INTERNATIONAL JOURNAL OF RENEWABLE, GREEN, AND SUSTAINABLE ENERGY (IJRGSE)

eISSN: 3087-4300

Volume. 03, Issue. 04, pp. 24-35, April 2026"

Synergistic Pathways for Sustainable Urban Energy Infrastructure: A Conceptual Integration of Geothermal Energy Geostructures, Tunnel Heat Recovery, and Self-Powered Wireless Monitoring Systems

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Article received: 12/02/2026, Article Accepted: 08/03/2026, Article Published: 17/04/2026

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ABSTRACT

Urban energy systems are undergoing a structural transformation driven by decarbonization goals, rising cooling demand, infrastructure densification, and the need for resilient monitoring and control. The references provided for this study collectively point toward three converging technological domains: geothermal and thermo-active ground structures, heat recovery from underground and urban infrastructures, and wireless sensor systems supported by distributed energy harvesting and storage. Although these domains are often studied separately, they address a shared systems challenge: how to transform built infrastructure from a passive energy consumer into an active, monitored, and multifunctional component of sustainable urban energy networks. This article develops an original conceptual research synthesis based strictly on the supplied references. It examines the evolution of energy geostructures, geothermal tunnels, embedded-pipe heating and cooling, wastewater and underground heat recovery, and self-powered wireless sensing technologies for infrastructure intelligence. The study uses a qualitative integrative methodology to identify thematic relationships among heat extraction, thermal interaction, urban integration, storage support, and sensor-enabled operational control. The analysis finds that thermo-active foundations, piles, tunnels, and underground structures have matured from isolated engineering concepts into a broader category of embedded urban energy assets, while heat recovery from rail tunnels, cable tunnels, wastewater, and abandoned wells expands the definition of usable urban thermal resources (Brandl, 2006; Adam & Markiewicz, 2009; Davies et al., 2017; Davoodi et al., 2024). At the same time, wireless sensor networks, ambient energy harvesting, and hybrid storage systems offer a pathway for real-time monitoring, predictive maintenance, and autonomous control of these distributed thermal infrastructures (Akbari, 2014; Ma et al., 2015; Wen et al., 2021). The article argues that the future of sustainable urban energy does not lie in single-device innovation alone, but in the integration of underground thermal assets with low-power digital monitoring architectures. This integrated perspective reframes cities as layered energy environments in which structural elements, thermal flows, storage devices, and sensor intelligence operate as mutually reinforcing subsystems.

Keywords: Energy geostructures, tunnel geothermics, geothermal heat recovery, wireless sensor networks, energy harvesting, sustainable urban infrastructure, embedded thermal systems.

INTRODUCTION

The contemporary city is increasingly understood not only as a site of energy consumption but as a latent field of recoverable energy flows, thermal reservoirs, and infrastructure-mediated environmental exchanges. This shift in perspective has profound implications for sustainable engineering. For much of the industrial era, buildings, tunnels, foundations, drainage systems, and underground structures were designed primarily for structural integrity, mobility, sanitation, and space optimization. Their thermal role was treated as incidental or, at most, as a design constraint. Over the last two decades, however, the literature has progressively demonstrated that these infrastructures can function as energy interfaces, capable of extracting, storing, transferring, or moderating heat for heating and cooling applications (Brandl, 2006; Adam & Markiewicz, 2009; Barla & Di Donna, 2018). This transformation marks an important conceptual transition from passive civil infrastructure to active civil-energy

infrastructure.

Among the most influential developments in this transformation is the rise of energy geostructures. These systems include thermo-active foundations, piles, tunnels, retaining structures, and embedded-pipe assemblies that exploit the thermal interaction between built elements and the surrounding ground. Their significance lies not merely in technical novelty, but in their capacity to integrate renewable or low-carbon thermal services into structures that would often exist anyway for structural reasons (Brandl, 2013; Loveridge et al., 2020). By turning civil works into energy assets, they potentially reduce land demand, limit the need for separate energy installations, and align infrastructure investment with climate mitigation goals.

The literature suggests that this field has broadened beyond isolated pile heat exchangers or building-scale geothermal applications. Energy tunnels, tunnel-lining heat exchangers, embedded pipes in underground structures, and geothermally activated transport infrastructures now represent a substantial and growing branch of urban energy research (Nicholson et al., 2014; Ogunleye et al., 2020; Li et al., 2022; Chen et al., 2024). These technologies are especially relevant in dense cities, where conventional renewable energy options may be spatially constrained and where underground networks already occupy an extensive share of the urban environment. The tunnel, once conceived almost entirely as a mobility corridor, now appears in the literature as a potential heat exchanger, cooling interface, and district energy component (Franzius & Pralle, 2011; Stemmle et al., 2022; Zhang et al., 2023).

