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Analysis of Experimental Data for Energy Walls

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Abstract

Energy walls are a type of energy geostructure that converts the earth-retaining walls of underground structures into shallow geothermal heat exchangers, combining a structural and a thermal function within a single element. While numerical and laboratory studies have demonstrated their potential, field-scale experimental evidence remains scarce. This thesis analyses the experimental data collected from a full-scale energy-wall prototype based on the Geothermskin concept, installed at the Politecnico di Torino Energy Center in Turin and substantially upgraded in 2024–2025 with six independent hydraulic circuits across three fields, solar coupling, and a macro-encapsulated phase change material (PCM) integrated into part of the wall.

A six-month monitoring campaign, comprising dedicated heating and cooling tests, is interpreted using a dense thermo-hydro-mechanical (THM) instrumentation network of PT100 temperature sensors, soil-moisture and water-tension probes, strain gauges, and total-pressure cells. After data cleaning and sensor selection, the work characterises the thermal response of the wall and the surrounding soil, the depth and lateral extent of thermal penetration, the vertical temperature distribution along the wall, the buffering effect of the PCM, and the three-dimensional thermal field around the structure.

The results show that the ground temperature is governed primarily by the seasonal cycle, on which the localised, short-range thermal signal of wall operation is superimposed; that the applied thermal loads do not measurably redistribute soil moisture; and that the associated mechanical response remains small. The exchanged power was of the order of 1 kW, with specific rates of approximately 20–40 W/m² of activated wall area.

Overall, the thesis provides field-scale experimental evidence on the thermal, hydraulic, and mechanical behaviour of energy walls under realistic operating conditions, and identifies priorities for the instrumentation and operation of future prototypes.

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1 Introduction

The shift toward a low-carbon energy system has accelerated in recent years as countries confront the combined challenges of climate change, energy security, and the growing energy demands of urban areas. In this global context, the building sector plays a vital role. According to the International Energy Agency (2023), building-related activities made up about one-third of global energy-system emissions in 2022, including 26% from operational energy use and 7% from embodied emissions related to construction materials and processes. A significant portion of these operational emissions comes from space heating, cooling, and hot water production—systems that still rely heavily on fossil fuels in many areas.

To address these challenges, decarbonising the thermal energy demand of buildings has become a strategic priority within international and European policy frameworks. The European Commission (2019), through the European Green Deal, sets a legally binding objective for climate neutrality by 2050, supported by the Fit-for-55 Package, through which the European Commission (2021) mandates a 55% reduction in greenhouse gas emissions by 2030. Within this regulatory landscape, the Official Journal of the European Union (2023) presents the recast Renewable Energy Directive (RED III, 2023/2413), which explicitly recognizes shallow geothermal energy as a key contributor to renewable heating and cooling targets. These policies emphasise the need for reliable, local, and sustainable thermal-energy technologies capable of operating efficiently in densely built environments.

Shallow geothermal systems, particularly Ground-Source Heat Pump technologies, offer a promising pathway to achieving these energy and climate objectives. By exploiting the relatively stable temperature of the shallow ground—typically around 10–15°C in many European climatic contexts—Shallow Geothermal Energy (SGE) systems provide high energy efficiency and can significantly reduce both operational costs and carbon emissions. However, Cen and Xia (2025), Figueira et al. (2024), and Loveridge et al. (2020) highlighted that widely adopted configurations such as vertical Borehole Heat Exchangers or horizontal collector fields often face limitations related to drilling costs, land availability, regulatory constraints, and thermal interference in dense urban settings.

To overcome these barriers, a new class of systems known as energy geostructures has emerged over the past two decades. Baralis and Barla (2021) described these systems as integrating geothermal heat-exchange functions directly into structural elements that are already required for geotechnical reasons—such as piles, slabs, tunnel linings, and retaining walls. By using the building’s own foundation as a geothermal exchanger, energy geostructures reduce installation costs, minimise land use, and offer a scalable solution for urban renewable heating and cooling. Among these systems, energy walls (also known as geothermal diaphragm walls) represent one of the most promising yet least understood technologies.

Despite their potential, energy walls are still rarely studied in full-scale experimental research. Most of the scientific literature focuses on conceptual studies, numerical models, and small-scale laboratory tests, with few long-term, in situ monitoring projects. As recent reviews by Alvi et al. (2025) and Loveridge et al. (2020) point out, our understanding of key

mechanisms—including operational strategies, soil thermal recharge, and thermo-hydro-mechanical interactions—remains limited. These gaps hinder the development of robust design guidelines and limit the integration of energy walls into larger sustainable energy systems, such as hybrid renewable networks or 5th-Generation District Heating and Cooling systems.

In response to these challenges, the Politecnico di Torino developed the Geothermskin prototype—an innovative modular energy-wall system designed for retrofitting existing underground structures without the need for drilling. Baralis and Barla (2021) and Nguyen (2020) described this prototype, located at the Energy Center in Turin, as combining heat-exchange pipes fixed to the external face of the basement wall with a wide array of PT100 temperature sensors, strain gauges, and moisture sensors. It offers one of the most comprehensive field-scale monitoring datasets available today, allowing for direct measurement of thermal performance, operational behaviour, and thermo-hydro-mechanical coupling under actual climatic and boundary conditions.

This thesis builds upon the existing experimental infrastructure to address fundamental research questions related to the thermal, hydraulic, and mechanical behaviour of energy walls. Specifically, this study aims to:

- evaluate the heating and cooling performance of the Geothermskin system under the available operating tests;
- characterise the spatial and temporal thermal response of the near-wall soil, including penetration depth, vertical temperature distribution, lateral interaction, and recovery behaviour;
- assess the thermal response of phase change materials and non-phase change material zones in order to identify possible buffering effects under field conditions;
- interpret the thermo-hydro-mechanical response of the prototype using temperature, moisture, suction, pressure, and strain measurements;
- relate system-level exchanged energy and power to the measured soil-side thermal response.

Through these objectives, this research provides field-scale experimental evidence that directly addresses gaps identified in the literature and can support future performance assessment, design interpretation, and operational optimisation of shallow modular energy walls. Ultimately, this work supports the broader goal of integrating energy geostructures into sustainable urban energy systems and advancing the European transition to low-carbon building technologies.

The remainder of this thesis is structured as follows. Chapter 2 presents a comprehensive review of shallow geothermal systems, energy geostructures, and the state of research on energy walls, concluding with the identification of research gaps and objectives. Chapter 3 describes the Geothermskin prototype, including the experimental site, system configuration, heat exchange circuits, instrumentation, and monitoring setup. Chapter 4 presents and discusses the results of the thermal, mechanical, and hydraulic analyses under various operational scenarios. Chapter 5 concludes the thesis by summarising key findings, discussing limitations, and outlining directions for future research.

2 Shallow geothermal systems and energy walls

2.1 Global energy context and strategic motivation

The global energy system is undergoing a significant transformation driven by the dual objectives of mitigating climate change and strengthening energy security. Buildings sit at the centre of this transition. As noted in the introduction, the International Energy Agency (2023) reported that the built environment accounts for a large share of global energy-system emissions, most of which arise from building operation rather than from construction. Within this sector, the challenge is strongly linked to thermal conditioning, as roughly 80% of direct emissions in buildings are associated with space and water heating. Reducing the reliance on fossil fuels for heating, cooling, and domestic hot water production is therefore one of the most immediate and effective levers for decarbonising the urban built environment.

A largely underused resource for this purpose lies directly beneath buildings themselves. Loveridge et al. (2020) noted that, below the near-surface zone affected by seasonal air-temperature fluctuations, the shallow ground maintains a relatively stable temperature throughout the year, typically around 10–15 °C in many European climatic contexts, making it a suitable heat source in winter and heat sink in summer. Compared with ambient air, this stable thermal boundary condition allows ground-source systems to operate efficiently for space heating and cooling. The technologies that exploit this resource include shallow geothermal energy systems and, more recently, energy geostructures such as energy piles, tunnels, slabs, and energy walls. These systems are reviewed in detail in Sections 2.2–2.4.

This technical potential is strongly reinforced by the European policy framework. The European Commission (2019), through the European Green Deal, sets the objective of climate neutrality by 2050, while the European Commission (2021) strengthens intermediate targets for greenhouse-gas emission reduction by 2030 through the Fit-for-55 Package. Within this framework, the Official Journal of the European Union (2023) recognises geothermal and ambient energy sources exploited through heat-pump technologies as contributors to renewable heating and cooling targets under the revised Renewable Energy Directive. Solutions that provide renewable thermal energy from the urban underground, while limiting additional land occupation, are therefore well aligned with European decarbonisation strategies. Figueira et al. (2024) highlighted that their possible integration into fifth-generation district heating and cooling networks further increases their strategic value, especially in dense urban contexts.

The convergence of these three elements—the urgency of decarbonising building heating and cooling, the availability of a stable shallow-ground thermal resource in urban areas, and the European policy mandate for renewable thermal energy—motivates the research presented in this thesis. The Geothermskin project at the Politecnico di Torino addresses this opportunity through a full-scale experimental energy-wall prototype, described in Chapter 3. The remainder of this chapter reviews the state of the art, moving from shallow geothermal systems in general to energy geostructures and, finally, to energy walls and the open questions surrounding their real-world performance.

2.2 Shallow geothermal systems

2.2.1 Classification: open-loop vs. closed-loop systems

SGE systems are mainly divided into two types: open-loop systems and closed-loop systems. Gizzi et al. (2020) described open-loop groundwater heat pump systems as systems that use groundwater abstracted from an aquifer as the heat-exchange medium. Water is pumped to the surface, passed through a heat exchanger to absorb or release thermal energy, and then reinjected into the ground or discharged according to local hydrogeological and regulatory conditions. These systems can be advantageous in areas with plentiful groundwater resources, offering a direct and cost-effective way to utilise geothermal heat. In contrast, closed-loop systems feature a network of pipes buried underground that circulate a heat transfer fluid (usually water or a water-antifreeze mix). This fluid exchanges heat with the surrounding soil without direct contact with groundwater. Casasso et al. (2018) and Mohamad et al. (2021) explained that closed-loop systems can be further categorised into vertical and horizontal configurations. Vertical systems, based on BHEs, employ deep boreholes for efficient heat transfer, while horizontal systems lay pipes in trenches at shallow depths. Each type has distinct advantages and limitations, influencing its use in different settings.

Table 1: Main shallow geothermal system configurations and their relevance to urban applications

System type	Typical configuration	Main advantages	Main limitations	Relevance to this thesis
Open-loop system	Groundwater is abstracted from an aquifer, passed through a heat exchanger, and then reinjected or discharged.	High heat-exchange efficiency; direct use of groundwater as thermal source or sink.	Requires suitable aquifer conditions; may involve hydrogeological constraints, water-quality issues, and regulatory limitations.	Useful background, but not the system analysed in this thesis.
Closed-loop vertical system	Borehole heat exchangers with pipes installed in vertical boreholes, typically connected to a ground-source heat pump.	High efficiency due to stable ground temperature; limited surface occupation compared with horizontal collectors.	High initial cost due to drilling; possible thermal interference between boreholes in dense installations.	Represents the conventional solution that energy walls try to avoid or reduce.
Closed-loop horizontal system	Pipes installed in shallow trenches over a horizontal field.	Lower drilling cost; simpler installation where land is available.	Requires large surface area; less suitable for dense urban sites.	Explains the land-availability problem addressed by energy geostructures.
Energy geostructures	Heat-exchange pipes integrated into structural or geotechnical elements such as piles, slabs, tunnels, and walls.	Reduce or avoid dedicated boreholes; exploit elements already required for structural or geotechnical purposes.	Design methods are less standardized than for borehole systems; thermal and mechanical behaviour must be assessed together.	Directly introduces the family of systems to which energy walls belong.

Energy walls / Geothermskin	Heat-exchange pipes are integrated into, or installed against, earth- contact retaining or basement walls.	Compact solution for urban areas and existing buildings; limited additional land occupation and no dedicated deep boreholes.	Still requires field validation, performance assessment, and understanding of soil response.	Main focus of the thesis.
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2.2.2 Review of conventional closed-loop systems and their limitations

Conventional closed-loop geothermal systems are widely used for building heating and cooling, but they face several significant limitations.

The most common vertical closed-loop configuration is based on borehole heat exchangers (BHEs), which are highly effective at exchanging geothermal heat. However, installing BHEs requires drilling operations that can be costly and logistically demanding. Casasso et al. (2018) and Radioti et al. (2017) reported that these high initial costs can lead to long payback periods, reaching approximately 20 years in some applications, and may represent a barrier to adoption, especially for residential systems. When properly designed, however, these systems remain highly efficient because they exchange heat with the thermally stable ground. Mohamad et al. (2021) reported Seasonal Performance Factors typically between 3 and 5, meaning that the system can deliver three to five units of thermal energy for each unit of electricity consumed.

Horizontal collectors, another type of closed-loop system, avoid the expense of deep drilling by laying pipes in shallow trenches, typically 1 to 2 meters deep. While they are less invasive, Cui et al. (2019) highlighted that they require much larger land areas, which are often unavailable in dense urban environments.

