

Advancing sustainable climatization by way of energy geostuctures in the retrofiting of buildings

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Abstract. Ground Source Heat Pump systems can significantly contribute to the decarbonization of the built environment but may incur high groundwork costs. Energy Geostuctures (EGs) are alternative solutions that combine Heat Pumps with heat exchanger circuits embedded in ground structures, such as foundations and retaining walls, thus reducing installation costs. This paper reviews the state of the art of EGs and the recent advances by the Italian project GEOREFIT, specifically addressing the applicability and efficiency of this technology in energy retrofiting of existing buildings and infrastructures. The paper exemplifies technical solutions for EG installation in refurbishment projects and shows that EG energy performance is generally comparable and sometimes higher than conventional Ground Heat Exchangers.

Keywords: Climatization, Energy Geostuctures, Energy Retrofitting, Near-Surface Geothermal Energy, Thermo-Active Foundations.

1 Introduction

In the ongoing energy transition process, sustainable solutions for the climatization of buildings need to be prioritized due to the sector's significant contribution to fossil fuel consumption and associated harmful emissions [1].

In Europe, considering that 85% of the building stock was built before 2000, when clean energy and energy conservation were not prior targets, existing buildings have a poor energy performance in 75% of the cases. As highlighted by the recent revision of the European Commission's Energy Performance of Buildings Directive [2], the renovation of the current building stock has the greatest potential for energy savings and emissions reductions in the coming decades. Since about 80% of the energy used in

buildings is for heating, cooling and domestic hot water, it is evident that a widespread use of Ground Source Heat Pump (GSHP) systems can fruitfully contribute to the decarbonization efforts. Besides the traditional GSHPs coupled with Ground Heat Exchangers (GHE), coupling the heat pump with so-called Energy Geostructures (EGs) represents a low-cost alternative solution, nowadays well validated for new buildings and highly promising for existing ones. EGs are structural elements embedded in the soil or in contact with it, equipped with water loops and thus capable of serving as ground heat exchangers [3-4].

GEOREFIT is a funded Italian research project that aims to assess the applicability and efficiency of EG technology for energy retrofitting of existing buildings and infrastructure, with the latter leveraging the renovation process currently underway in Italy, which will result in a significant upgrade of infrastructure property. The paper discusses the key features of EGs and reports on research findings, with a focus on thermal analysis and exemplary field studies and applications that show energy and cost savings.

2 Key features of energy geostructures

GSHPs coupled with borehole or horizontal heat exchangers incur critical groundwork costs, limiting their spread. In turn, combining the GSHP with a heat exchanger loop embedded in the building's foundation, such as piles and slabs, helps to reduce installation costs as the foundation already exists to provide a load-bearing function. Similarly, any ground-embedded structure could be thermally activated if equipped with heat exchangers. Thus, the concept of EGs, first introduced less than 50 years ago, now expands to include retaining walls, tunnel liners, steel sheet piles, and so on [5].

The energy produced by EGs is mostly used for building climatization and domestic hot water, but also for space climatization in service infrastructures such as underground stations and parking lots. The technology is also used as thermal control system to mitigate the effects of extreme temperatures: in transportation infrastructures, to preserve the integrity of surface materials as well as to improve road safety by melting snow and ice (road pavements, bridge decks, and airport runways) and in massive concrete structures subjected to high-temperature gradients between sunny and shaded areas [6-7].

Considering the dual structural and thermal function of EGs, the thermally induced stress-strain variation may cause concern. Extensive research has shown that structural stability is not compromised, but additional displacements may occur and should be taken into account, as they may be irreversible and accumulate over the seasonal cycles of system operation [8-9].

EGs are typically limited to the depth of a building's foundation, unless deep thermally activated structures, such as tunnel liners, are considered. Given their shallow depth, they are more susceptible to seasonal temperature fluctuations, resulting in variable thermal performance year-round, that may also be limited in extreme climates.

Comparing the heat exchange potential of EGs with Borehole Heat Exchangers (BHEs), the former can exploit the large mass of highly thermally conductive concrete, enhancing heat transfer efficiency, while BHEs can be drilled to significant depths,

accessing more stable temperatures and greater thermal potential. For EGs, since heat transfer efficiency depends on the concrete material, foundation dimension, and proximity of multiple thermally activated elements, optimal performance necessitates careful design, including the best layout of activated elements, that avoids thermal interference [10]. On the contrary, BHEs have greater flexibility in design and placement because independent of structural functions, easily allowing to optimize efficiency and to scale up the system in time. This makes them also suitable for retrofit applications, whenever additional drilling is possible.