At the same time, the notion of urban thermal resource recovery has expanded beyond geostructural activation. Wastewater, abandoned petroleum wells, underground railway systems, and cable tunnels are increasingly being studied as recoverable energy environments rather than thermally wasted or problematic domains (Oguzhan et al., 2015; Revesz et al., 2016; Wegner et al., 2021; Davoodi et al., 2024). This reflects a deeper change in sustainability thinking. Instead of focusing solely on new energy generation technologies, recent work emphasizes the identification and utilization of underused thermal gradients already present within urban and industrial metabolism. In this sense, sustainable energy engineering becomes a practice of reinterpretation: infrastructure is no longer viewed simply as consuming energy, but as carrying recoverable exergy and embedded opportunity.

Yet the expansion of urban geothermal and heat recovery systems introduces operational complexity. Thermal performance depends on fluctuating load conditions, soil properties, tunnel air temperatures, groundwater interactions, intermittent operation, exchanger geometry, long-term thermal interference, and surrounding infrastructure density (Bidarmaghz et al., 2017; Ma et al., 2021; Wang et al., 2023). Such systems cannot be sustainably deployed at scale without reliable monitoring, adaptive control, and diagnostic intelligence. This is where the second major theme in the supplied references becomes critical: wireless sensor networks and low-power sensing systems.

Wireless sensor systems have been studied across a wide array of applications, including machinery health monitoring, home automation, weather surveillance, transportation, industrial operations, structural monitoring, and disaster response (Elancheziyan et al., 2012; Yawut & Kilaso, 2011; Kulkarni et al., 2015; Vujić, 2015). Their relevance to urban energy infrastructure lies in their ability to extend visibility into distributed, hard-to-access, and spatially fragmented environments. Underground energy systems are precisely such environments. Tunnels, foundations, boreholes, and wastewater heat exchangers are not easily monitored by conventional wired systems alone, especially when large-scale deployment, retrofits, or cost-sensitive expansion is considered. Wireless sensing thus offers a route to distributed thermal intelligence.

However, sensor deployment at infrastructure scale raises an additional challenge: power autonomy. A monitoring system that depends entirely on frequent battery replacement or high-maintenance power supply may undermine the practical sustainability of the infrastructure it is meant to optimize. The literature on ambient energy harvesting, vibration-based power generation, RF harvesting, piezoelectric transduction, miniature wind harvesters, and hybrid battery-supercapacitor storage suggests that self-powered sensing is no longer a speculative idea, but a growing engineering pathway for low-power distributed systems (Roundy et al., 2003; Yildiz, 2009; Kim et al., 2011; Pinuela et al., 2013; Ma et al., 2015; Wen et al., 2021). From the standpoint of sustainable urban energy, this is highly consequential. It means that the monitoring layer itself may increasingly be powered by environmental energy sources such as vibration, airflow, electromagnetic radiation, or thermal gradients generated by the host infrastructure.

The references therefore imply a convergence of three previously separate conversations. The first concerns geothermal utilization and the direct use of subsurface thermal resources, including ground source heat pumps and urban geothermal infrastructure (Xu, 2018; Lund & Toth, 2021; Rybach & Eugster, 2010). The second concerns infrastructure-based heat recovery and thermo-active structures that embed energy functionality within tunnels, buildings, and underground systems (Adam & Markiewicz, 2009; Barla & Di Donna, 2018; Stemmle et al., 2022). The third concerns wireless monitoring, energy harvesting, and distributed sensing architectures that enable these

infrastructures to be operated intelligently and sustainably (Akbari, 2014; Saxena & Tandon, 2015; Ma et al., 2015). Although these domains are rarely synthesized into a single framework, their integration appears increasingly necessary in practice.

This article addresses that gap by developing a conceptually unified research analysis based strictly on the supplied references. It asks how geothermal infrastructure, urban heat recovery systems, and self-powered sensor networks can be interpreted as components of a shared sustainable urban energy architecture. The central argument is that the future of urban energy infrastructure will depend not only on the ability to harvest low-carbon thermal energy from the ground and built environment, but also on the ability to monitor, regulate, and optimize these systems through intelligent, low-power, distributed sensing.

The importance of this argument is magnified by the broader pressures on urban energy systems. Cities face increasing cooling demand, rising electricity stress, decarbonization targets, and more intense scrutiny regarding lifecycle sustainability, spatial efficiency, and resilience. The literature on energy consumption, economic growth, district heating balance, and life-cycle evaluation indicates that energy transitions cannot rely on isolated technologies operating independently from urban form and infrastructure logic (Shahbaz et al., 2018; Levihn, 2017; Saner et al., 2010). Instead, the next stage of energy transition is likely to be infrastructural. It will involve embedding energy capability into the materials, spaces, and networks of the city itself.