This presents a clear implementation gap: conventional closed-loop systems are often constrained either by drilling cost, as in the case of vertical borehole heat exchangers, or by land availability, as in the case of horizontal collectors. Energy geostructures address this limitation by using structural or earth-contact elements that are already part of the built environment as heat exchangers. Among these systems, energy walls are particularly relevant in urban contexts because they can exploit basement or retaining walls without requiring dedicated borehole fields or large horizontal collector areas. Their specific development, performance, and open research questions are discussed in Sections 2.3 and 2.4.

In conclusion, while conventional closed-loop systems offer benefits, their high installation costs, drilling requirements, and space constraints limit wider adoption. Ongoing innovations, like energy walls, may help resolve these issues, but further research is essential to validate long-term performance and improve the viability of all shallow geothermal energy systems.

2.3 Energy geostructures

Energy geostructures mark a significant advancement by combining structural and thermal energy functions in a single element. They operate on a dual-function principle, serving both as load-bearing components and as closed-loop geothermal heat exchangers: pipes embedded within the concrete of piles, tunnel linings, or diaphragm walls circulate a heat-carrier fluid that exchanges energy with the surrounding ground, allowing the structure to act as a renewable heat source in winter and as a heat sink in summer. Di Donna et al. (2021) and Loveridge et al. (2020) noted that integrating thermal systems directly into foundations or retaining structures reduces the need for separate boreholes, limits surface occupation, and lowers installation costs, which are key benefits in dense urban environments. The concept also enhances long-term system reliability by minimising mechanical interfaces and leveraging the durability of the concrete itself. The structural implications of thermal activation must nevertheless be evaluated for each case, because temperature changes may induce additional stresses and strains. In the Geothermskin prototype, Baralis and Barla (2021) reported stress changes lower than 0.15 MPa and strains limited to about 80 $\mu\epsilon$ during operation, indicating a negligible mechanical influence for that specific installation.

The concept has been applied to a range of geotechnical elements. Energy piles are among the earliest and most common types, functioning both as deep foundation elements and as heat exchangers. Loveridge et al. (2020) reported that long-term operational studies commonly show heat-exchange rates in the range of about 15–35 W/m, although short-term test results can vary more widely depending on pile geometry, pipe configuration, flow rate, soil properties, temperature difference, and test duration. Their dual role enables efficient energy recovery, although Di Donna and Laloui (2015) and Wang et al. (2016) showed that thermal-mechanical coupling must be considered during design to prevent additional settlement or bending issues. Energy tunnels expand the concept to large underground structures by embedding pipe networks within tunnel linings, exploiting the extensive contact area with the surrounding ground; Barla et al. (2025) and Cen and Xia (2025) noted that this makes them well suited to transit or utility tunnels, although construction complexity, varying ground conditions, and limited accessibility for maintenance remain the main limitations.

Energy walls, also referred to as geothermal diaphragm walls or retaining-wall heat exchangers, apply the same dual-function principle to retaining walls, basement walls, and other earth-contact vertical structures. Their compact geometry makes them particularly relevant in dense urban environments, where borehole drilling or horizontal collector fields may be difficult to implement. Compared with energy piles, however, energy walls are less standardized and their performance depends strongly on wall geometry, pipe layout, ground conditions, boundary conditions on the excavation side, and operating mode. Since energy walls are the focus of this thesis, their development, performance, and open research questions are discussed separately in Section 2.4.

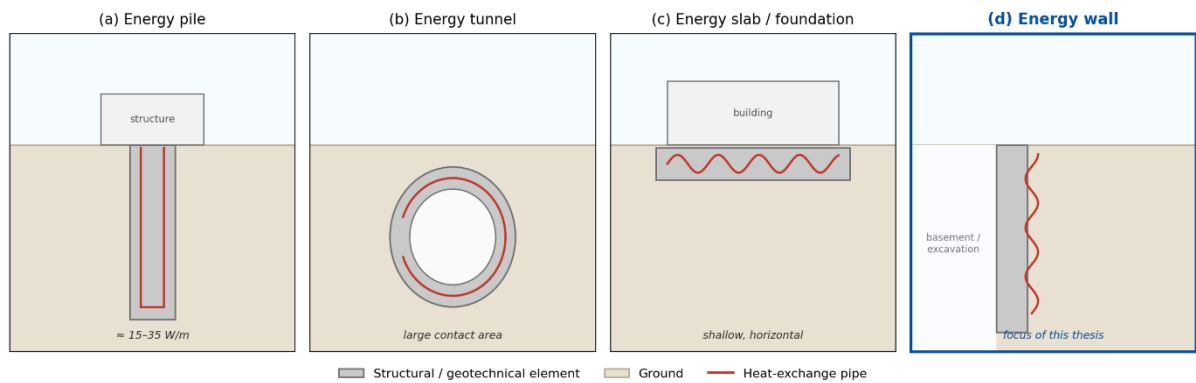


Figure 1: Schematic illustration of the energy-geostructure family, in which closed-loop heat-exchange pipes are integrated into load-bearing elements: (a) energy pile, (b) energy tunnel, (c) energy slab or foundation, and (d) energy wall, the configuration stud

Historically, Brandl (1998) and Di Donna and Laloui (2015) traced the evolution of energy geostructures back to the first thermo-active piles of the 1980s, followed by the development of energy diaphragm walls in the mid-1990s and energy tunnels in the early 2000s. Baralis and Barla (2021) later described fully instrumented prototypes such as the Geothermskin system. Over the last twenty years, the focus of research has correspondingly shifted from feasibility studies and analytical modelling toward long-term monitoring, coupled thermo-hydro-mechanical analysis, and hybrid energy integration.

In summary, energy geostructures redefine how the built environment interacts with the subsurface thermal field. By combining structural and geothermal functions, they support low-carbon building strategies and urban energy resilience, and ongoing research into design optimisation, Thermo Hydro Mechanical (THM) coupling, and field validation — such as the work conducted at the Politecnico di Torino — remains crucial for the mainstream adoption of this technology.

2.4 Energy walls

Energy walls, also known as energy diaphragm walls or retaining-wall heat exchangers, are a relatively recent application of the energy-geostructure concept. They use closed-loop heat-exchange pipes embedded within retaining walls, diaphragm walls, or installed against earth-contact wall surfaces, allowing the wall system to contribute to both structural support and geothermal heat exchange. In conventional embedded retaining walls, the thermal response may be influenced by excavation geometry, wall thickness, groundwater flow, and boundary conditions on the excavated side. In retrofit-oriented systems such as Geothermskin, the interaction is instead concentrated in the shallow near-wall ground around existing basement or underground structures, making the system particularly relevant for dense urban contexts where borehole drilling or large horizontal collector fields are difficult to implement.

Cen and Xia (2025) and Zhu et al. (2025) showed that energy-wall research has developed through engineering applications, laboratory experiments, numerical simulations, and multi-field coupling studies. However, compared with energy piles, energy walls remain less standardised, and analytical heat-transfer models for energy walls are still scarce. Existing

studies also highlight the need for additional field monitoring to validate performance under different operating modes, ground conditions, and thermo-mechanical constraints. These gaps are directly relevant to the Geothermskin monitoring campaign analysed in this thesis.

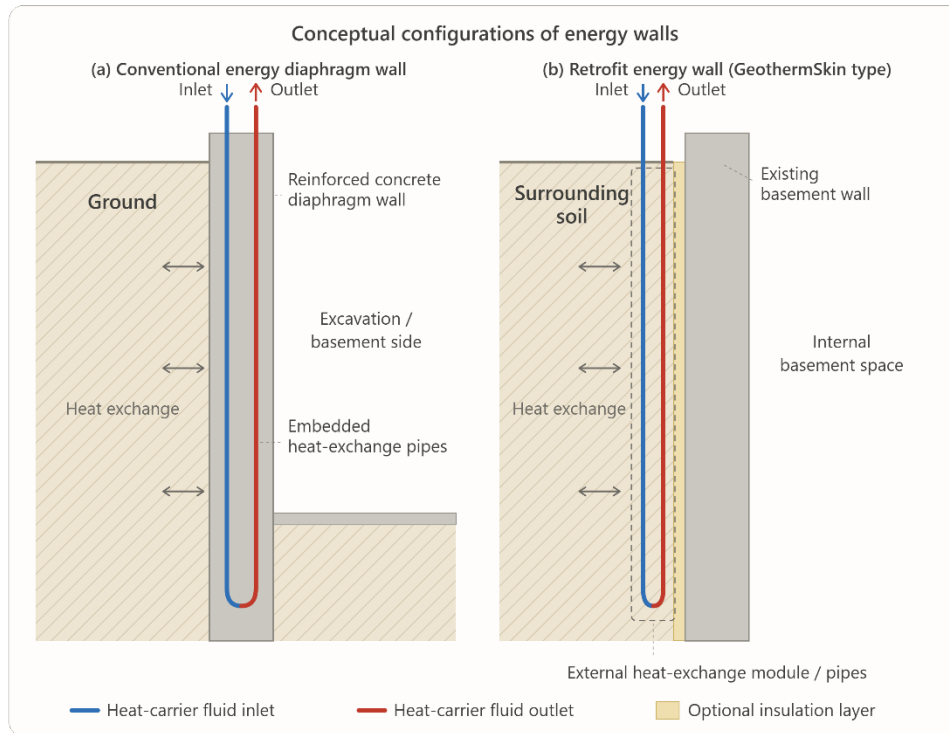


Figure 2: Conceptual configurations of energy walls: (a) conventional energy diaphragm wall with heat-exchange pipes embedded in the structural wall, and (b) retrofit-oriented Geothermskin-type system with heat-exchange pipes installed externally against an existing earth-contact wall

2.4.1 Development and early prototypes

The concept of thermo-active retaining walls was introduced in the late 1990s, with Brandl (1998) discussing energy piles and diaphragm walls as ground heat exchangers. However, compared with energy piles, fewer energy-wall case studies have reported detailed thermal performance data. Loveridge et al. (2020) note that several energy walls have been constructed in commercial buildings and infrastructure projects, but published information on their thermal capacity is still limited. In this context, Baralis and Barla (2021) developed and tested the Geothermskin prototype in Turin, Italy, as a modular and externally mounted energy-wall system for shallow applications. The experimental campaign reported an average heat-exchange rate of about 17 W/m² in heating mode and about 68 W/m² in cooling mode. Structural monitoring showed stress variations lower than 0.15 MPa and strains limited to about 80 $\mu\epsilon$, indicating a negligible mechanical impact for the tested prototype.

2.4.2 Numerical and parametric studies

Several authors have furthered the analysis through numerical modelling. Nguyen (2020) validated a FEFLOW finite-element model against Geothermskin measurements, reproducing temperature fields and wall heat flux evolution. Di Donna et al. (2021) conducted a parametric study showing that higher soil thermal conductivity and the presence of groundwater

significantly increase heat-exchange efficiency. Bodas Freitas et al. (2024) investigated the influence of wall and excavation geometry using three-dimensional simulations. Their study identified the excavation ratio H/L , defined as the ratio between excavation depth and total wall panel depth, together with the wall thickness D , as practical geometric parameters for estimating heat-exchange potential under given thermal properties and boundary conditions. Gerola et al. (2025) extended numerical research on energy walls to Cutter Soil Mix (CSM) walls, combining laboratory characterisation of CSM material with a three-dimensional finite-element model of a full-scale test site in Amstelveen, the Netherlands. Their results showed that long-term performance is strongly influenced by the energy-demand scenario, with combined heating and cooling operation maintaining higher heat-exchange rates than heating-only operation. They also found that non-insulated connection pipes can increase the overall heat exchange, while reducing the number of U-loops decreases thermal interaction and increases exchange rates per activated area, although at the cost of lower total heat exchange.

2.4.3 Laboratory investigations

Laboratory-scale energy-wall mock-ups enable controlled testing of material, boundary-condition, and operational effects. Wang et al. (2025) performed model-scale experiments on an energy diaphragm wall under different relative temperature differences and operation modes. Increasing the relative temperature difference between the inlet fluid and the soil from 15 °C to 30 °C increased the wall thermal efficiency by 108.2% and the total heat exchange by 116.2%. Intermittent operation also produced a maximum improvement of 35.7% in thermal efficiency compared with continuous operation. These results confirm the importance of operational strategy, although their transfer to full-scale field conditions still requires validation.

2.4.4 Field monitoring in infrastructures

Long-term field evidence remains limited but is increasing in scope. Sauvenier and Di Donna (2025) analysed the Cleunay geothermal metro station in Rennes, France, a fully operational energy geostructure equipped with heat exchangers in both diaphragm walls and the station slab. The system includes approximately 1532 m² of active wall surface, 1394 m² of active slab surface, and about 7.9 km of pipes. During a 49-day Thermal Response Test (TRT) under operational conditions, the extracted power per unit active surface was about 12 W/m² when the western walls and slab were active, about 20 W/m² during slab-only operation, and about 23 W/m² when the active area was reduced. During 2.5 years of normal heating operation, the actual extracted power per active area was around 7–8 W/m². This study is particularly relevant because it provides rare long-term operational monitoring data for a complex energy-geostructure system under real service conditions.

