infrastructure facilities. As low-carbon technology, these structures can substantially reduce CO2-eq emissions and support global decarbonization objectives. In urban areas where subsurface heat islands can be expected, shallow geothermal systems can achieve improved heating performance by exploiting excess subsurface heat resulting from human activity (Zhu et al., 2010; Bayer et al., 2019; Benz et al., 2022; Rotta Loria, 2023).

The integrated heat exchanger tubes, with diameters between 10 to 40 mm, circulate a heat-circulating fluid, typically water mixed with an anti-freeze or salt solution, to facilitate thermal exchange with the soil. The arrangement of the tubes can be varied to fit design requirements and has an influence on installation, operation and maintenance of the systems. Through considering such design and integration effects, energy geostructures provide an integrated solution

where structural demands are met, and sustainable energy management in buildings and infrastructure is simultaneously supported (e.g., Laloui and Rotta Loria, 2019). Their operational costs over a 50-year building lifecycle often surpass initial construction costs, highlighting the economic and environmental value of developing these energy-efficient structures (Brandl, 2016).

Extensive research over the past three decades has developed a rich scientific basis for the conception and design of energy geostructures, going from simplified calculations to sophisticated computational methods. The work of Laloui and Rotta Loria (2019) presents a synthesis of key principles governing the implementation and behavior of these systems and is one of the main contributions to this research field. Building upon this knowledge, the current work presents available approaches for the design of these structures and then connects this scientific progress with applied engineering practice.

2 DESIGNING ENERGY GEOSTRUCTURES

The primary mode of heat transfer for energy piles or barrettes in soils or rock is conduction. Convection is only relevant here when significant groundwater flow is present. Energy walls and slabs also exchange energy with the internal air domain of the energy geostructure, allowing the collection of both geothermal and aerothermal energy. Heat is exchanged both through conduction with the ground and convection with the internal air domain for these situations.

When looking at their mechanical behavior, there is also a difference between the energy piles and barrettes, where their response is largely governed by axial forces from vertical loads and thermal expansion, and energy walls and slabs, where bending rather than axial forces govern their mechanical behavior. Such considerations are visualized in Figure 2 for both types of structures.

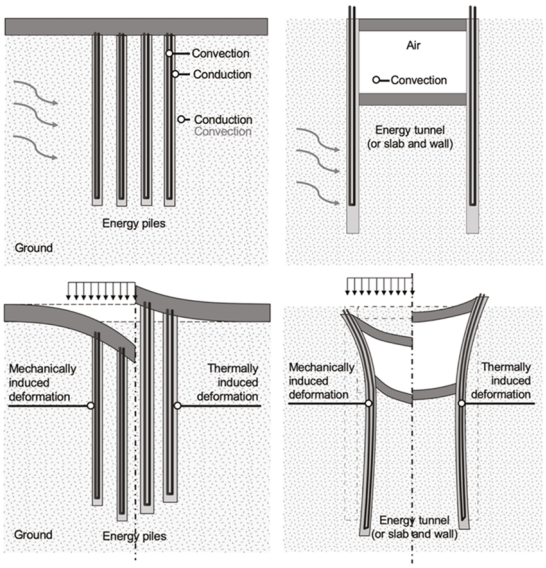

Figure 2. (Top) heat transfer modes and (bottom) schematic of deformations (for positive temperature variations) characterizing (left) energy piles and barrettes and (right) energy walls and slabs (modified from Rotta Loria (2020)).

The design and analysis of energy geostructures require an understanding of all thermo-hydro-mechanical interactions that govern their behavior. Phenomena such as heat transfer, fluid movement, and deformation require the solution of constitutive and balance equations to determine temperature fields, flow patterns, and displacement and stress fields. The governing continuity and momentum equations are

$$\rho_f \nabla \cdot \boldsymbol{v_f} = 0 \tag{1}$$

$$\rho_f (\boldsymbol{v_f} \cdot \nabla) \boldsymbol{v_f} = \nabla \cdot [-p\boldsymbol{I} + \boldsymbol{K}] + \boldsymbol{F} \tag{2}$$

in which ρ_f is the fluid density, $\boldsymbol{v_f}$ is the velocity vector, p is the pressure, $\boldsymbol{K}$ the viscous stress tensor and $\boldsymbol{F}$ the volume force vector. The energy conservation equation where conduction and convection characterize heat transfer reads

$$\rho_f c_{p,f} \boldsymbol{v_f} \cdot \nabla T - \nabla \cdot (\lambda \nabla T) = Q \tag{3}$$