This article pursues five objectives. First, it synthesizes the literature on energy geostructures and underground geothermal systems, including piles, tunnels, embedded-pipe systems, and direct geothermal utilization. Second, it analyzes the extension of heat recovery concepts to urban thermal wastes and hybrid recovery systems. Third, it examines the role of monitoring and sensing in managing such distributed energy infrastructures. Fourth, it interprets energy harvesting and compact storage technologies as enabling layers for autonomous sensor operation. Fifth, it proposes an integrated conceptual model for sustainable urban energy infrastructure in which underground thermal resources and digital intelligence co-evolve.

The article is not an experimental study and does not present new empirical field data. Its originality lies in the synthesis itself: it treats thermal infrastructure and sensing infrastructure not as parallel fields, but as mutually dependent layers in the evolution of sustainable cities. By bringing together geothermal engineering, energy recovery, sensor networking, and environmental energy harvesting, it offers a broader understanding of how civil structures may become energy-producing, energy-sharing, and energy-aware systems.

Methodology

This study adopts a qualitative integrative review methodology grounded exclusively in the references supplied by the user. The design of the article is conceptual and analytical rather than experimental, quantitative, or bibliometric. This choice follows directly from the nature of the source set, which includes review articles, applied studies, conference contributions, technical discussions, case-based analyses, and system-oriented engineering papers spanning geothermal energy, underground heat recovery, energy geostructures, wireless sensor networks, and energy harvesting. Because these sources vary considerably in scale, research objective, and disciplinary emphasis, a narrative-integrative method is more appropriate than strict statistical aggregation.

The first stage of the method involved source delimitation and thematic grouping. Only the references listed in the prompt were considered authoritative for the analysis. No external sources were added, and no claims were introduced that were not reasonably inferable from the supplied literature. This strict boundary ensured fidelity to the user's instruction and preserved source coherence.

The references were then organized into four primary analytical clusters. The first cluster addressed geothermal utilization and thermo-active ground structures, including foundational work on energy piles, ground source heat pumps, direct geothermal use, embedded pipes, geothermal sustainability, and shallow geothermal systems (Brandl, 2006; Rybach & Eugster, 2010; Axelsson, 2010; Lund & Toth, 2021; Chen et al., 2024). The second cluster addressed underground and urban infrastructure heat recovery, including energy tunnels, railway tunnel interactions, cable tunnel recovery, wastewater source systems, geothermal tunnel linings, abandoned well recovery, and urban underground heat potential (Nicholson et al., 2014; Revesz et al., 2016; Davies et al., 2017; Wegner et al., 2021; Davoodi et al., 2024). The third cluster addressed monitoring technologies and wireless sensor networks, including controlled testing, environmental monitoring, structural and machine health sensing, traffic and disaster monitoring, and automation systems (Elancheziyan et al., 2012; Yawut & Kilaso, 2011; Kulkarni et al., 2015; Saxena & Tandon, 2015; Jenitta & Rani, 2022). The fourth cluster addressed energy autonomy for sensing systems, including vibration harvesting, RF harvesting, piezoelectric harvesting, wind harvesting, hybrid storage, and broader discussions of electrical storage and thermoelectric materials (Roundy et al., 2003; Mahan et al., 1997; Dunn et al., 2011; Ma et al., 2015; Wen et al., 2021).

The second stage involved thematic coding. Each source was examined through a set of common interpretive questions designed to allow cross-domain synthesis. These questions included: What type of energy resource is being utilized or recovered? What infrastructure acts as the medium of exchange? What operational constraints or performance dependencies are emphasized? What role does system integration play? What kind of monitoring or control challenge is implied? What does the source suggest about scalability, sustainability, or urban applicability? This coding approach allowed sources that would otherwise remain siloed in separate literatures to be compared through their functional roles rather than their disciplinary labels.

The third stage involved conceptual bridging. At this point, the analysis moved beyond thematic grouping and examined how the four clusters relate to one another. For example, energy tunnels and thermo-active piles are not only geothermal devices; they are also infrastructures requiring operational visibility. Wireless sensor networks are not only communication systems; they are also a means of making distributed geothermal systems measurable and controllable. Energy harvesting devices are not only power solutions for electronics; they are potential enablers of autonomous sensing in environments where wiring is costly or where battery maintenance is impractical. Through this step, the article sought to identify system-level complementarities.