2.4.5 Synthesis

In summary, the literature on energy walls shows that:

- Reported heat-exchange rates vary widely depending on wall geometry, pipe layout, boundary conditions, ground thermal properties, groundwater flow, operating

temperature difference, and test duration. Long-term monitored values are generally lower than short-term or highly favourable numerical scenarios.

- Numerical and analytical studies have clarified the role of ground conditions, groundwater flow, wall geometry, and excavation-side boundary conditions, but routine design methods for energy walls remain less developed than for conventional borehole heat exchangers or energy piles.
- Laboratory investigations confirm the importance of operational strategy, especially temperature difference and intermittent operation, but their transferability to full-scale field conditions requires further validation.
- Full-scale monitoring datasets remain limited, especially for systems combining thermal, hydraulic, and mechanical measurements. This supports the relevance of the Geothermskin prototype, where temperature, moisture, and strain data are analysed under real operating conditions.

Table 2 summarises representative heat-exchange rates reported in the literature.

Table 2: Reported heat-exchange rates for energy geostructures in the literature, compared with the results of this thesis

Study	System type	Mode	Reported rate	Basis / notes
Loveridge et al. (2020)	Energy pile	Long-term operation	$\approx 15\text{--}35 \text{ W/m}$	Review; per unit length
Baralis & Barla (2021)	Energy wall (Geothermskin)	Heating	$\approx 17 \text{ W/m}^2$	Field prototype, Turin
Baralis & Barla (2021)	Energy wall (Geothermskin)	Cooling	$\approx 68 \text{ W/m}^2$	Field prototype, Turin
Sauvenier & Di Donna (2025)	Energy wall + slab (Cleunay metro)	Extraction (TRT)	$\approx 12\text{--}23 \text{ W/m}^2$	49-day TRT; varies with active area
Sauvenier & Di Donna (2025)	Energy wall + slab (Cleunay metro)	Heating (2.5 yr)	$\approx 7\text{--}8 \text{ W/m}^2$	Long-term normal operation
Wang et al. (2025)	Energy diaphragm wall (lab)	Heating/cooling	+108% efficiency*	Model-scale; ΔT raised $15 \rightarrow 30^\circ \text{ C}$
Wang et al. (2025)	Energy diaphragm wall (lab)	Intermittent vs continuous	+35.7% efficiency*	Model-scale; relative gain
Di Donna et al. (2021)	Energy wall (numerical)	Parametric	Rate increases with soil conductivity and groundwater	3-D FE; qualitative trend
Gerola et al. (2025)	CSM energy wall (numerical)	Heating & cooling	Higher with combined mode	3-D FE; Amstelveen site
This thesis (Chapter 4)	Energy wall (Geothermskin)	Heating & cooling	$\approx 20\text{--}40 \text{ W/m}^2$	Field campaign, 2025

*Wang et al. (2025) report relative improvements in thermal efficiency rather than absolute exchange rates. Energy-pile rates are expressed per unit length (W/m), whereas wall and slab rates are expressed per unit activated area (W/m^2); the two are not directly comparable.

2.5 Performance assessment methods for energy walls

Assessing the performance of energy walls requires both thermal and geotechnical monitoring, because these systems act simultaneously as heat exchangers and ground-contact structural elements. In the literature, performance assessment is generally based on three complementary levels: thermal performance indicators, monitoring of the wall–ground system, and, more recently, data-driven interpretation of monitored datasets. For this thesis, the most relevant assessment methods are those based on measured inlet and outlet fluid temperatures, flow rate, ground temperature evolution, soil moisture conditions, and mechanical response of the wall.

2.5.1 Key performance indicators

The most direct thermal indicator for an energy wall is the exchanged thermal power, usually calculated from the heat-carrier fluid flow rate, specific heat capacity, and inlet–outlet temperature difference. To compare systems of different size, this value is commonly normalised by the active wall area and expressed as W/m^2 . This indicator is particularly useful for energy walls because their heat-exchange surface is planar, unlike energy piles, which are often reported in W/m . Other useful indicators include the cumulative exchanged energy, the temperature difference between the fluid and the ground, the recovery of ground temperature after operation, and the temporal evolution of near-wall soil temperature.

At the system level, the coefficient of performance (COP) or seasonal performance factor (SPF) can be used when the heat pump and auxiliary electricity consumption are included in the analysis. However, these indicators describe the performance of the whole geothermal heat-pump system rather than the wall–ground heat exchanger alone. Recent studies have also proposed additional indicators for energy walls. Hu et al. (2024), for example, introduced the Energy Utilization Ratio, Thermal Saturation, and Effectiveness to evaluate energy-wall performance in multiple dimensions. These indicators are promising, but they are not adopted in the present thesis because the available analysis focuses on measured heat exchange, ground-temperature response, phase change materials influence, and thermo-hydro-mechanical behaviour.

2.5.2 Common instrumentation

Field assessment of energy walls depends on continuous monitoring of both the hydraulic circuit and the surrounding ground. On the hydraulic side, inlet and outlet fluid temperatures, flow rate, and energy meters are required to calculate exchanged power and cumulative energy. In the ground, temperature sensors are used to identify the spatial and temporal development of the thermal plume, while moisture sensors and tensiometers provide information on the hydraulic state of the soil, which can influence thermal conductivity and heat transfer. On the structural side, strain gauges and pressure cells can be used to evaluate whether thermal activation induces measurable stress or strain variations in the wall.

This type of multi-sensor monitoring is particularly important for experimental systems such as Geothermskin. Baralis and Barla (2021) installed a dense monitoring network including 96 PT100 temperature sensors, 18 water-content sensors, 3 tensiometers, strain gauges, pressure

cells, and energy meters, allowing the thermal, hydraulic, and mechanical response of the prototype to be evaluated together. The upgraded experimental configuration analysed in this thesis follows the same logic, with ground-temperature, moisture, suction, strain, pressure, and energy-flow measurements described in Chapter 3.

2.5.3 Data-driven approaches

Data-driven approaches are emerging as a complementary tool for interpreting energy-wall performance. Hu et al. (2024) used field-test data from an underground energy wall to develop a support vector regression model for predicting thermal performance and proposed additional performance indicators such as Energy Utilization Ratio, Thermal Saturation, and Effectiveness. More generally, recent reviews identify machine learning as a promising method for reducing evaluation time and improving performance prediction of energy geostructures. However, these methods require large and diverse datasets for reliable application, and Hu et al. noted that prediction stability under different site conditions remains a limitation. For this reason, data-driven modelling is considered in this thesis only as a future research direction, while the present analysis remains based on direct experimental interpretation of monitored data.

2.6 Operational strategies and thermal recharge

The efficient operation of shallow geothermal systems depends not only on the geometry and thermal properties of the heat exchanger, but also on how the system is operated over time. If heat is extracted or injected in a strongly unbalanced way, the near-wall ground temperature may progressively drift away from its initial condition, reducing the temperature difference available for heat exchange. This issue is particularly relevant for energy walls because their thermal disturbance is concentrated near the wall–ground interface and may be influenced by boundary conditions on both the ground side and the excavated or internal side.

For this reason, recent studies have investigated operational strategies such as continuous operation, intermittent operation, seasonal load balancing, and active thermal recharge. These strategies aim to preserve the thermal gradient between the fluid and the ground, reduce long-term temperature drift, and improve the repeatability of system performance over successive operating periods.

2.6.1 Continuous vs. Intermittent operation

Continuous operation is the simplest strategy, but it may progressively reduce the local temperature gradient as the soil surrounding the heat exchanger warms or cools during operation. Intermittent operation introduces rest periods between active phases, allowing partial redistribution of heat in the surrounding ground and a partial recovery of the temperature gradient.

Wang et al. (2025) investigated this effect through model-scale tests on an energy diaphragm wall. Their results showed that intermittent operation can improve thermal efficiency compared with continuous operation, with a maximum reported improvement of 35.7%. The same study also confirmed the strong influence of the thermal driving potential: increasing the relative

temperature difference between the inlet fluid and the soil from 15 °C to 30 °C increased the wall thermal efficiency by 108.2% and the total heat exchange by 116.2%. These results demonstrate that operational schedule and inlet-fluid temperature are key parameters for energy-wall performance.

2.6.2 Seasonal and nightly thermal recharge

Beyond short rest periods, active thermal recharge has been proposed to reduce seasonal imbalance. In heating-dominated operation, heat extraction during winter can progressively cool the ground; conversely, in cooling-dominated operation, repeated heat injection can lead to ground warming. Seasonal balancing aims to compensate these effects by alternating extraction and injection over the year or by using external renewable sources to recharge the ground.

For the Geothermskin system, Alvi et al. (2025) numerically investigated underground heat storage using the energy-wall circuit connected to solar thermal collectors and storage tanks. The study considered summer scenarios with no operation, cooling operation, and high-temperature heat storage, followed by winter scenarios with heat extraction and optional night-time heat storage at different inlet temperatures. The results showed that the storage temperature, storage duration, and seasonal operating sequence can significantly affect the thermal state of the near-wall ground and the energy that can be extracted in winter. These findings are important for future optimisation of Geothermskin-type systems, although the present thesis does not directly validate a dedicated solar-recharge strategy.

2.6.3 Groundwater and moisture effects

The effectiveness of operational recovery and recharge also depends on the hydrogeological and hydraulic conditions of the site. Numerical studies on energy walls show that groundwater flow can increase heat exchange by advecting heat away from, or toward, the heat exchanger, thereby reducing local thermal accumulation. Di Donna et al. (2021) showed that hydrogeological conditions, including groundwater temperature and flow velocity, strongly influence the heat-exchange potential of energy walls.

However, groundwater effects are site-specific and should not be assumed in all cases. Sauvenier and Di Donna (2025), for example, analysed the Cleunay geothermal metro station under long-term operational conditions, where the estimated groundwater flow velocity was very low. Their study nevertheless showed that real performance is strongly affected by site-specific parameters such as initial ground temperature, concrete thermal conductivity, and the thermal environment of the station. In shallow retrofit systems such as Geothermskin, moisture variations in the near-wall soil may also influence thermal conductivity and heat transfer, which justifies the combined monitoring of temperature and water-content sensors.

2.6.4 Hybrid and smart-control approaches

Operational optimisation can also be extended to hybrid and smart-control strategies, where energy walls are combined with heat pumps, solar thermal systems, thermal storage, or district-scale thermal networks. These approaches can help balance heat extraction and injection across

daily and seasonal time scales. However, their application requires reliable monitoring, control strategies, and validated field data. For this reason, hybrid integration is treated in this chapter mainly as an outlook, while the experimental analysis in the present thesis remains focused on the measured field response of the Geothermskin prototype.

2.6.5 Research outlook

The literature shows that operational mode can strongly influence the performance of energy walls. Intermittent operation can support partial ground-temperature recovery, while seasonal or active recharge can reduce long-term thermal imbalance. Nevertheless, much of the available evidence still comes from laboratory tests or numerical simulations, and full-scale monitored datasets remain limited.

Within this context, the Geothermskin prototype provides useful field-scale evidence on how a modular energy wall responds under real heating and cooling tests. The present thesis does not directly assess a dedicated solar-recharge strategy; instead, it analyses measured heat exchange, near-wall temperature evolution, soil recovery between tests, PCM-related behaviour, and thermo-hydro-mechanical response. These results provide a basis for future work on optimised intermittent operation and active recharge strategies.

2.7 Thermo-hydro-mechanical coupling and ground response

Thermal activation of energy geostructures produces coupled thermal, hydraulic, and mechanical effects in the structural element and in the surrounding ground. Temperature variations modify the thermal field, may induce expansion or contraction of concrete and soil, and can affect soil hydraulic behaviour through changes in water viscosity, suction, and moisture redistribution. These processes are commonly described as THM coupling.

For energy walls, THM coupling is relevant because the wall is not only a heat exchanger but also a retaining or earth-contact structural element. The importance of each coupling mechanism depends strongly on the wall type, ground conditions, water-table depth, boundary conditions, and operating temperature range. In shallow retrofit systems such as Geothermskin, the activated ground volume is located in the unsaturated near-wall soil, so temperature, water content, suction, and strain measurements are particularly useful for interpreting the coupled response.

2.7.1 Introduction

The THM response of an energy wall can be interpreted through three linked mechanisms. The thermal component concerns the propagation of heat from the heat-exchange pipes into the wall and soil. The hydraulic component concerns the influence of water content, suction, and groundwater conditions on heat transfer. The mechanical component concerns stress and strain changes induced by temperature variations in the wall–soil system. These mechanisms are coupled, but their relative importance depends on the site and on the operating conditions.

2.7.2 Thermal-mechanical interaction

Thermal-mechanical interaction occurs because temperature changes can induce expansion or contraction of both the structural element and the surrounding soil. In energy walls, non-uniform temperature distributions may produce additional stresses, bending moments, or horizontal displacements, especially where the wall is restrained by slabs, floors, or the surrounding ground. Similar THM mechanisms have been identified in other energy geostructures. Fang et al. (2024), for example, showed that thermal loading beneath energy shallow foundations can modify settlement behaviour through thermally induced pore-water pressure and thermal volume changes of the soil skeleton. Liu and Zhou (2022) also showed, for energy tunnels, that ground settlement and soil–structure normal stress are sensitive to soil thermal expansion, elastic modulus, and burial depth.