where $c_{p,f}$ is the heat capacity at constant pressure, λ is the thermal conductivity, T is the temperature, and Q is the heat source. Solving this equation next to the mass conservation equation allows addressing conductive-convective heat transfer problems and highlights the thermo-hydraulic coupling between mass and heat transfer. The momentum conservation equation, when simplified by neglecting the influence of body forces, becomes

$$\nabla \cdot \boldsymbol{\sigma} = \boldsymbol{0} \tag{4}$$

in which $\nabla \cdot$ is the divergence operator and $\boldsymbol{\sigma}$ is the total stress tensor, which can be expressed as

$$\boldsymbol{\sigma} = \boldsymbol{D}\colon [\boldsymbol{\varepsilon} + \boldsymbol{\beta}(T - T_0)] \tag{5}$$

where $\boldsymbol{D}$ is the elastic stiffness tensor, which contains the material parameters (i.e., Young's modulus, E, and Poisson's ratio, ν), $\boldsymbol{\varepsilon}$ is the total strain tensor, β is a vector that comprises the linear thermal expansion coefficient, α, and $\Delta T = T - T_0$ is the applied temperature variation.

The theoretical frameworks used to describe the complex behavior of energy geostructures can be used to categorize their study and design. Analytical and semi-analytical methods offer a valuable understanding of the thermo-hydro-mechanical behavior of these systems. However, as geostructure projects grow in scale and complexity, these simplified models cannot completely capture the coupled processes of structural deformation, fluid movement, and heat transfer. For these larger, more intricate projects, numerical modeling techniques are necessary because they allow for considering all the processes that affect the geostructures' performance (Rotta Loria, 2020). The following sections provide a non-exhaustive summary of the theory that supports understanding of the behavior and performance of energy geostructures, as well as an overview of the current state of knowledge and expertise in this evolving field.

2.1 *Analytical methods*

The strength of analytical methods for the analysis of energy geostructures lies in their ability to provide efficient and relatively simple solutions for initial assessments, which makes them suitable for preliminary evaluations and conceptual design stages. They allow for obtaining a first-order understanding of the systems' behavior before more detailed numerical analyses. Analytical methods are available to look at the energy, the structural and the geotechnical aspects that govern the behavior of energy geostructures.

Thermal power charts and thermal resistance models can be used to look at the energy performance of the structures. Power charts (as in Figure 3A) help estimate the amount of thermal energy that can be extracted from or injected into the different types of energy geostructures (e.g., SIA-D0190, 2005; Batini et al., 2015; Zannin et al., 2022; Rotta Loria et al., 2023). It is worth noting that such charts provide a conservative estimate of the thermal power since they are based on steady-

flux energy operating conditions. Thermal resistance models are a more advanced analytical method where the energy performance is evaluated by applying the concept of thermal resistance. Both time-dependent and time-independent thermal resistance formulations are incorporated. Traditionally, these approaches were developed for vertical borehole heat exchangers, but currently, adaptations have been introduced to address the unique characteristics of energy geostructures (Li and Lai, 2012; Loveridge and Powrie, 2014; Kürten et al., 2015; Tinti et al., 2017).

To assess the structural behavior of energy geostructures analytically, stress charts, continuum analysis models, or load-transfer models can be used. Stress charts have been adapted from conventional foundation piles under purely mechanical loading to account for the additional thermal effects present in energy piles and barrettes (e.g., Garbellini and Laloui, 2019; Laloui and Rotta Loria, 2019; Rotta Loria et al., 2023). Using continuum analysis models is a more advanced approach, where simplified formulations from continuum elastic theory are used (Laloui et al., 2003; Zannin et al., 2020). Last, load-transfer models provide a way to evaluate the equilibrium of energy geostructures by discretizing the structure into a series of elements. The interaction of each element with the surrounding soil is governed by a constitutive law, which can be derived theoretically or determined experimentally. They thus offer the most detailed analytical representation of the effects of both mechanical and thermal loads and can be applied to a range of configurations (e.g., Knellwolf et al., 2011; Ravera et al., 2020; Zannin et al., 2020). Load-transfer methods also address geotechnical aspects by providing information on displacements and soil-structure interface resistance.