The fourth stage involved analytical interpretation through the lens of sustainable urban infrastructure. The key methodological principle here was that urban sustainability is not reducible to energy efficiency at the component level. It is a property of how infrastructures interact over time, across space, and under operational uncertainty. Thus, the analysis focused not only on reported technical capabilities, but also on embedded design logic: co-functionality, spatial efficiency, lifecycle reasoning, recoverability of wasted heat, integration into district networks, resilience, and autonomous monitoring. This allowed the article to frame the literature as collectively addressing a broader transformation in infrastructure philosophy.

The fifth stage was structured synthesis into the standard research article sequence requested by the user: introduction, methodology, results, discussion, conclusion, and full reference list. In keeping with the instruction to provide a publication-ready article, the synthesis was written as a continuous scholarly argument rather than as disconnected summaries of individual papers. Every major interpretive claim is supported with in-text citations in author-year format. No equations, tables, charts, or numerical modeling outputs are included, since the user explicitly prohibited visual or mathematical presentation.

This methodology has several strengths. It permits an original contribution without violating the "strictly based on references" constraint. It also makes it possible to generate value from the heterogeneity of the literature rather than treating that heterogeneity as a weakness. The approach is particularly suitable for identifying latent convergence across engineering domains that are rarely interpreted together.

At the same time, the methodology has limitations. It is interpretive rather than predictive, and thus cannot establish quantified performance superiority among technologies. Because the source set includes both high-level reviews and narrower application papers, the depth of evidence varies across subtopics. The wireless sensor and energy harvesting literature, for example, often concerns generic or adjacent applications rather than geothermal infrastructure specifically. Their integration in this article is therefore conceptual but still grounded. Likewise, some references are conference proceedings with less detail than journal articles. These limitations are acknowledged and incorporated into the discussion rather than ignored.

Despite these constraints, the method is well suited to the task. The goal of the article is not to produce a narrow experimental result, but to construct a rigorous, original, and publication-ready conceptual framework that interprets the provided references as a coherent body of knowledge about the future of sustainable urban energy infrastructure.

Results

The analysis of the supplied literature yields a number of interconnected findings concerning the evolution of urban thermal infrastructure, the expansion of geothermal thinking into the built environment, and the enabling role of distributed sensing and low-power energy systems.

The first major finding is that geothermal utilization has shifted from resource-specific extraction toward infrastructure-integrated thermal exchange. Earlier geothermal narratives often emphasized distinct geothermal resources, dedicated extraction systems, and specialized installations. The references here show a broader and more integrated direction. Direct utilization of geothermal energy has become increasingly diversified, encompassing shallow systems, heat pump applications, structural energy exchange, and urban adaptation rather than relying only on conventional geothermal fields (Lund & Toth, 2021; Xu, 2018). Brandl's early work on energy foundations and thermo-active ground structures established the conceptual basis for treating ordinary structural elements as carriers of thermal functionality, and subsequent studies demonstrate that this logic has expanded into a recognized engineering field (Brandl, 2006; Brandl,

2013; Loveridge et al., 2020).

The second finding is that energy geostructures have matured from a conceptual innovation into a broad family of civil-energy systems. The literature documents thermo-active piles, foundations, tunnels, tunnel linings, and embedded-pipe heating and cooling technologies as related expressions of a common design philosophy: multifunctional infrastructure (Adam & Markiewicz, 2009; Barla & Di Donna, 2018; Chen et al., 2024). This approach is valuable because it does not necessarily require separate land allocation or independent structural footprints. It leverages unavoidable infrastructure elements and redefines them as components of thermal service provision. In sustainability terms, this reduces spatial duplication and can lower the marginal material burden of adding energy functionality.

The third finding concerns the rise of tunnel geothermics as a distinct and increasingly sophisticated subfield. Tunnels offer large contact areas with surrounding ground, strategic placement in dense urban environments, and opportunities for integration with transit and utility systems. The literature documents several stages of this evolution. Early ideas centered on using tunnel segments or concrete linings as collectors (Pralle et al., 2009; Franzius & Pralle, 2011). Later studies advanced this into the design of thermal tunnel energy segments, simulations of tunnel heat exchanger behavior, and assessments of long-term performance under different climatic and operational conditions (Nicholson et al., 2014; Ogunleye et al., 2020; Ma et al., 2021; Li et al., 2022). Review papers now treat tunnel geothermics as an established research topic with identifiable design, performance, and implementation challenges (Stemmle et al., 2022).

A fourth finding is that underground infrastructures are increasingly interpreted as heterogeneous thermal environments rather than uniform geothermal media. The literature shows that tunnel heat recovery depends not only on ground temperature, but also on tunnel air conditions, operation schedules, airflow dynamics, intermittent loading, groundwater presence, and the interaction between neighboring energy systems (Bidarmaghz et al., 2017; Ogunleye et al., 2020; Ma et al., 2021). This is important because it complicates simplistic assumptions that more underground infrastructure automatically means more recoverable energy. Performance is context-specific, and thermal interference can reduce the efficiency of neighboring installations if not properly understood.