However, the advantages of EGs stem from the cost and space efficiency, as well as the reduced environmental impact, since they reduce the need for separate drilling operations and materials, are installed within the building footprint, and minimize land disruption. These features make EGs ideal for new construction projects in space-constrained urban settings. The new challenge is to provide EG solutions for retrofitting existing buildings and infrastructure. In the following Sections, suitable concepts, prototypes and applications are described

3 Energy Micro-Piles

Micro-piles are foundation piles with a small diameter (less than 30 cm), particularly suitable for structural underpinning, and thus used in the rehabilitation of existing buildings, often of historical significance. When thermally activated, the so-called Energy Micro-Piles (EMPs) allow for combined structural and energy retrofitting. EMPs have a smaller diameter and length than conventional energy piles, which results in lower heat transfer rate due to shorter exchanger pipes and smaller contact surface with the ground. However, this limitation is partially offset by the fact that EMPs are typically installed in large numbers to perform their strengthening function.

The first thermo-mechanical tests on prototypes developed at the Engineering Campus of the University of Perugia, Italy [11-12] monitored fundamental data, including pile and soil temperatures, soil pore water pressures, and heat flow characteristics in the pipe circuit. Additional insights were gained through 3D Finite Element numerical modelling, which allowed for the analysis of the coupled thermo-mechanical process while accounting for the geometric complexity of practical applications [13-16].

Specifically, two full-scale EMP prototypes were installed to conduct thermomechanical loading tests, with comprehensive monitoring of field data. The prototype EMP2 features an "energy tip" (fig. 1a), a steel tank integrated into the primary circuit, designed to ensure uniform temperature distribution in the deepest part of the pile, where ground temperatures remain stable and are less influenced by seasonal surface variations. Preliminary results from Thermal Response Tests were analyzed and validated through Finite Element simulations and further parametric simulations were performed to optimize the technology [12].

Literature results confirm that thermal cycles have a minimal impact on the system's structural response, and that EMPs can provide steady-state heat exchange rate per meter length of the pile in the range of 20-40 W/m (fig. 1b) [14], comparable to that of energy piles. The thermal conductivities of the soil and pile, as well as the pile length

and diameter, are key parameters in estimating the heat flux. This emphasizes the importance of conducting a site-specific assessment of soil thermal properties for a reliable prediction of EMP system performance. Additionally, while changes in fluid flow rate have limited effect on heat flux, they do impact the temperature difference between the circuit's inlet and outlet, which decreases as flow rate increases.

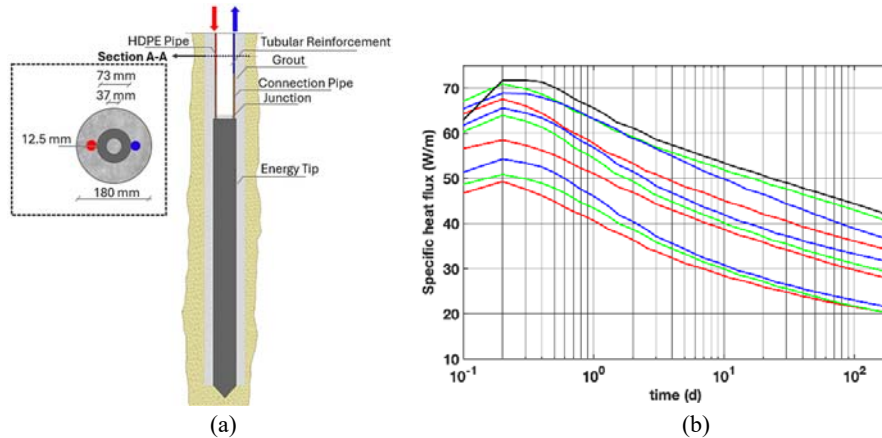


Fig. 1. (a) Schematic view of the tip of EMP2 prototype with blue and red exchanger pipes adjacent to the central tubular reinforcement (redrawn after [12]), and (b) time history of EMP thermal power from a parametric study with different combinations of design parameters [14].