Other analytical methods to look at the geotechnical behavior of energy geostructures are the use of displacement charts, interaction factor charts or continuum-based methods. Displacement charts (as in Figure 3B) are similar to the stress charts, but present estimates of vertical displacements for energy geostructures (e.g., Rotta Loria and Laloui, 2016; 2017; Rotta Loria et al., 2023). The displacement values are often normalized per unit of applied thermal load, thereby allowing a straightforward assessment across different loading conditions. Interaction factor charts (as in Figure 3C) are used to consider the interaction that arises when energy piles are placed in closely spaced groups and provide a means to quantify how the loading of one pile affects the neighboring piles under both thermal and mechanical loads, thereby enabling engineers to account for group effects in the preliminary design of energy pile systems (e.g., Rotta Loria and Laloui, 2016; 2017; Ravera et al., 2020a). The charts exist for configurations with and without a slab connecting the pile heads. Continuum analysis models that incorporate geotechnical aspects have been developed for energy pile groups, based on Mindlin's equations (e.g., Rotta Loria et al., 2017). They allow interaction factors to be defined along the length of the pile instead of only at the pile head.

2.2 *Numerical methods*

Numerical analyses represent a more advanced approach to analyze and design energy geostructures. They allow for the simultaneous analysis of energy, structural and geotechnical behavior. Simulations model heat and mass transfer of the structure and temperature or thermal power variations are applied to the geostructure. Some simulation tools can also represent the embedded pipes and their interaction with the surrounding material in the models. Time-dependent simulations are used to represent the thermal loads in energy systems that fluctuate over time.

The structural behavior is analyzed by prescribing displacements or applying forces, with either structural elements in the simulations or simplified stiffness quantifications. Concrete is often idealized as a linear thermo-elastic material, but advanced analyses may include tensile resistance or thermal creep effects. Geotechnical simulations include soil properties to represent the heat transfer, mass transfer, and deformation phenomena.

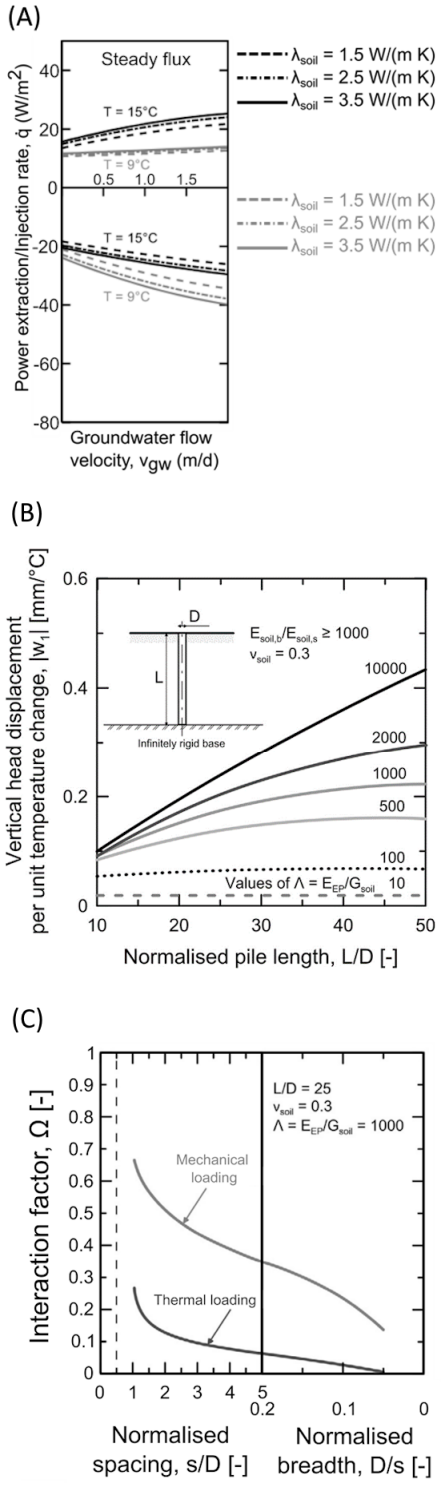

Figure 3. Examples of (a) a thermal power chart (modified from Zannin et al. (2022), (b) a displacement chart (Rotta Loria and Laloui, 2017) and (c) an interaction factor chart (modified from Rotta Loria and Laloui, 2016).

3 APPLICATIONS

This section introduces several case studies that illustrate the use of energy geostructures in real-world engineering projects. The section begins with a complex thermo-active foundation system of a building. It then transitions to the topic of underground energy infrastructures, where the analysis specifically integrates the influence of the internal air domain on the performance of energy geostructures in two different settings.

3.1 *Energy buildings*

The recent geothermal activation of the Upper One Tower in Warsaw (Ravera et al., 2024) represents an example of a complex energy foundation system, integrating energy barrettes, walls, and slabs. Time-dependent thermo-mechanical numerical simulations were employed during the design phase, enabling a comprehensive assessment of the energy, geotechnical, and structural performance of the foundation over the building's design lifetime (Figure 4).