For energy walls specifically, field evidence from the Geothermskin prototype suggests that these effects can remain limited under moderate operating temperatures. Baralis and Barla (2021) reported stress variations lower than 0.15 MPa and strains limited to about 80 $\mu\epsilon$ during heating and cooling operation. These values indicate that, for the tested prototype and operating conditions, the mechanical impact of thermal activation was negligible. Nevertheless, this conclusion should not be generalized without considering wall restraints, soil conditions, and operating temperature range.

2.7.3 Thermal-hydraulic processes

Thermal-hydraulic interaction controls the way heat is transferred and dissipated in the ground. In saturated ground, groundwater flow can add an advective component to heat transfer, which may increase heat-exchange potential and reduce local thermal accumulation. Di Donna et al. (2021) showed that hydrogeological conditions, including hydraulic conductivity, groundwater temperature, and groundwater flow velocity, can strongly influence the heat-exchange potential of energy walls.

In unsaturated soils, water content and suction are also important because thermal conductivity generally increases with increasing soil moisture. As a result, drying or wetting of the near-wall soil can modify the local heat-transfer capacity. This aspect is particularly relevant for shallow retrofit energy walls such as Geothermskin, where the activated soil volume is above the water table and where moisture sensors and tensiometers are included in the monitoring system. In this thesis, the hydraulic response is therefore interpreted mainly through measured water-content and suction trends rather than groundwater-flow effects.

2.7.4 Fully coupled THM models

Fully coupled THM models aim to describe heat transfer, water movement, and mechanical deformation within a single numerical framework. Such models are useful because purely thermal analyses may neglect hydraulic and mechanical processes that influence the behaviour of the ground–structure system. Fang et al. (2024) showed that, for energy shallow foundations in soft fine-grained soils, neglecting thermally induced mechanical effects could lead to large errors in settlement prediction under the considered conditions. Liu and Zhou (2022) similarly

demonstrated that the mechanical response of energy tunnels depends strongly on ground conditions, with thermally induced normal stress variations being more significant for shallow tunnels than for deep tunnels.

Although these studies do not directly concern energy walls, they support the broader need to consider coupled THM behaviour in energy geostructures. For energy walls, reliable THM modelling remains challenging because it requires accurate soil thermal and hydraulic properties, mechanical boundary conditions, and field data for calibration. Therefore, monitored datasets such as those from the Geothermskin prototype are valuable for checking whether thermal operation produces measurable hydraulic or mechanical effects under real field conditions.

2.7.5 Experimental evidence and monitoring needs

Comprehensive field datasets that combine thermal, hydraulic, and mechanical measurements are still limited. Many existing studies focus mainly on thermal performance, while mechanical and hydraulic measurements are less frequently available together. This limits the possibility of validating coupled THM models and of defining general design limits for energy walls.

The Geothermskin prototype is relevant in this context because it combines temperature monitoring with measurements of soil water content, suction, pressure, and strain. The monitoring system therefore allows the wall response to be interpreted not only in terms of heat exchange, but also in terms of near-wall soil condition and mechanical response. The analysis presented in Chapter 4 uses these measurements to evaluate whether thermal operation produced detectable coupled effects under the tested field conditions.

2.7.6 Synthesis

In summary, current research indicates that:

- Thermal activation can induce stress and strain variations in the wall–soil system, but these effects are often small under moderate operating temperatures and should be evaluated in relation to wall restraints and boundary conditions.
- Hydraulic conditions influence heat transfer. Groundwater flow can enhance advective heat transport in saturated ground, while water content and suction can affect thermal conductivity in unsaturated near-wall soils.
- Fully coupled THM models are useful for understanding energy-wall behaviour, but their reliability depends on field calibration and site-specific material properties.
- Long-term monitoring that combines temperature, hydraulic, and mechanical measurements remains necessary to support design guidelines and validate coupled models.

For the present thesis, these points justify the use of temperature, moisture, suction, pressure, and strain data to interpret the Geothermskin response. The aim is not to develop a full THM numerical model, but to identify whether the monitored thermal operation produced measurable hydraulic and mechanical effects in the near-wall ground and retaining wall.

2.8 Recent advances and outlook in integration and sustainability context

Recent developments in energy geostructures are increasingly moving beyond the evaluation of heat-exchange capacity alone. Current research also considers thermal storage, phase change materials, hybrid renewable systems, district-scale integration, and data-driven monitoring. These topics are relevant because energy walls may contribute not only as individual ground heat exchangers, but also as components of broader low-carbon thermal-energy systems.

However, not all of these developments are directly addressed in the present thesis. Therefore, this section reviews them as an outlook and identifies which aspects are directly connected to the Geothermskin experimental campaign: phase change materials influence, monitored thermal response, and thermo-hydro-mechanical behaviour.

2.8.1 Phase change materials and thermal energy storage

Phase change materials (PCMs) have attracted attention in shallow geothermal applications because they can store and release latent heat within a narrow temperature range. When placed in the ground volume affected by the heat exchanger, PCMs may increase the apparent thermal inertia of the system and reduce temperature fluctuations during heating or cooling operation. In energy-wall applications, this concept is still relatively recent, and full-scale field evidence remains limited.

In the upgraded Geothermskin experimental site, macroencapsulated PCM was introduced in the ground volume associated with one experimental field to investigate its effect on the thermal response of the soil and on the performance of the energy wall. This makes PCM one of the few recent advances that is directly analysed in the present thesis. The comparison between PCM and non-PCM zones is therefore treated not only as an outlook topic, but as part of the experimental interpretation presented in Chapter 4.

2.8.2 Hybrid solar–geothermal and multi-energy systems

Furthermore, Aresti et al. (2024) and Figueira et al. (2024) showed that hybridization boosts system energy efficiency and allows bidirectional thermal exchange between buildings, fitting with the operational concept of next-generation urban energy networks. This integration is especially relevant for the modular Geothermskin concept, which can serve as both a heat sink and a heat source within mixed renewable energy networks.

Hybrid operation is another important research direction for energy geostructures. In principle, energy walls can be combined with heat pumps, solar thermal systems, storage tanks, or other renewable sources to improve load balancing between heat extraction and heat injection. This approach is particularly relevant for systems that experience seasonal imbalance, because surplus heat can potentially be stored in the ground and later recovered during heating demand.

For the Geothermskin system, the 2024–2025 upgrade included an improved hydraulic connection between the geothermal circuit and solar thermal storage tanks, allowing future investigation of low- and high-temperature underground thermal energy storage. The upgraded

system was designed to support charging and discharging of thermal energy through a controlled hydraulic layout. However, the present thesis does not experimentally validate solar recharge efficiency; instead, it focuses on the monitored response of the wall–soil system during the available heating and cooling tests.

2.8.3 Fifth-generation district heating and cooling

Fifth-generation district heating and cooling networks (5GDHC) are low-temperature, bidirectional thermal networks that can exchange heat among multiple buildings and distributed energy sources. Energy geostructures may contribute to these systems by acting as local heat sources, heat sinks, or underground thermal storage elements. Recent reviews identify the integration of energy geostructures into district-scale networks as a promising direction for improving flexibility and resilience in urban energy systems.

For energy walls, this role is still mostly prospective. Their compact geometry and location within urban underground structures make them suitable candidates for distributed thermal nodes, but further work is needed on control strategies, long-term thermal balance, ownership models, and design guidance. In this thesis, 5GDHC is therefore considered only as a long-term integration pathway, not as a direct object of analysis.

2.8.4 Data-driven modelling and digitalisation

Data-driven modelling is also emerging as a tool for interpreting monitored energy-wall datasets. Hu et al. (2024) used field-test data to develop a support vector regression model for predicting energy-wall thermal performance and introduced additional indicators such as Energy Utilization Ratio, Thermal Saturation, and Effectiveness. Their results show the potential of machine learning as a complementary design and prediction tool, although the authors also note that the model was trained on a limited dataset and requires more diverse samples from different sites to improve prediction stability.

For the present thesis, data-driven modelling is not adopted as a method. The monitored data are interpreted through direct experimental analysis, while machine-learning approaches are considered a possible future development once longer and more diverse datasets are available.

2.8.5 Outlook

Overall, recent advances show that energy walls are evolving from individual heat exchangers toward components of integrated renewable thermal-energy systems. PCM-enhanced ground volumes, solar-assisted recharge, underground thermal storage, district-scale energy sharing, and data-driven monitoring all represent promising directions. Nevertheless, the available literature still shows several limitations. Many studies remain numerical or laboratory-based, full-scale monitored datasets are limited, and the long-term behaviour of PCM-enhanced or hybrid energy-wall systems is not yet fully validated.

Within this context, the Geothermskin prototype provides field-scale temperature, moisture, suction, pressure, strain, and energy-flow data under real heating and cooling operation. The present thesis contributes to this research direction by analysing measured heat exchange, near-

wall temperature evolution, PCM and non-PCM response, recovery behaviour between tests, and thermo-hydro-mechanical monitoring data. It does not aim to validate 5GDHC integration, machine-learning prediction, or solar thermal recharge efficiency. Instead, it provides experimental information that can support future work on these topics.

Table 3: Main research gaps identified in the literature and their connection with the objectives of the present thesis

Research gap identified in the literature	Relevance for energy walls	Connection with this thesis
Limited full-scale monitoring data for energy walls	Many studies are based on numerical simulations, laboratory tests, or short-term experiments, while long-term field datasets remain limited.	The Geothermskin prototype provides field-scale monitoring data under real heating and cooling operating conditions.
Uncertainty in thermal response under different operating modes	Energy-wall performance depends on inlet temperature, operation duration, active area, and recovery periods, but these effects are not yet fully standardised.	The thesis analyses heating and cooling tests, exchanged power, near-wall temperature evolution, and recovery behaviour between operating periods.
Need for better understanding of near-wall ground response	The thermal disturbance around energy walls is affected by wall geometry, boundary conditions, soil properties, and moisture conditions.	The thesis evaluates the spatial and temporal thermal response of the soil surrounding the Geothermskin wall.
Limited field evidence on PCM-enhanced energy walls	PCM integration has been proposed as a way to improve thermal storage and buffering, but field-scale evidence remains scarce.	The thesis compares PCM and non-PCM zones to assess whether PCM modifies the measured thermal response.
Need for combined thermal, hydraulic, and mechanical interpretation	Most studies focus mainly on thermal performance, while hydraulic and mechanical measurements are less frequently analysed together.	The thesis uses temperature, moisture, suction, pressure, and strain data to interpret the thermo-hydro-mechanical response of the prototype.
Lack of direct validation for future hybrid and recharge strategies	Solar-assisted recharge, underground heat storage, and smart operation are promising, but require reliable field evidence before optimisation.	The thesis does not directly validate solar recharge efficiency, but provides experimental data that can support future optimisation of Geothermskin-type systems.

3 Description of the prototype

This chapter describes the Geothermskin energy-wall prototype that provides the experimental data analysed in this thesis. The system has evolved through two construction phases: the original three-module prototype installed at the Energy Center in 2019, and a major upgrade carried out in 2024–2025 that enlarged the installation to six circuits arranged in three fields, introduced macro-encapsulated PCM into the soil of one field, and coupled the geothermal circuit to the building’s solar-thermal system for underground thermal energy storage. Because

the measurements interpreted in Chapter 4 were acquired on the upgraded configuration, the description below presents the system as it currently stands while making clear which elements date from 2019 and which were added during the upgrade. The concept is introduced first Section 3.1, followed by the site and its geology Section 3.2, the original prototype Section 3.3, the 2024–2025 upgrade Section 3.4, the phase change material Section 3.5, the monitoring system and instrumentation Section 3.6, the measured soil thermal properties Section 3.7.

3.1 The Geothermskin concept

Baralis and Barla (2021) described Geothermskin as a very shallow geothermal technology, patented at the Politecnico di Torino, that turns the earth-contact surfaces of a building into an active heat exchanger for heating and cooling. Heat-exchange pipes are fixed externally to a retaining or basement wall and backfilled, so that the structural element also operates as a thermally activated envelope. Unlike conventional energy geostructures, in which the pipe layout is constrained by the reinforcement cage cast inside the element, the Geothermskin circuits are surface-mounted and therefore independent of the structural characteristics of the wall.



Figure 3: Exterior views of the Energy Center building at Politecnico di Torino, where the Geothermskin experimental prototype is installed on the underground retaining wall

The system is conceived as modular equipment. Each module can take a different pipe geometry depending on the wall and on site constraints, and modules can be connected either in parallel or in series. Parallel connection generally yields higher thermal efficiency, whereas series connection reduces the total flow rate demanded of the circulator while maintaining an adequate fluid velocity. The main advantages of the concept are:

- **Structural neutrality:** the thermal activation does not weaken the strength or stiffness of the wall, as the pipes are mounted on its surface rather than embedded in the structural section.
- **Cost-effectiveness:** by avoiding the drilling required by borehole heat exchangers, the main residual cost is the excavation, which is incurred only when related construction works are already taking place.

- **Modularity and scalability:** modules can be added, excluded or replaced individually — for instance, in case of localised damage — without compromising the rest of the system.
- **Suitability for retrofit:** the on-site, surface-mounted installation makes the technology applicable to existing underground structures in dense urban areas, where free land for conventional systems is scarce.