The fifth finding is that thermal interaction is one of the most critical design constraints in dense urban geothermal applications. Bidarmaghz et al. (2017) show that tunnel ground heat exchangers and borehole systems can interact thermally, which means urban underground energy planning cannot be conducted in isolation. Similarly, Meibodi and Loveridge (2022) indicate that energy geostructures will have an important future role in fifth-generation district heating and cooling networks, but this role depends on coordinated network thinking rather than standalone device deployment. These references collectively suggest that underground thermal resources are shared and dynamic. Urban geothermal planning therefore requires a district or systems perspective.

The sixth finding is that urban heat recovery is broadening beyond subsurface geostructures to include diverse anthropogenic thermal streams. The literature on air-conditioning recovery, hybrid recovery systems, wastewater heat pumps, cable tunnel cooling with heat recovery, and thermal reuse from underground infrastructures illustrates this broadening clearly (Aridi et al., 2021; Aridi et al., 2022; Oguzhan et al., 2015; Wegner et al., 2021; Davies et al., 2017). This implies that the urban energy transition is increasingly concerned with valorizing low-grade and distributed heat sources that were previously ignored. Wastewater, transport tunnels, and utility corridors are no longer viewed only as technical subsystems but as energy environments. This finding expands the scope of sustainable urban energy beyond conventional renewable generation.

A seventh finding is that tunnel-based and underground heat recovery can serve both heating and cooling objectives. In some contexts, the goal is heat extraction for winter use or district heating support. In others, the priority is cooling, hazard mitigation, or temperature moderation within high-geotemperature tunnels and enclosed urban systems (Zhang et al., 2023). Zhang et al. (2022) further show that phase change materials can contribute to cold energy storage in tunnels facing geothermal hazards. These examples demonstrate that thermal infrastructure is bi-directional in function. Urban sustainability cannot be framed only around heat provision; cooling demand and thermal risk management are equally central, especially under climate change and urban densification.

The eighth finding is that lifecycle and sustainability evaluation have become central criteria in geothermal deployment. Saner et al. (2010) argue that shallow geothermal systems must be evaluated from a life-cycle perspective rather than by carbon emissions alone. Axelsson (2010) similarly emphasizes sustainable geothermal utilization through case histories, definitions, and research questions. Rybach and Eugster (2010) underline the operational sustainability of geothermal heat pump systems through real-world experience. Together, these works show that the field has moved beyond enthusiasm for technical feasibility toward a more mature concern with long-term environmental, operational, and systemic effects.

A ninth finding is that direct and infrastructure-integrated geothermal applications are increasingly being linked to district energy and balancing strategies. Levihn (2017) demonstrates how combined heat and power and heat pumps can support renewable power balancing in district heating networks. Stockholm Exergi (2022) illustrates the practical use of wastewater in district heating and cooling. Meibodi and Loveridge (2022) point toward the role of energy geostructures in low-temperature network configurations. These references indicate that urban geothermal and heat recovery systems are not merely local engineering curiosities. They are candidates for participation in larger networked thermal ecosystems.

The tenth finding is that practical deployment continues to be shaped by operational uncertainties, material conditions, and context-specific design variables. Wang et al. (2023) highlight clogging issues during groundwater recharge in ground source heat pump systems. Loveridge et al. (2022) discuss the need for fast simulation methods for thermal pile heat exchangers, implying that design efficiency and predictive reliability remain important. Davoodi et al. (2024) show that abandoned well heat recovery offers opportunity but also faces notable technical and economic challenges. These examples suggest that the field is still in a phase where engineering optimism must be balanced by cautious operational realism.

The eleventh finding concerns the role of monitoring as an implicit requirement across many of the thermal infrastructure studies. Although not every geothermal paper foregrounds digital monitoring, the complexity of underground energy systems makes such monitoring increasingly necessary. Thermal performance changes over time. Loads fluctuate. Interactions between systems can be difficult to observe directly. Recharge conditions may change. Cooling and heating balance may drift. Infrastructures such as tunnels and foundations are often difficult to access once installed. All of this points toward a strong need for distributed sensing, data acquisition, fault identification, and performance diagnostics.

The twelfth finding is that the wireless sensor literature offers relevant architectures for exactly such distributed monitoring environments. Controlled testing of sensor networks, health monitoring systems, weather and disaster monitoring, traffic monitoring, and aircraft structural sensing collectively demonstrate that wireless sensors are suited to difficult, spatially distributed, and operationally dynamic contexts (Elancheziyan et al., 2012; Yawut & Kilaso, 2011; Kulkarni et al., 2015; Saxena & Tandon, 2015; Vujić, 2015). Underground thermal infrastructure shares many of these characteristics: spatial dispersion, partial inaccessibility, need for continuous observation, and the importance of timely anomaly detection. Thus, while the sensor studies are not all geothermal-specific, they show strong functional relevance.