4 Energy Walls

The term Energy Wall commonly refers to thermally activated diaphragm walls, supporting surface excavations for building basements, underground parking lots, and subway stations. Their energy performance is demonstrated to be in the range of 20-30 W/m² (as heat exchange rate per square meter surface of the wall based on literature values) [17]. It has to be remarked that in contrast to energy piles the wall is fully embedded in the ground only for its deepest part, while the upper has one side exposed to the excavation space [18-19].

In general, geothermal energy can be exploited using the walls of any underground space. As an example, the solution named *GeothermSkin* thermally activates the wall side in contact with the soil [20], by mounting the piping network on it, as a skin at the soil-wall interface. The system is versatile and can be adapted to the available surface. The solution is ideal for new buildings, as the piping network can be mounted during basement construction. For existing buildings undergoing refurbishment, an excavation may be planned to expose the wall surface, followed by backfilling after installation.

Compared with energy diaphragm walls, the *GeothermSkin* solution can provide less thermal energy (in the order of 15-20 W/m²) due to the generally shallow depth but still valuable given the limited installation costs. To provide the designer with a tool for easy *GeothermSkin* sizing, data collected during heating tests carried out on a prototype available at the Politecnico di Torino, Italy [20-21] was processed. The data processing

results conceal the relationship between the supplied thermal power and climate variables like solar radiation, outdoor air temperature, ground temperature and moisture.

To discover such correlation, a data-driven approach was followed by training an artificial neural network multilayer perceptron, belonging to supervised machine learning algorithms [22]. The correlation between the performance and the variables allows to predict the geothermal system performance in different environmental and ground conditions and to size the *GeothermSkin* surface to meet the building heat load. The data reported in fig. 2 show that the surface of *GeothermSkin* per unit floor area of building (GSA, *GeothermSkin* Specific Area) able to provide an annual average thermal power sufficient to meet the annual average heat load varies between 0.12-0.43 [22]. The required area generally decreases from North to South because the maximum annual average power required by a building is lower. The warmer, sunnier and more stable weather in the Southern region allows *GeothermSkin* to extract a higher thermal power and operate with a great coefficient of performance thanks to the smaller difference between the ground and the indoor temperatures.

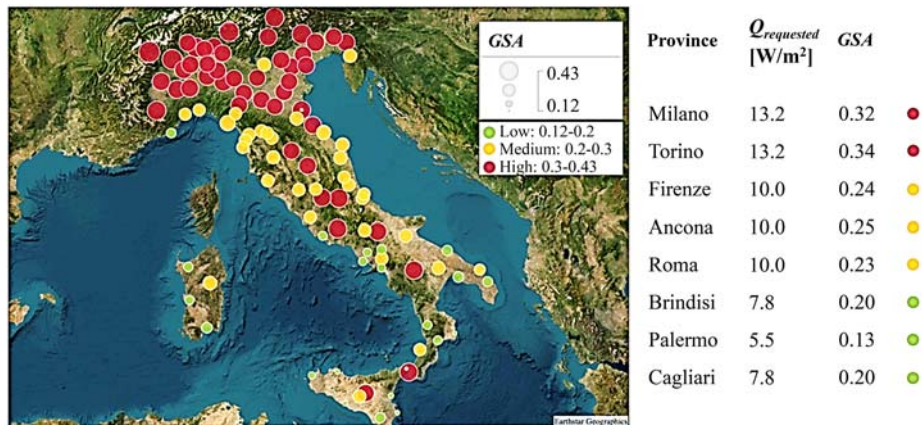


Fig. 2. Required *GeothermSkin* surface per unit floor area of building (GSA) and summary for main Italian cities (redrawn after [22]).

5 Energy tunnels

Tunnels are linear assets that, when thermally activated, can supply energy on an urban scale to a large number of surface buildings by exploiting large ground volumes. In this way, the concept of EG evolves from a geothermal system serving a single user to an urban-scale district service [23-24]. Their thermal performance is highly dependent on the tunnel depth, ground conditions and temperatures that develop inside the tunnel, and is, on average, comparable to that of energy walls (20-30 W/m² according to the literature review) [17].

Full-scale implementations have so far been limited to new tunnelling projects, with the possibility of instrumenting existing tunnels for heat exchange only recently being investigated. Indeed, [25-26] proposed a variety of energy retrofitting solutions that

would enable the instrumentation of tunnel liners either during renovation works or as part of repurposing strategies.