Baralis and Barla (2021) stated that durability of the embedded circuits is ensured by selecting pipes with a high-resistance oxygen barrier, such as cross-linked (PE-Xa) or high-density (PE-HD) polyethylene, which are designed to withstand the alkaline conditions associated with contact with concrete.



Figure 4: Energy center building model, created and rendered by REVIT software



Figure 5: Energy center building model with the Geothermskin, created and rendered by REVIT software

3.2 The Energy Center experimental site

The prototype is installed on the external face of the north-eastern basement wall of the Energy Center, a research building of the Politecnico di Torino campus. The site was selected because it offers representative urban subsurface conditions together with an existing technical infrastructure for monitoring. On the inner side of the wall a technical cavaedium — an open-air corridor whose ceiling is a walkable steel grid at street level — houses the manifolds, the data-acquisition cabinets and part of the pipework, and provides permanent access for inspection.



Figure 6: Conceptual rendering of the Geothermskin energy-wall system applied to the building basement

Baralis and Barla (2021) described the subsoil of the Turin plain as consisting of coarse alluvial fluvioglacial deposits — pebbles, gravel and sand in a sandy-silty matrix — with randomly distributed cemented lenses. At the experimental site the stratigraphy comprises about 0.3 m of topsoil, an upper layer of gravel with pebbles in a sandy and locally silty matrix, and a sandy-gravelly deposit with oxidation traces at greater depth. The water table lies at roughly 23 m below ground surface, so that the entire activated volume of the wall is located in the unsaturated zone. These conditions give the ground a moderate thermal conductivity and limited groundwater flow, which is relevant for interpreting the thermal response of the wall in Chapter 4.

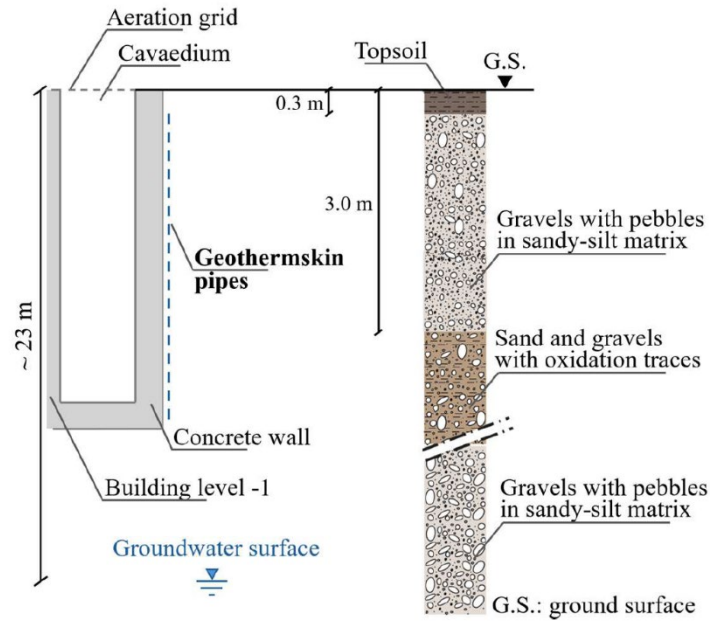


Figure 7: Cross-section of the Geothermskin prototype with indication of the stratigraphy (after Baralis & Barla, 2021).

3.3 The original prototype (2019)

The original site was built between May and July 2019. Its size was intentionally intermediate between a laboratory specimen and a full-scale application, and its operation is managed by a ground-source heat pump. The external face of the basement wall was exposed by a vertical excavation reaching 4.60 m below ground surface (the footing of the wall), stabilised with iron trench shores, and a lean-concrete slab was cast at the bottom to support the scaffolding and the heat-exchange loops.

3.3.1 Wall, modules and heat-exchange pipes

Three independent heat-exchange circuits were fixed to the bare wall using metallic clamps at approximately 0.75 m spacing. Each circuit corresponds to one module 2.50 m wide and 4.60 m high. Two modules use a predominantly horizontal pipe layout and one a predominantly vertical layout, so that different deployment geometries could be compared. To limit the influence of external air, the upper bend of each coil is set at about 1.45 m below ground surface; consequently the effective pipe-covered area of each module is about 6.3 m² (2.10 m wide × 3.0 m high), against a total earth-contact area of 11.5 m² per module.

The heat-exchange pipes are Rehau Rautherm S cross-linked polyethylene (PE-Xa), 20.0 mm in diameter with a 2.0 mm wall thickness, the same product used in radiant floor systems and in the ENERTUN tunnel-lining prototype. The branches of each coil are spaced 0.30 m apart. The pipes pass through the wall to the cavaedium by means of 130 mm core-drilled holes and are connected to a tailored manifold equipped with ball valves, which allow individual modules to be excluded and circuits to be linked either in parallel or in series. The supply and return header pipes are high-density polyethylene PE100 (PN16, DN32) and run about 65 m from the

manifold to the heat pump. All branches and headers in the open cavaedium are insulated with 20 mm closed-cell elastomeric foam (nominal thermal conductivity 0.034 W/(mK) at 0 °C).

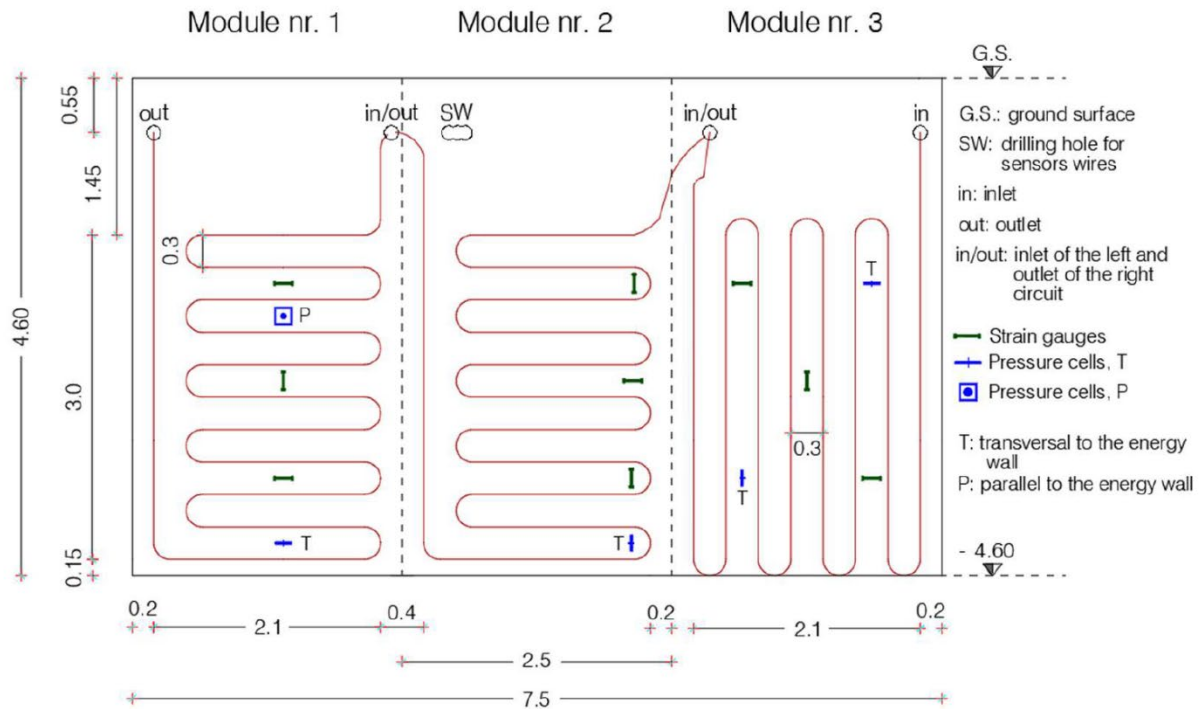


Figure 8: Pipe deployment in the original three-module prototype with the thermo-mechanical sensors installed on the wall; dimensions in metres (after Baralis & Barla, 2021)

3.3.2 Heat pump and heat-carrier fluid

Heat exchange between the ground-side (primary) circuit and the user-side (secondary) circuit is regulated by a reversible electric heat pump (NIBE F1155-6) installed in a basement technical room. The unit has a nominal thermal power of 3.15 kW with a certified COP of 4.72, a declared electrical input of about 0.67 kW including the two on-board circulation pumps GP1 and GP2, and uses R407C refrigerant. On the ground side the nominal flow rate is 0.65 m³/h (0.18 l/s). Compressor start-up and shut-down follow the degree-minutes logic of the controller, and the supply temperature can be fixed or set to follow a climate curve referenced to the cavaedium temperature (probe BT1). On the user side the secondary circuit feeds a 1.5 kW fan coil and a 100 l buffer tank (probe BT25) that prevents short cycling of the compressor.

The heat-carrier fluid in the primary circuit is a mixture of water and 25% by volume propylene glycol, chosen for safety and environmental reasons, which protects the loop down to a freezing point of about -10 °C. The same fluid circulates on the user side during free cooling. This 25% propylene-glycol mixture is the fluid for which the thermo-physical properties are evaluated when converting measured flow rates into exchanged power in Chapter 4.

3.3.3 Irrigation system

To study the response of the wall under controlled soil-moisture conditions, 45 sprinklers arranged in five rows of nine were installed at the ground surface, fed by three parallel circuits connected to the building's irrigation network through a dedicated manifold. This allows the moisture content of the backfill to be varied deliberately during testing.



Figure 9: Irrigation sprinklers of the Geothermskin experimental site.

3.4 The 2024–2025 upgrade

The construction of the adjacent Digital Revolution House offered the opportunity to upgrade the experimental site. The upgrade had two objectives: to assess the feasibility of using a shallow energy geostructure as a conduit for underground thermal energy storage (UTES) over a range of temperatures, and to evaluate the influence of PCM on the thermal performance of the wall and on the thermal inertia of the surrounding ground. The excavation that exposed the wall and the existing circuits began in June 2024, and the enlargement works were carried out from April 2025; monitoring of the rebuilt site resumed in June 2025.

3.4.1 Enlargement to six circuits and three fields

Three new heat-exchange circuits were added to the three existing ones, bringing the total to six circuits grouped into three distinct fields. The new circuits use the same PE-Xa pipe and were fixed to the wall with U-bolts of 20 mm internal diameter holding the pipe about 2 cm from the concrete; each new circuit is about 27 m long and covers an earth-contact area of 11.5 m².



Figure 10: Upgraded geothermal wall with 6 circuits during construction

Fields 1 and 3 use a horizontal pipe layout, while field 2 includes a vertically arranged circuit, so that layout effects can again be compared. Expanded-polystyrene (EPS) thermal-insulating panels, filled with lightweight expanded clay aggregate (LECA) for stabilisation, were built between the fields during backfilling to suppress unwanted heat exchange between adjacent activated volumes and to approximate adiabatic lateral boundaries. After installation the new circuits were pressure-tested (4.0 bar, holding within 0.2–0.3 bar over two hours), purged, saturated with the antifreeze fluid and insulated with elastomeric foam in the cavaedium.

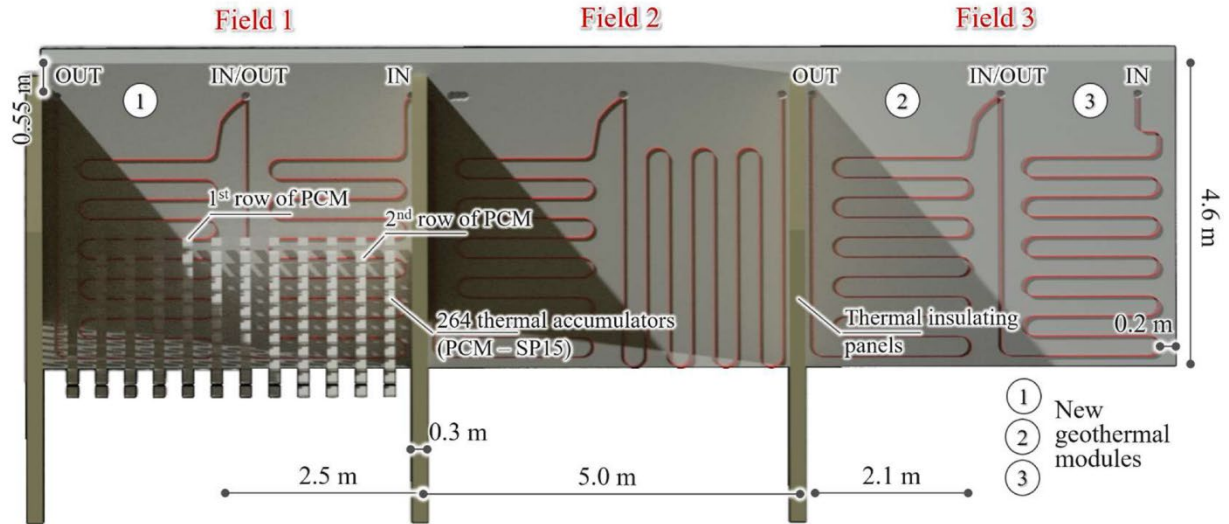


Figure 11: 3D of the improved Geothermskin experimental site at ground side based on (Alvi, 2026)

The PCM was introduced only in the ground of field 1. The experimental design therefore compares the response of circuits in the PCM field against geometrically equivalent circuits in the PCM-free fields. In particular, circuit 2 (field 1, horizontal layout, with PCM) and circuit 6 (field 3, horizontal layout, without PCM) share an identical piping geometry and instrumented headers, which makes them the natural pair for the PCM versus non-PCM comparison developed in Chapter 4.