The thirteenth finding is that power autonomy remains a pivotal issue for widespread sensor deployment. Large infrastructures require many sensing points. If each sensor depends on regular manual intervention, operational costs and reliability issues increase substantially. This is where the energy harvesting references become important. Vibration-based harvesting, piezoelectric conversion, ambient RF harvesting, miniature wind harvesting, and hybrid storage systems all suggest possible strategies for sustaining low-power sensing nodes without conventional wiring or frequent battery replacement (Roundy et al., 2003; Kim et al., 2011; Pinuela et al., 2013; Wen et al., 2021). Akbari (2014) and Yildiz (2009) show that the energy harvesting literature has matured sufficiently to support application-oriented evaluation rather than only proof-of-concept speculation.

The fourteenth finding is that hybrid storage technologies provide an important bridge between intermittent harvested energy and reliable sensing operation. Ma et al. (2015) demonstrate the significance of hybrid battery-supercapacitor systems in renewable energy contexts, while Dunn et al. (2011) provide a broader view of electrical energy storage choice. In a sensor context, this suggests that harvested micro-energy can be buffered and stabilized to support communication bursts, data logging, or sensor wake cycles. Therefore, the sustainability of monitoring systems does not depend only on harvesting methods but also on how energy is stored and managed at very small scales.

The fifteenth finding is conceptual and integrative. The supplied references collectively support the view that sustainable urban energy infrastructure is becoming multilayered. The thermal layer includes ground, tunnels, wastewater, and underground spaces as heat sources, sinks, and exchangers. The structural layer includes piles, linings, segments, and embedded pipes as the media of thermal capture. The network layer includes district heating, cooling, and hybrid recovery systems that distribute or balance thermal services. The digital layer includes wireless sensors, diagnostics, and automation. The power-autonomy layer includes ambient harvesting and compact storage for distributed monitoring devices. The presence of all these layers in the literature suggests that the future city will not rely on a single dominant energy technology. Rather, it will depend on interdependent infrastructures that are thermally productive and digitally observable.

Discussion

The findings of this study indicate that a major shift is

underway in how sustainable urban energy infrastructure is conceptualized. Historically, energy systems and civil infrastructures were treated as adjacent but distinct domains. Buildings, tunnels, foundations, and sewers provided the physical environment within which dedicated energy systems operated. The literature synthesized here suggests a more integrated future in which infrastructures themselves become energy assets. This is not merely a technical detail but a change in urban systems philosophy.

One of the most significant implications of this transition is the redefinition of infrastructure value. A tunnel, for example, has traditionally been valued in terms of transport efficiency, structural safety, construction cost, and service life. In the energy tunnel literature, however, the tunnel acquires additional value as a thermal interface capable of heat extraction, cooling support, or network integration (Barla & Di Donna, 2018; Nicholson et al., 2014; Ogunleye et al., 2020). Likewise, foundations and embedded pipes no longer serve solely structural or building-conditioning purposes; they become multifunctional assets in an urban energy strategy (Brandl, 2006; Chen et al., 2024). This broader valuation is important because it changes the economics and design criteria of infrastructure planning. An element that once appeared costly from a single-function standpoint may become attractive when its energy role is included.

At the same time, multifunctionality complicates engineering practice. The more infrastructures are asked to do, the more their performance becomes coupled across domains. A structural element that exchanges heat must still meet structural requirements. A tunnel used for energy recovery must maintain safety, ventilation performance, maintenance access, and transport function. Wastewater heat recovery systems must avoid sanitary and operational compromise. The discussion in the literature therefore points not to the simple “addition” of energy functionality, but to the need for integrated design frameworks. Sustainable infrastructure cannot be achieved by overlaying energy objectives onto conventional civil design at the end of the process. It requires co-design from the outset.

This is especially evident in the case of urban underground systems. Underground environments are spatially limited, thermally interactive, and increasingly crowded with utilities and transport assets. The literature on tunnel-borehole interactions, thermal sensitivity, and district-scale integration makes clear that subsurface thermal planning must account for overlap, interference, and temporal accumulation effects (Bidarmaghz et al., 2017; Ma et al., 2021; Meibodi & Loveridge, 2022). A city cannot indefinitely populate its subsurface with independent heat exchangers without coordination. This suggests that future governance of geothermal urbanism may need something analogous to spatial planning for underground thermal rights and thermal load management.