Taking advantage of Italy's current motorway tunnel refurbishment plan, one of the aforementioned solutions was implemented and is currently being tested on the right tube of Olimpia tunnel (Alessandria, Italy). The heat exchanger pipes were arranged in a transversal meandering pattern along the interface between the existing and the newly built tunnel liners, as depicted in Fig. 3a. Such a solution is ideal when traditional moulds are envisaged to replace part or all of the tunnel liner. When precast elements are used, geothermal pipes can be installed during the manufacturing process in prefabrication plants.

According to preliminary numerical analyses [25], the solution implemented in Olimpia tunnel extracts around 13 W/m^2 and injects $23\text{-}35 \text{ W/m}^2$ of thermal energy during winter and summer, respectively. The latter variability is due to the influence of the internal airflow's athermal conditions on the heat exchange process, modelled using different heat exchange rate values at the tunnel liner's inner surface (fig. 3b). The thermal energy is higher in summer due to greater difference between the inlet fluid and the tunnel internal temperatures, resulting in a larger temperature gradient and, thus, a larger thermal energy exchange.

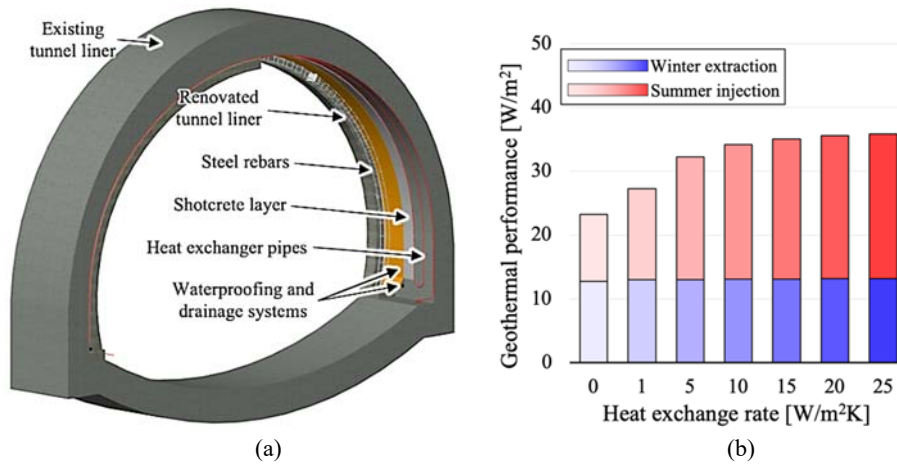


Fig. 3. (a) 3D view of the energy retrofitting solution implemented in Olimpia tunnel and (b) exploitable thermal power as a function of the heat exchange rate due to internal airflow, modified from (redrawn after [25]).

6 Other energy geostructures

6.1 Cutter Soil Mix (CSM) energy diaphragm walls

In an attempt to thermally activate any structure potentially capable of exchanging heat with the soil, a novel EG is represented by diaphragms constructed using the Cutter Soil Mixing technique (CSM), in which weak soil within a trench is blended with a

cementitious binder that improves its mechanical and/or hydraulic properties, to serve as retaining wall and/or hydraulic barrier. The diaphragm is built by treating one segment at a time and, as required by structural design, installing reinforcing steel beams outfitted with heat exchangers while the mix is still fresh [27]. The mixing technique ensures that the final treated zone is uniform and that no interface layers form between the final diaphragm and the surrounding soil, as can occur with traditional reinforced concrete walls. The absence of interface layers and the presence of highly conductive steel beams improve energy flow in these EGs, making them suitable for energy retrofitting of overlying or nearby buildings that are not structurally connected to them.

In Amstelveen (NL), energy CSM diaphragms were installed (fig. 4), to serve three functions: (i) as a hydraulic barrier during the construction phase, (ii) as a retaining wall for the basement, and (iii) as a load-bearing foundation for a two-story building [28-30]. Field monitoring data and numerical simulation results showed that, in Dutch climate conditions, this type of CSM energy wall achieves a steady-state heat extraction rate of the order of 25 W/m^2 and a heat injection rate of the order of 30 W/m^2 . It was also revealed [29] that the presence of both heating and cooling demands results in a higher heat exchange rate over the years compared to heating demand alone, and that non-insulated connection pipes increase the overall heat exchange rate of the system.