3.4.2 Solar coupling and operating modes

The geothermal circuit was hydraulically coupled to the evacuated-tube solar collectors on the roof of the Energy Center (15 m², 15 kW nominal). The collectors charge a 1000 l storage tank (BP-02), connected in turn to a 200 l buffer tank, from which a dedicated galvanised-steel circuit (DN32), an electromagnetic mixing valve, diverter and ball valves and an external twin variable-speed pump (Grundfos MAGNA3) can route the hot fluid directly into the ground loop, by-passing the heat pump. The by-pass is necessary because the heat pump locks out when the temperature on the evaporator side exceeds 30 °C; the dedicated connection therefore enables heat storage in the ground at both low (below 30 °C) and medium-to-high temperature (assumed 30–90 °C). The tank temperatures are monitored by probes BT53 (1000 l) and BT54 (200 l).

An automation system developed for the site allows four operating modes — charging, discharging, manual and off. In charging mode the heated fluid from the solar buffer tank is driven into the ground loop by the twin pump according to a user-defined schedule and temperature threshold; in discharging mode the stored heat is recovered through the heat pump. These modes underlie the storage and heating-with-storage tests analysed later.

3.5 Phase change material

The distinguishing feature of the upgraded prototype is the introduction of macro-encapsulated PCM into the ground of field 1. PCM stores and releases latent heat at an almost constant temperature during its solid–liquid phase transition, adding thermal inertia to the soil and,

potentially, buffering the temperature of the volume exchanging heat with the wall. Because common PCMs have low thermal conductivity, the choice of phase-change temperature, material type and the position of the material relative to the wall are all important, and were supported by thermo-hydraulic numerical modelling during design.

The material adopted is Rubitherm SP15 gel, an inorganic salt-hydrate PCM selected for its low unit cost and comparatively higher thermal conductivity among the available macro-encapsulated products. According to its datasheet it has a melting range of 15–17 °C and a solidification (congealing) range of 13–15 °C, with a main peak at about 15 °C in both directions, and a maximum operating temperature of 30 °C. This 13–17 °C phase-change band is the reference used in Chapter 4 to judge, from the measured soil temperatures, whether the PCM in front of a given circuit was melting, solidifying or already fully solid during a test.

The PCM is supplied as flat tabs measuring $0.132 \times 0.213 \times 0.025$ m, each filled with 0.5 l of material (density about 1.3 kg/l liquid and 1.4 kg/l solid; about 0.65 kg per tab excluding the casing). A total of 264 tabs were installed. Because the material must be initialised (melted, homogenised and frozen) to reach its specified properties and had exceeded 30 °C in transport, the tabs were re-initialised by freezing them in batches below 0 °C in the DISEG and MastrLAB laboratories before installation.

The tabs were placed in field 1 from the wall footing up to 2.6 m below ground surface: 24 tabs on each of 11 planes spaced about 0.18 m apart in depth. Each plane holds two rows — a first row of 12 tabs at about 0.10 m from the wall and a second row about 0.20 m behind it, at roughly 0.51 m from the wall. This places the PCM in the lower part of the activated volume, which is why, in Chapter 4, a PCM influence is sought principally at the deeper measurement levels and near the wall footing rather than in the shallow soil.



Figure 12: Macro-encapsulated PCM (Rubitherm® SP15 gel) installed in field 1: (a, b) tab distribution on the ground in front of the energy wall during backfilling; (c) single tab, 13.2 × 21.3 cm, 765 g; (d) main material properties (Rubitherm SP15_gel data sheet), after Alvi (2026).

3.6 Monitoring system and instrumentation

Because of the experimental nature of the prototype, a dense monitoring system was deployed to characterise the thermal and hydraulic behaviour of the unsaturated soil, the mechanical response of the wall, and the energy performance of the installation. The instrumentation acquired for this thesis comprises soil and wall sensors read by two acquisition units and energy-metering instruments on the hydraulic circuits. The sensor types, quantities and main metrological specifications are summarised in Table 4.

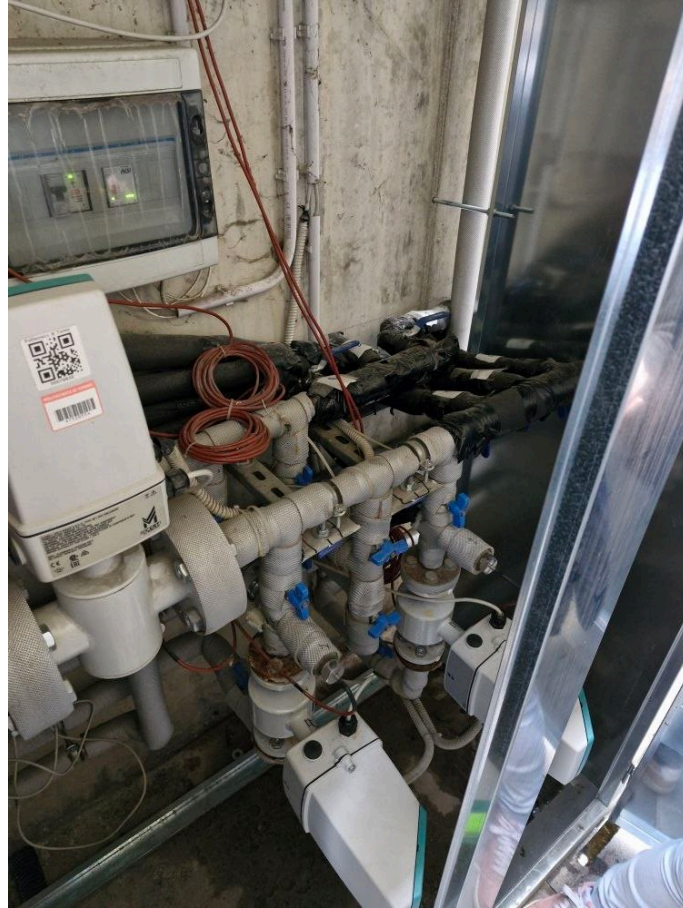


Figure 13: Energy flow meters positioned on the secondary (technical room) and primary circuits

Ground temperature is measured with 96 PT100 platinum resistance thermometers sealed in stainless-steel casings, distributed in horizontal planes at the key depths used in the analysis. Soil volumetric water content (and an auxiliary temperature) is measured with Sentek Drill & Drop encapsulated probes, and soil matric suction with METER TEROS 21 tensiometers, saturated before installation. The mechanical response of the wall is captured by resistive strain gauges (installed in both the horizontal and vertical directions) and by oleodynamic pressure cells (200×200 mm plates measuring the normal stress). During the 2024 excavation a number of sensors were damaged and replaced (including 10 PT100, 2 humidity sensors, 1 tensiometer and 4 strain gauges); two pressure cells were affected, one damaged and one rotated about 10° during recompaction, which is relevant when interpreting the mechanical records.

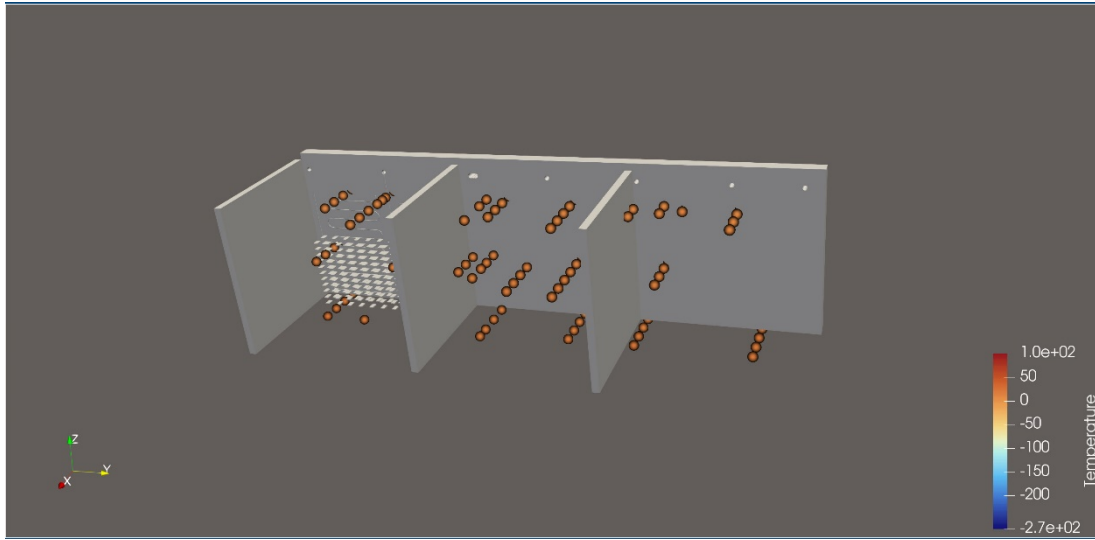


Figure 14: 3D model of all the sensors located in front of the energy wall, created in ParaView software

The sensors are read by two acquisition units (a GPRS-based unit near the manifold and a wireless sensor network), and the records are uploaded to web platforms from which they can be viewed and downloaded. On the hydraulic side, three SIEMENS volumetric flow meters, five SIEMENS ultrasonic energy meters and three SIEMENS PT1000 immersion probes (in the header thermowells and the 200 l solar tank) measure the flow, the exchanged thermal energy and the fluid temperatures, providing the basis for the system-level performance indicators. The energy meters compute heating or cooling energy from the measured fluid volume, the supply–return temperature difference and a heat coefficient.

After the upgrade, most soil sensors (96 PT100 and 12 humidity sensors) were positioned in horizontal planes at three key depths — 4.60 m (wall footing), 2.35 m and 1.10 m below ground surface — while the tensiometers and four additional humidity sensors were placed in the shallowest metre of soil, where rainfall-driven moisture gradients are largest. Sensors were embedded in and covered with washed river sand to protect the cables and were individually labelled. The resulting plan and cross-sectional layouts of the circuits, PCM tabs and sensors define the spatial reference used throughout Chapter 4.

Table 4: Monitoring sensors of the Geothermskin prototype with quantities and main specifications (compiled from Alvi, 2026 and Baralis & Barla, 2021). Dashes denote specifications not reported.

Sensor (type / model)	Qty	Measured quantity	Range / accuracy / resolution
PT100 (Pt resistance thermometer)	96	Soil temperature	−20 to +80 °C / 0.1 °C / 0.01 °C
Hygrometer (Sentek Drill & Drop)	15	Volumetric water content, soil T	0–80% / ±0.03% / 10 ^{−4}
Tensiometer (METER TEROS 21)	2	Soil matric suction, T	0 to −100 kPa / 10% + 2 kPa / 0.1 kPa
Pore-water pressure sensor	3	Pore-water pressure	—

Sensor (type / model)	Qty	Measured quantity	Range / accuracy / resolution
Resistive strain gauge	5	Wall strain (horizontal & vertical)	$\pm 1500 \mu\epsilon$ / $\pm 0.2\%$ FS / $1.0 \mu\epsilon$
Oleodynamic pressure cell	5	Normal stress on wall	0–200 bar / $\pm 0.5\%$ FS / 0.01 bar
Immersion probe (SIEMENS PT1000)	3	Fluid T (headers, solar tank)	—
SIEMENS volumetric flow meter	3	Circuit flow rate	—
SIEMENS ultrasonic energy meter	5	Exchanged thermal energy	—

3.7 Measured soil thermal properties

The backfill of the upgraded site was characterised in the laboratory to provide the thermal and physical parameters needed to interpret the field response and to feed the numerical model. The two relevant materials are the washed silica sand used to embed the sensors and the silty-loam agricultural soil of the levelled working surface. Their measured thermal conductivity, volumetric heat capacity, thermal diffusivity, bulk and particle density, porosity and water content are summarised in Table 5; representatively, the dry sand has a thermal conductivity of about 0.35 W/(mK), rising to about 2.31 W/(mK) when saturated, while the loam ranges from about 0.48 to 1.49 W/(mK) between the dry and saturated states. These values confirm the strong dependence of the soil thermal behaviour on water content, which is central to the moisture-dependent interpretation of the thermal field in Chapter 4.