The analysis showed that geostructures with a higher density of closely spaced thermally activated elements experience more pronounced temperature variations. This non-uniform thermal distribution induces complex mechanical responses that can deviate significantly from the expected behavior of individual foundation components (walls, slabs, barrettes), highlighting the need for an advanced engineering design approach for such systems.

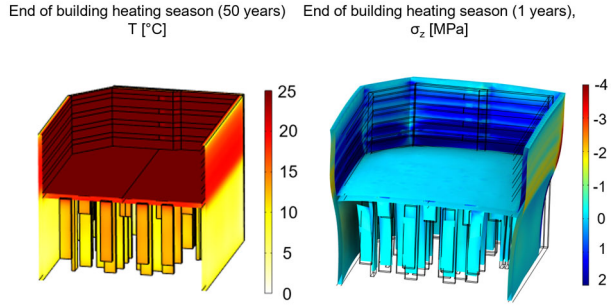

Figure 4. Numerical model used to predict (left) the temperatures and (right) stress fields of the energy barrettes, walls and slabs (modified from Ravera et al., 2024).

3.2 *Energy metro stations*

A numerical study on the energy performance of a metro station in Bucharest is summarized here (Ten Bosch et al., 2025). The work provides a valuable foundation for practitioners seeking to estimate the geothermal potential of these structures. The metro station studied has a common design that is employed in many underground stations worldwide.

A novel way to account for the internal airflow dynamics of these geostructures was used. Since internal airflow dynamics play a large role when estimating the overall harvestable heat from energy infrastructure (e.g., Di Donna et al., 2017; Zannin et al., 2022), it is important to properly represent this domain in numerical simulations. Complex patterns of airflow and temperature development are expected in underground metro stations as a result of metro train movement, braking, passenger flow, and technical infrastructure inside the air domain of the station (Figure 5).

Fire Dynamics Simulations (FDS) were used to look at these factors, which provided a detailed understanding of the stations' internal air domain. Representative convective heat flux boundary conditions for heat transfer simulations of the full station could then be deduced, allowing for estimation of the geothermal potential of the structure.

For cases with comparable geometry and conditions to the setting analyzed in this study, the thermal power charts presented in Figure 6 can be used to make this estimation. Otherwise, advanced numerical modelling with an equivalent convective heat transfer coefficient over time can provide reasonable results while considering varying airflow conditions over time caused by metro movements.

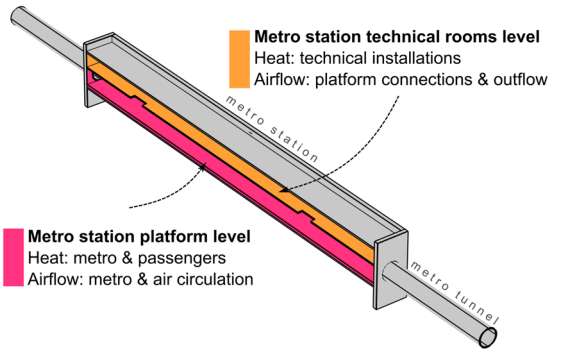

Figure 5. Cross-section of a metro station with the relevant airflows and heat sources (modified from Ten Bosch et al., 2025).

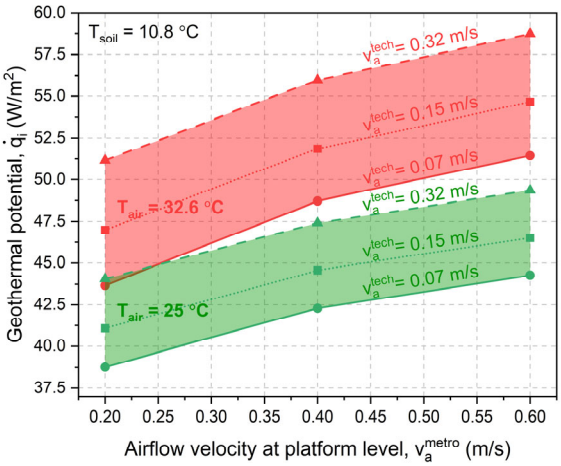

Figure 6. Geothermal potential for an energy metro station, considering variations in internal airflow conditions (modified from Ten Bosch et al. (2025).

3.3 *Underground data center*

Another advanced application is the use of the technology in the setting of underground data centers, which are increasingly more popular due to both digitalization and population growth. In this setting, it is important to consider the interactions between ventilation and geothermal systems, since daily ventilation requirements are often determined by internal air temperature limitations.