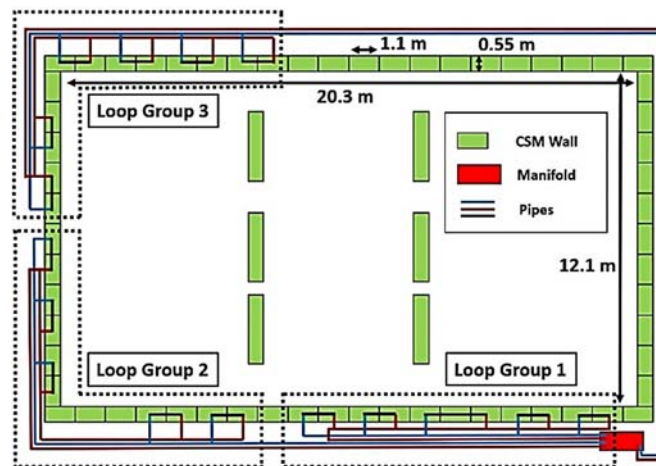


Fig. 4. Schematic plan view of the Amstelveen CSM energy wall site, including external connection pipes represented in red and blue colors [28].

6.2 Energy sheet pile walls

Thermal energy can also be exchanged with water bodies, such as canals and reservoirs. To achieve this, steel sheet piles installed along quays and piers can be thermally activated by welding steel pipe heat exchangers to their ground side face. Harvested energy can be distributed to nearby buildings as part of an energy retrofit. An alternative solution is to upgrade existing traditional sheet piles by welding heat exchangers to additional panels tied to the sheet pile's water side face. In this case, heat is almost entirely exchanged with the water body [31].

Both solutions, namely steel exchangers in contact with the ground and add-on thermo-active panels facing the water, were investigated at a real-scale field test site near Delft (NL) (fig. 5). Extensive site monitoring and numerical simulations indicate enhanced thermal performance compared to average planar EGs, which can be attributed to the presence of surface water [28, 32]. Field monitoring data revealed that low-depth ground-side geothermal loops and add-on panels can achieve the highest exchanged thermal power per activated surface area, proportional to the temperature difference between the open water and the inlet fluid, up to 400 W/m^2 in winter heating mode. On the other hand, deep ground-side loops are less affected by open water temperature, allowing for more stable energy extraction during colder periods when water temperatures are low, while still achieving a heat extraction rate of around 60 W/m^2 .

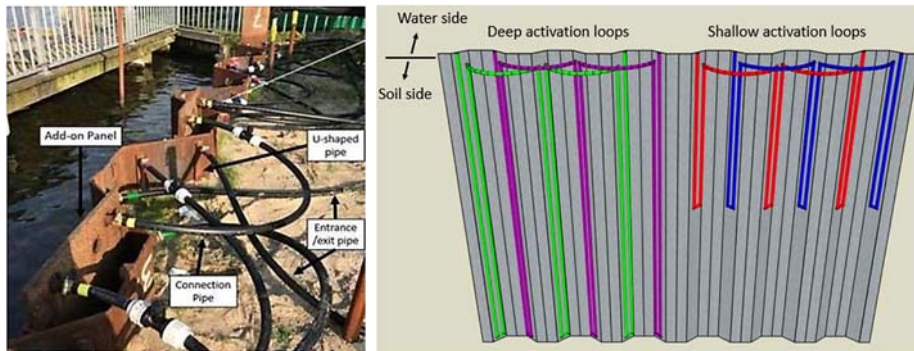


Fig. 5. Energy sheet pile wall test site installed near Delft (NL): (a) picture of test set-up, (b) schematic of soil-facing side geothermal loops extending to two different depths [28].

7 Conclusions

This study shows the potential of EGs for sustainable retrofitting of buildings and infrastructure. EMPs, energy walls and tunnels serve both structural and thermal purposes, providing energy and cost savings while reducing environmental impact. EMPs have demonstrated comparable heat exchange rates to conventional energy piles, making them viable for building rehabilitation. Energy walls and tunnels offer opportunities for urban-scale energy solutions, leveraging existing infrastructure, and new applications, such as CSM diaphragm walls and energy sheet pile walls, further expand near-surface geothermal energy technology.

EG performance varies depending on depth, soil properties, and seasonal temperature fluctuations. Accurate thermo-hydraulic modelling and design optimization are critical for maximizing efficiency, and integrating data-driven approaches enhances performance prediction and system scalability.

EGs play a key role in the energy transition, particularly in retrofit applications when conventional ground heat exchangers are impractical. Future research should focus on refining design methodologies, improving predictive models, and expanding field applications to fully realize their potential in global decarbonization efforts.

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