Table 5: Properties of the sand and loam of the experimental site evaluated in the laboratory after (Alvi, 2026)

	Dry silica sand	Saturated silica sand	Dry loam	Saturated loam
Thermal conductivity, λ [W/(mK)]	0.35 $\pm$ 0.02	2.31 $\pm$ 0.17	0.48 $\pm$ 0.01	1.49 $\pm$ 0.12
Volumetric heat capacity, ρc_p [MJ/(m ³ ·K)]	1.49 $\pm$ 0.03	-	1.49 $\pm$ 0.01	2.2 $\pm$ 0.04
Thermal resistivity, R [m·K/W]	2.87 $\pm$ 0.13	0.44 $\pm$ 0.03	2.09 $\pm$ 0.04	0.68 $\pm$ 0.05
Thermal diffusivity, α [mm ² /s]	0.24 $\pm$ 0.03	-	0.2 $\pm$ 0.01	0.64 $\pm$ 0.02
Bulk density, ρ_d [kg/m ³]	1579.7	1970.8	1205.5	1722.9
Particle density, ρ_p [kg/m ³]	2594.0	2594.0	2498.0	2498.0
Specific heat capacity (solid phase), $c_{p,s}$ [J/(kg·K)]	945.43	945.43	1245.72	1245.72

	Dry silica sand	Saturated silica sand	Dry loam	Saturated loam
Gravimetric water content, θ_g [-]	0	0.25	0	0.43
Porosity, n [-]	0.39	-	0.53	-

4 Results and discussion of the experimental campaign

This chapter presents the results of the experimental campaign carried out on the Geothermskin system at the Energy Center in Turin. The analysis combines the temperature measurements recorded by the soil sensor network with the operating conditions of the cooling and heating tests. The results are first discussed on a campaign scale, in order to identify the seasonal thermal background, and then at test scale, focusing on the response of the soil around the active geothermal circuits. Attention is given to the comparison between PCM and non-PCM zones, the propagation of temperature variations into the soil, and the vertical temperature distribution along the wall. The final sections relate the thermal response to system-level performance indicators and, where available, to Thermo-Hydro-Mechanical observations.

4.1 Experimental campaign and data preparation

The experimental dataset was prepared from the continuous temperature records collected during the monitoring campaign. The raw measurements were cleaned, synchronized, and averaged at 30-minute intervals to obtain a consistent dataset for time-series analysis and spatial comparison. Each sensor was then classified according to its position within the corrected coordinate system and assigned to the corresponding circuit zone, gap zone, wall separator zone, or PCM-influenced region. This classification provides the basis for comparing the thermal response of different parts of the geothermal wall and surrounding soil.

4.1.1 Test program and operating conditions

The experimental campaign included four main operating tests, carried out between July and December 2025. Two tests were performed in cooling mode during the summer period, while two tests were performed in heating mode during autumn and early winter. The tests differed in terms of duration, active circuits, hydraulic connection configuration, heat pump operating time, and total exchanged energy. This variation allows the system response to be evaluated under different operating conditions and seasonal backgrounds.

The cooling tests were shorter and were mainly intended to assess the immediate thermal response of the soil during heat exchange with the ground. Cooling Test 1 involved four circuits, namely Circuits 1, 2, 5, and 6, while Cooling Test 2 involved Circuits 2 and 6.

The heating tests were conducted over longer periods and were affected by the seasonal decrease of soil temperature. Heating Test 1 was the longest test of the campaign and involved Circuits 2 and 6, with Circuit 4 added later during the test period. Heating Test 2 involved Circuits 2 and 4 and was characterised by a shorter duration and a lower active cycle. These heating tests are therefore useful not only for evaluating the response of the wall during heat extraction from the soil, but also for understanding the influence of seasonal cooling on the measured temperature field.

A summary of the main operating conditions of the four tests is reported in Table 6.

Table 6: Summary of the experimental operating tests

Test	Period	Mode	Active Circuit	Hydraulic Connection	Duration [h]
Cooling Test 1	24 Jul - 28 Jul 2025	Cooling	1, 2, 5, 6	Serial	93.52
Cooling Test 2	25 Aug–28 Aug 2025	Cooling	2, 6	Parallel	78.88
Heating Test 1	08 Oct–13 Nov 2025	Heating	2, 6, and 4 from 30 Oct	Parallel	856.93
Heating Test 2	19 Nov–01 Dec 2025	Heating	2, 4	Parallel	288.28

4.1.2 Sensor coordinate system and spatial zoning

The spatial position of each temperature sensor was defined using a three-dimensional coordinate system referenced to the geothermal wall. The origin of the coordinate system was placed at the lower-left point of the wall. In this system, **X** represents the distance from the wall into the soil, **Y** represents the horizontal distance along the wall from left to right, and **Z** represents the vertical height from the base of the wall. Therefore, **Z = 0 m** corresponds to the base of the wall, while **Z = 4.6 m** corresponds to the upper part of the wall, as shown in Figure 15. Red, green, and blue represent X, Y, and Z, respectively.

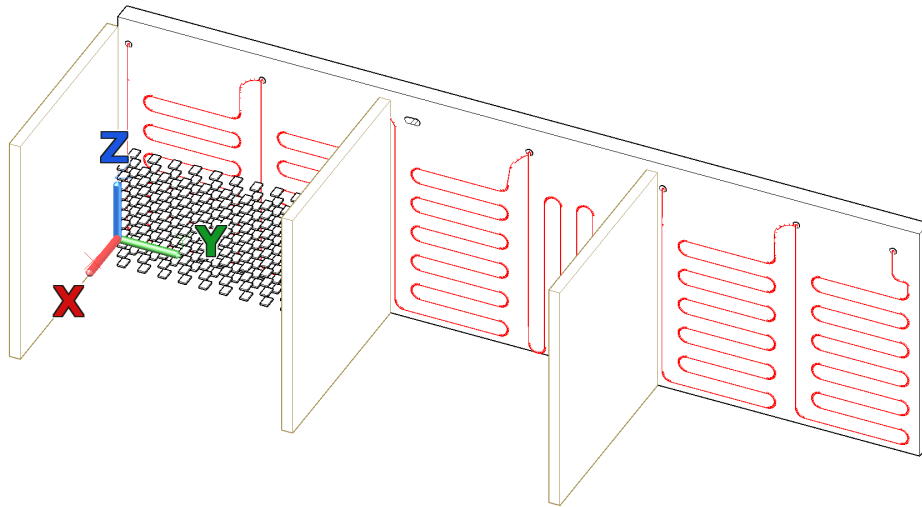


Figure 15: Depiction of the point of origin of the coordinate system and the Phase Change Materials

The PCM panels were installed only in the lower part of the wall, in front of Circuits 1 and 2. For the analysis, the PCM zone was therefore defined using the corrected spatial envelope:

$$0 < X < 0.8 \text{ m}, 0 < Y < 4.6 \text{ m}, 0 < Z < 2.03 \text{ m}$$

This definition was used to distinguish sensors located within the PCM-influenced region from sensors located in non-PCM zones. It is important to note that not all sensors in front of Circuits 1 and 2 were automatically classified as PCM-zone sensors. Only sensors satisfying the combined **X**, **Y**, and **Z** limits were considered to be within the PCM region. This approach

allowed the later comparison between PCM and non-PCM areas to be based on the actual physical location of the PCM panels rather than only on the circuit number. Figure 16 to Figure 19 provide the sensors locations in front of the circuits.

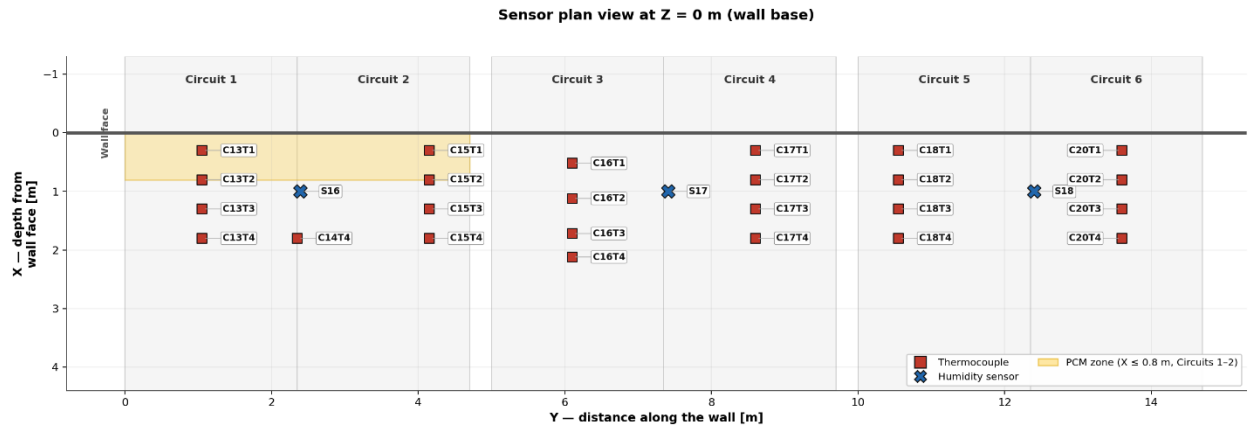


Figure 16: Plan view of the sensor layout at $Z = 0$ m, at the base of the wall, showing the position of every sensor in the horizontal X - Y plane, where X is the distance from the wall face and Y is the distance along the wall

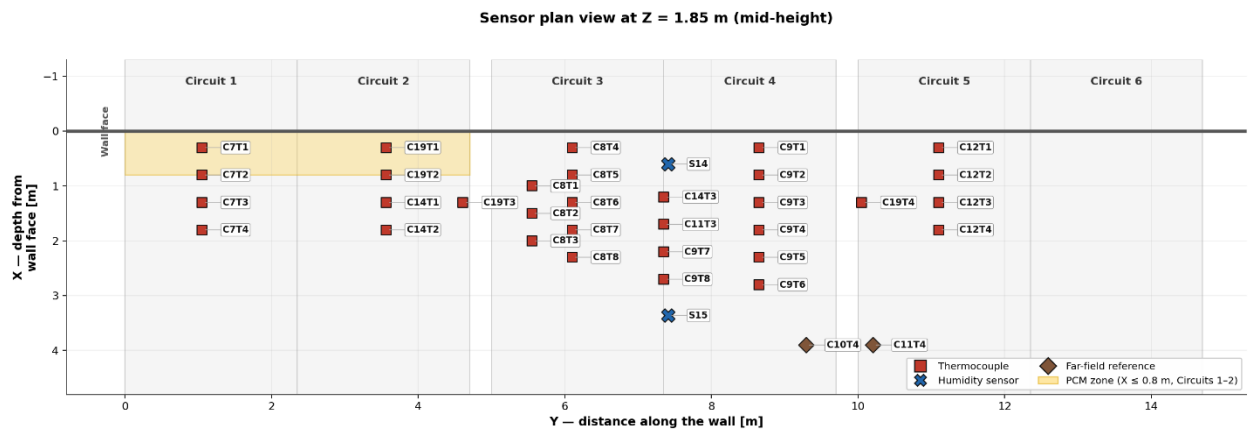


Figure 17: Plan view of the sensor layout at $Z = 1.85$ m, at mid-height of the wall

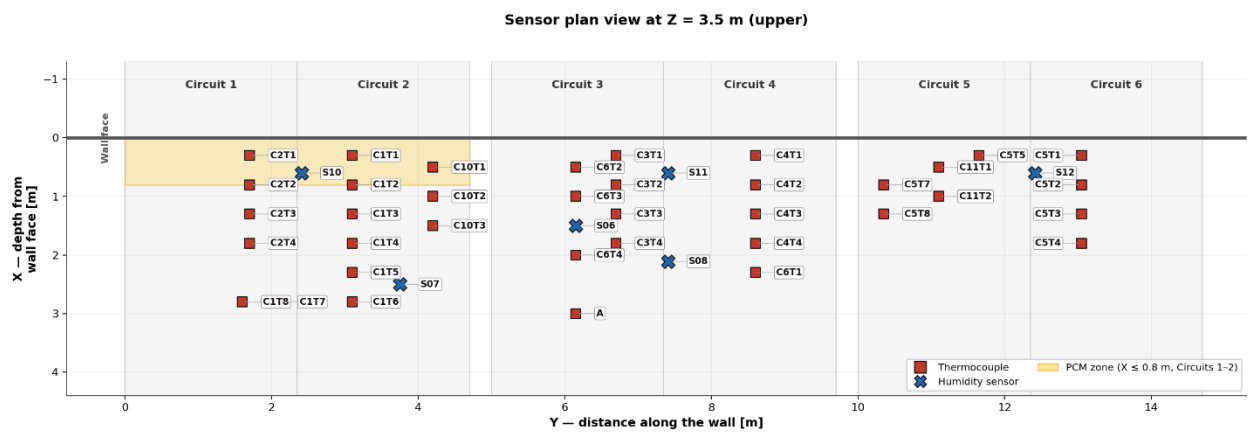


Figure 18: Plan view of the sensor layout at $Z = 3.5$ m, in the upper part of the wall, the most densely instrumented level

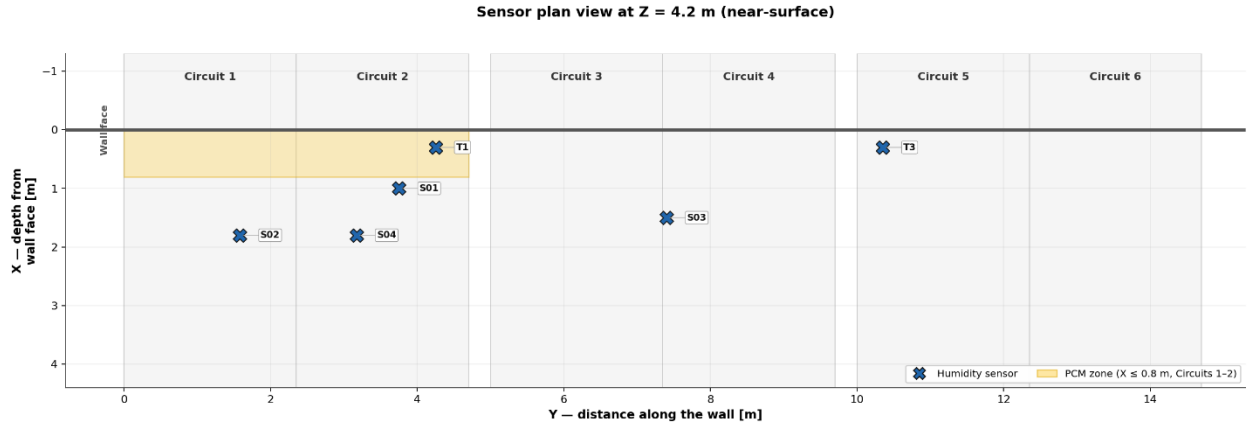


Figure 19: Plan view of the sensor layout at $Z = 4.2$ m, near the ground surface

4.1.3 Data cleaning and sensor selection

The raw monitoring data were first combined into a single dataset and filtered to include the relevant monitoring period starting from 31 May 2025 at 17:00. The time column was converted into a consistent datetime format, and the measurements were grouped into 30-minute intervals for each sensor. For each time interval, the average temperature value was calculated, producing a synchronized dataset suitable for time-series analysis, spatial comparison, and three-dimensional visualisation. A progressive time-step index was also assigned to each 30-minute interval to allow the dataset to be imported and animated in ParaView.