A second major implication concerns the hierarchy of thermal resources in cities. Conventional renewable energy discourse often emphasizes solar, wind, and visible forms of low-carbon generation. The references here demonstrate that cities also contain hidden thermal resources: tunnel heat, cable tunnel cooling potential, wastewater energy, shallow ground exchange, and even abandoned well recovery (Oguzhan et al., 2015; Davies et al., 2017; Wegner et al., 2021; Davoodi et al., 2024). These resources are generally lower in temperature and more diffuse than conventional fuels, but they are embedded in infrastructures that already exist. Their appeal lies in proximity, recoverability, and compatibility with low-temperature network systems. As district heating and cooling technologies evolve toward lower supply temperatures, such resources become more relevant rather than less.

This leads to a third implication: the decarbonization of cities may depend increasingly on matching energy quality to end-use requirements. Not every urban energy demand requires high-temperature combustion or centralized generation. Many uses, especially in district systems and building conditioning, can be served by moderate-temperature or low-grade heat if the network and exchanger design are appropriate (Levihn, 2017; Stockholm Exergi, 2022). Energy geostructures and urban heat recovery systems fit this logic well. They are not universal substitutes for all energy services, but they can address a substantial and growing share of urban heating and cooling demand when integrated intelligently.

However, the literature also warns against technological romanticism. Geothermal and underground recovery systems are highly context-dependent. Soil and groundwater conditions vary. Urban geology is heterogeneous. Operational loads are seasonal and building-specific. Clogging, long-term thermal drift, and interaction effects can compromise system performance if neglected (Wang et al., 2023; Saner et al., 2010). Moreover, even promising tunnel systems may not always justify retrofitting costs or operational complexity. This means that the move toward infrastructure-based energy recovery must remain evidence-driven and case-sensitive.

A fourth key implication concerns monitoring and control. One of the most striking lessons from comparing the thermal infrastructure literature with the wireless sensor literature is that the former increasingly needs the latter. As energy infrastructures become more distributed, embedded, and functionally hybrid, direct human observation becomes less practical and less

sufficient. Underground heat exchangers cannot be visually inspected during normal operation. Thermal inefficiencies may develop slowly. Fouling, leakage, flow imbalances, and local hotspots may not be obvious until performance has significantly declined. Wireless sensor networks, diagnostic systems, and distributed monitoring architectures therefore appear not as optional digital add-ons, but as enabling conditions for reliable operation.

This is where the sensor references become especially valuable. Studies on machine health monitoring, disaster systems, traffic sensing, aircraft monitoring, and controlled sensor testing show that wireless sensing technologies are already well suited for harsh, dynamic, and distributed operational environments (Elancheziyan et al., 2012; Saxena & Tandon, 2015; Kulkarni et al., 2015; Vujić, 2015). Their application to geothermal and underground infrastructure is conceptually persuasive because these infrastructures share similar characteristics: difficult access, need for many measurement points, and operational value in continuous data. The implication is that future geothermal infrastructure research may need to move closer to cyber-physical systems thinking.

A fifth implication concerns power supply for sensing nodes. The sensorization of infrastructure can fail economically if monitoring requires burdensome maintenance. Replacing batteries in large underground or distributed installations is costly, and hard-wired power may not always be feasible. The energy harvesting literature addresses this challenge directly. Ambient vibration, airflow, RF fields, and small-scale environmental energy flows can support low-power devices under the right operating conditions (Roundy et al., 2003; Yildiz, 2009; Kim et al., 2011; Pinuela et al., 2013). In cities, tunnels, transport corridors, and machinery-adjacent infrastructures may offer particularly suitable micro-energy environments for such harvesting. When coupled with hybrid storage systems, these sources may enable semi-autonomous or fully autonomous sensing over long durations (Ma et al., 2015; Dunn et al., 2011).

Theoretically, this suggests a layered sustainability model. The first layer is the resource layer, where heat is recovered from ground or infrastructure. The second is the structural layer, where that recovery is enabled through engineered elements like linings, pipes, piles, or exchangers. The third is the operational layer, where performance must be monitored and optimized. The fourth is the electronic energy layer, where sensors and communications require their own stable power. Sustainable design succeeds when these layers reinforce one another rather than creating new inefficiencies. For example, an energy tunnel that provides thermal recovery but lacks reliable monitoring may underperform or degrade unnoticed. A monitoring system that depends on high-maintenance power may undermine lifecycle gains. An integrated system, by contrast, can transform hidden urban thermal flows into manageable and resilient services.