This interaction was recently numerically explored by Ten Bosch et al. (2024), who observed a reduction in internal air temperature of the data center with the implementation of ground heat exchangers into the walls and slab of the structure. This cooling effect was observed after the position of the geothermally activated section, following the direction of airflow, and it was stronger for implementing more heat exchanger tubes, see Figure 7.

This effect of air temperature reduction was then used to explore optimization of the system design. By implementing geothermal heat exchangers in such settings, a reduction in mechanical ventilation requirements is possible while still respecting the air temperature limitations originating from acceptable work conditions within the data center (see

Figure 8). This reduction in mechanical ventilation requirements can also lead to significant savings in operational expenses for the ventilation system.

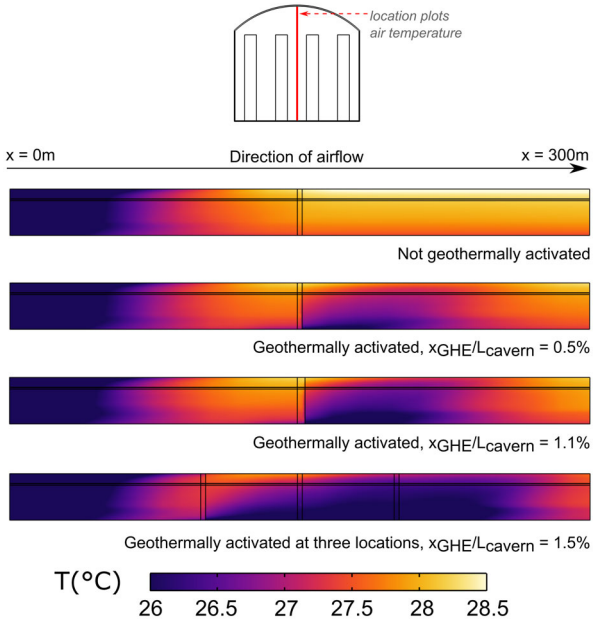

Figure 7. 2D plots of internal air temperature of the underground data center for different scenarios of geothermal activation (modified from Ten Bosch et al. (2024)).

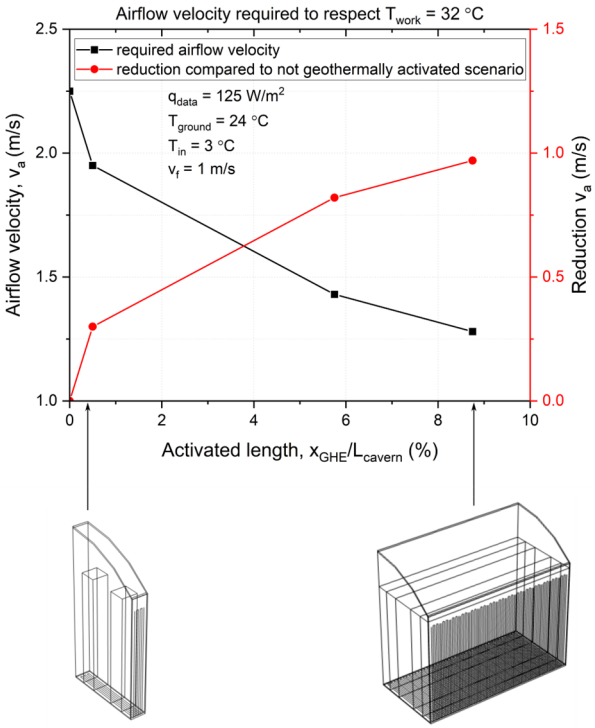

Figure 8. Relation between airflow velocity required to respect an air temperature limitation in the data center and the length of the geothermal activation in the cavern (Ten Bosch et al., 2024).

4 CLOSURE

Research into energy geostructures has rapidly matured over the last thirty years, evolving from studies focused on individual energy piles to a comprehensive investigation of different earth-contact structures, such as walls, slabs, and barrettes. This progression represents a shift from analyzing isolated structural components towards integrating them as holistic energy systems within urban environments. Despite this progress, energy geostructures are still often seen as innovations rather than the norm. There is massive untapped potential in existing underground infrastructures running through our cities, which should be leveraged to provide cooling and heating for both surrounding buildings and for the infrastructure itself. This work specifically highlighted this opportunity in complex applications, including major infrastructure like metro stations and underground data centers. The results presented demonstrate the inherent versatility and high efficiency of these large-scale energy geostructures, confirming that their adoption is a practical, impactful, and fully viable strategy for developing sustainable and resilient cities and infrastructure.

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