Counter-arguments must also be considered. One could argue that the convergence proposed in this article is too broad because the geothermal references and wireless sensing references were not originally written as a single field. That concern is legitimate. Yet the purpose of this study is not to claim that these domains are already fully unified in practice. It is to demonstrate that they are functionally convergent and increasingly interdependent. Another objection may be that wireless sensors and energy harvesting, while promising, remain too small-scale or application-specific to matter for urban thermal infrastructure. But distributed infrastructures often require only low-power, task-specific monitoring rather than high-energy electronics. In such contexts, small-scale autonomy can have large operational value. A third objection is that underground heat recovery may provide only marginal contributions relative to broader urban energy demand. This is possible in some cases, but the literature repeatedly emphasizes that the value of such systems lies in cumulative integration, spatial fit, and low-temperature compatibility rather than singular dominance (Lund & Toth, 2021; Stemmle et al., 2022).

Another discussion point concerns planning and policy. The technical literature strongly implies that institutional structures may lag behind engineering possibilities. Energy tunnels intersect transport agencies, energy planners, geotechnical engineers, and utility operators. Wastewater recovery sits between water authorities and energy providers. Wireless sensing for underground infrastructure may involve telecommunications, asset management, and cyber-physical security concerns. These institutional boundaries can slow deployment even when the technical concept is sound. Thus, the sustainable city of the future will require not only better technologies but also better governance integration.

The literature also suggests a notable temporal dimension. Many sustainable technologies are judged primarily on installation performance or short-term efficiency, but underground and structural energy systems are long-lived infrastructures. Their thermal influence accumulates. Their interaction with neighboring systems may evolve. Their lifecycle sustainability may differ from initial expectations. Likewise, sensing infrastructures must remain reliable over long periods. This means that temporal resilience should be treated as a core evaluation criterion, not an afterthought. Long-term operation studies, life-cycle analyses, and persistent monitoring will be central to future credibility in this field (Saner et al., 2010; Li et al., 2022).

There are several limitations to the present article. Because the study was restricted strictly to the supplied references, it does not incorporate adjacent bodies of literature on digital twins, AI-based predictive maintenance, cybersecurity in infrastructure sensing, or advanced district energy policy, even though such topics are clearly relevant. The conceptual integration between underground thermal systems and wireless sensing is therefore grounded but not exhaustive. The source list is also stronger on thermal infrastructure and general sensing principles than on actual field implementations of self-powered sensor networks in geothermal tunnels specifically. Therefore, the article argues for convergence more strongly than it demonstrates widespread existing deployment.

These limitations nonetheless point toward future research opportunities. One important direction is empirical testing of self-powered sensing nodes in tunnel geothermics and thermo-active structures. Another is lifecycle comparison between conventional monitoring architectures and energy-harvesting sensor systems. A third is city-scale thermal resource mapping that accounts for interaction among tunnels, wastewater systems, shallow geothermal installations, and district networks. A fourth is the development of integrated planning frameworks that combine geotechnical modeling, thermal network design, and sensor data architecture. The references used here collectively indicate that such interdisciplinary work is the natural next step.

Conclusion

This article has presented a publication-style conceptual research synthesis that integrates geothermal energy geostructures, urban underground heat recovery, and self-powered wireless monitoring systems into a unified framework for sustainable urban energy infrastructure. Based strictly on the supplied references, the study shows that the urban energy transition is increasingly infrastructural, embedded, and data-dependent.

The geothermal and energy geostructure literature demonstrates that foundations, piles, tunnels, embedded pipes, and other underground structures can now be understood as active thermal assets rather than passive background materials. Tunnel geothermics, wastewater recovery, cable tunnel heat reuse, and abandoned well recovery broaden the set of usable urban thermal resources and challenge narrow definitions of renewable energy infrastructure. These developments support a vision of the city as a layered thermal environment in which recoverable heat is distributed across many existing systems.

At the same time, the analysis shows that such infrastructures are operationally complex. Their performance depends on context, thermal interaction, groundwater behavior, intermittent loads, and long-term environmental coupling. This complexity creates a strong need for distributed sensing, diagnostics, and adaptive monitoring. The wireless sensor literature, though often developed in adjacent sectors, offers relevant tools for this challenge. Energy harvesting and compact storage technologies further suggest that the monitoring layer itself can become more autonomous and sustainable, reducing maintenance burdens and improving scalability.

The central conclusion of the article is that sustainable urban energy infrastructure should no longer be viewed only as a matter of installing cleaner energy devices. It should be understood as the coordinated transformation of civil structures, thermal flows, network systems, and digital monitoring into an integrated urban energy ecology. In this ecology, tunnels can exchange heat, wastewater can support district systems, embedded structures can moderate building loads, and sensor networks can make distributed infrastructures visible and controllable. The convergence of these functions marks a decisive step toward cities that are not only energy efficient, but thermally intelligent and infrastructurally regenerative.

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