Before averaging, the dataset was checked for invalid or physically unrealistic temperature values. Measurements outside the expected range of the experiment, such as values close to -270 °C, were considered acquisition errors and removed from the analysis. Values equal to or close to 0 °C were also treated as suspicious for the soil temperature field and were excluded unless otherwise justified by the experimental context. This filtering step was applied before the 30-minute averaging process to prevent false values from affecting the calculated mean temperatures.

After cleaning, each record was classified according to the test period, operating mode, circuit zone, and PCM-zone definition described in the previous section. This allowed the data to be filtered consistently for the different analyses presented in this chapter. In particular, the distinction between valid and excluded records was maintained in the dataset, so that the original sensor availability could remain traceable while only reliable measurements were used in the graphs and calculations.

A further sensor selection was applied for the cooling tests and sensors **C13T1**, **C13T2**, **C13T3**, **C13T4**, **C18T3**, **C18T4**, **C20T1**, **C20T2**, **C20T3**, and **C20T4** were excluded. These sensors were not removed from the entire dataset, but were flagged as invalid for cooling-period analysis as their measurements were not corrected for cable resistance during this timeframe.

The final cleaned dataset, therefore, contains synchronized 30-minute temperature records with associated spatial coordinates, circuit classification, PCM-zone identification, test labels, and validity flags. This structure provides the basis for the subsequent thermal analyses, including campaign-scale trends, circuit comparisons, PCM and non-PCM behaviour, spatial thermal propagation, vertical gradients, and three-dimensional visualisation.

4.2 Campaign-scale thermal evolution and seasonal baseline

The first stage of the analysis focused on the overall temperature evolution during the full monitoring campaign. This campaign-scale view is necessary because the experimental tests were conducted over different seasonal periods, from summer cooling operation to autumn and early-winter heating operation. As a result, the measured soil temperatures reflect both the local effect of the Geothermskin operation and the broader seasonal variation of the ground temperature. Establishing this background trend is therefore essential before interpreting the temperature response during each individual test.

4.2.1 Overall temperature evolution during the monitoring period

The full campaign temperature evolution is shown in Figure 20. Each curve represents one circuit, and is obtained by averaging, at each point in time, the readings of all the soil PT100 sensors located in front of that circuit, where a sensor is attributed to a circuit according to its position along the wall. This spatial averaging condenses the many individual sensors into a single representative temperature for each circuit, so that the overall behaviour of the six circuits can be compared over the monitoring period from June to December 2025. The cooling and heating test periods are highlighted to show the position of each experimental test within the broader seasonal trend. Circuits 1 and 2 correspond to the portion of the wall where the PCM panels are located, while the remaining circuits represent non-PCM zones.

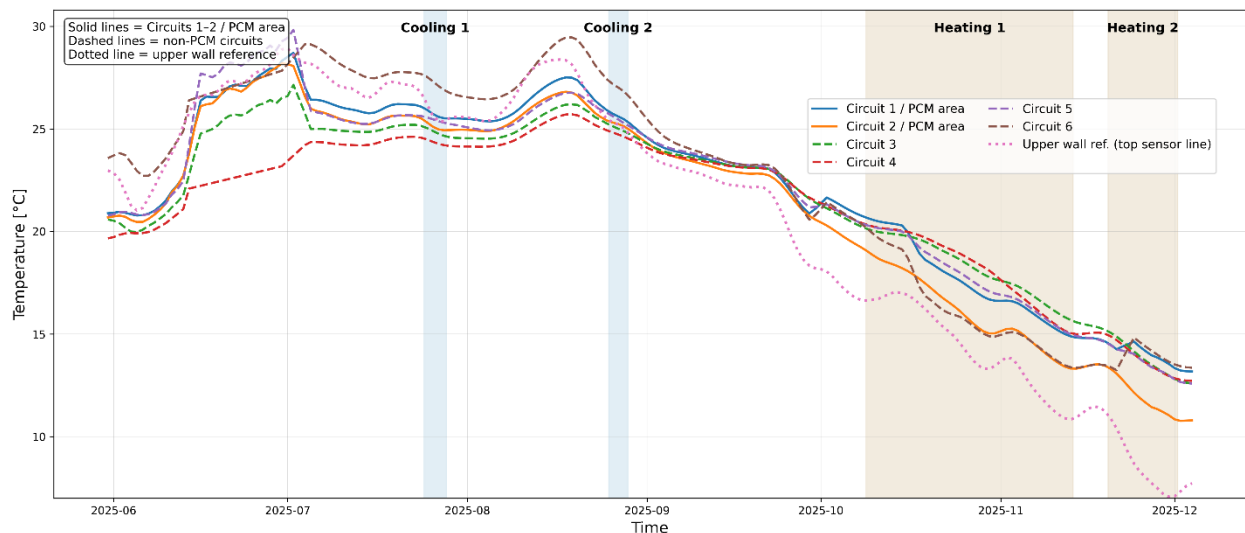


Figure 20: Full-campaign temperature evolution of the monitored circuit zones from June to December 2025. Cooling and heating test periods are highlighted.

The results show a clear seasonal pattern. From the start of the monitoring period at the end of May, when the circuit-average soil temperatures were around 20 to 21 °C, the temperatures rose through the summer to reach their highest values in the second half of August, with an overall peak of about 27 °C on 19 August 2025. After the end of summer, the temperatures decreased gradually through autumn and early winter, falling to about 12 to 14 °C by the beginning of December. The overall seasonal swing between the summer peak and the early-winter values was therefore of the order of 14 °C. This trend is visible across all six circuit zones, confirming that the monitored soil volume was strongly affected by the seasonal boundary condition; the warmest zone throughout was Circuit 6, which peaked near 29.5 °C, and the coolest was Circuit 4, reflecting their different positions and depths along the wall.

During the cooling tests, the soil temperature was generally high and relatively stable compared with the later heating period. In contrast, the heating tests were carried out while the soil temperature was already decreasing due to seasonal cooling. This is important for the interpretation of the heating results, because a decrease in measured temperature during a heating test does not necessarily indicate that the wall had no thermal effect. Instead, the operational response must be interpreted together with the natural seasonal trend.

4.2.2 Far-field reference and seasonal boundary condition

To distinguish the local thermal response of the Geothermskin wall from the broader seasonal variation of the soil, a far-field reference sensor was considered. Sensor **C10T4**, located at approximately **X = 3.9 m** from the wall, **Y = 9.29 m** along the wall, and **Z = 1.85 m** from the wall base, was selected as the reference point for the seasonal soil temperature trend. Due to its distance from the geothermal wall, this sensor is assumed to be less affected by the short-term operation of the active circuits and therefore provides a useful background condition for interpreting the measured thermal response.

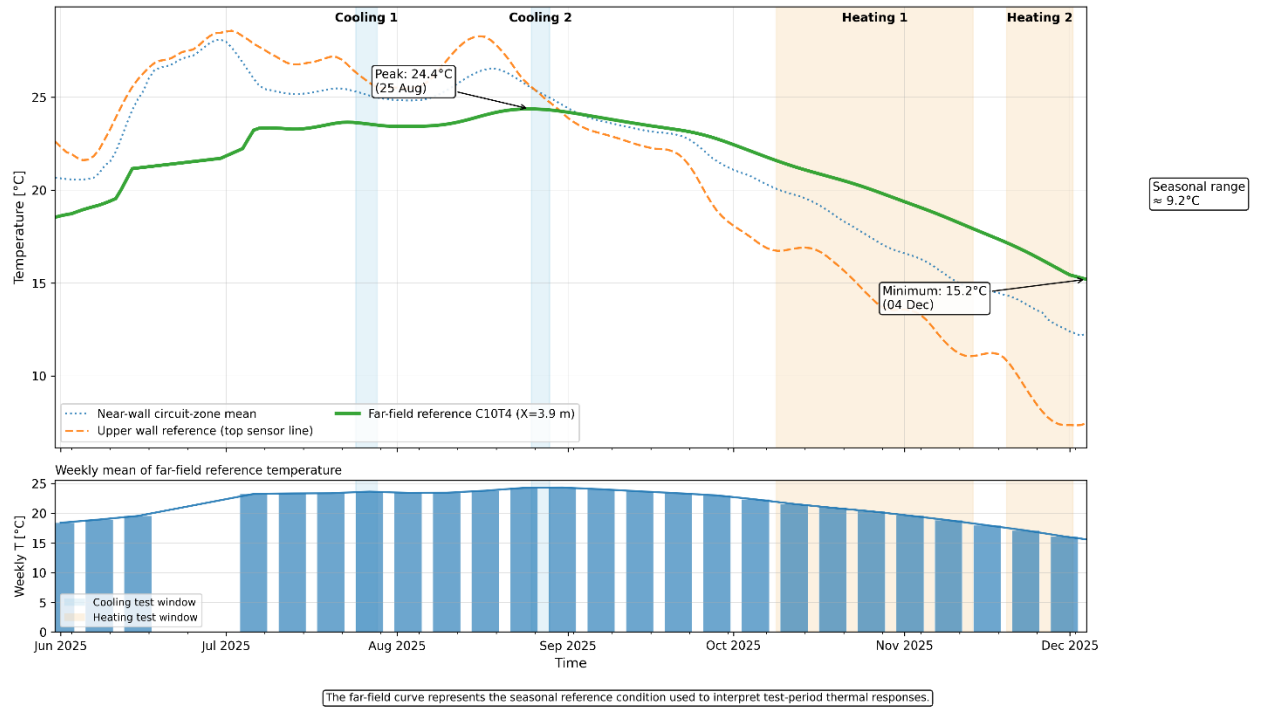


Figure 21: Far-field seasonal soil temperature baseline represented by sensor C10T4 at $X = 3.9$ m, compared with near-grade and wall-zone temperature trends.

Figure 21 also includes two additional temperature trends for comparison. The first is the **Upper wall reference**, calculated from sensors located at approximately $Z = 4.3$ m (S02 and S03). These sensors are positioned near the upper part of the wall, still within the soil-covered zone, and therefore should not be interpreted as ambient-air sensors. This curve is useful because it shows the behaviour of the upper soil/wall region, which is more sensitive to seasonal and near-surface thermal variations than the deeper far-field reference.

The second comparison curve is the **Near-wall circuit-zone mean**, calculated as the average temperature of sensors located within the corrected Y-coordinate ranges of the six geothermal circuits. This curve provides a general indication of the thermal behaviour of the monitored wall region. However, it should be interpreted only as a contextual average, because it includes sensors at different X distances, Z levels, and circuit positions. Therefore, it is not used as the main seasonal baseline; the far-field sensor C10T4 is used for that purpose.

The **Far-field temperature trend** shows a gradual increase during the summer period, followed by a progressive decrease from late summer to December. This confirms that the soil surrounding the geothermal wall was affected by a strong seasonal thermal cycle. The seasonal variation is particularly important for the heating tests, since Heating Test 1 and Heating Test 2 were conducted while the background soil temperature was decreasing. As a result, a negative final-minus-initial temperature difference during heating does not necessarily indicate the absence of a heating effect, but may reflect the superposition of the system response on the natural seasonal cooling of the ground.

For this reason, the far-field reference is used in the following sections as a background condition for interpreting the local temperature variations measured near the wall and around the active circuits.

4.2.3 Thermal response of the wall during the tests

This section takes a first look at the thermal response of the soil to the operation of the wall, at the scale of the individual circuits, and uses it to set out the main questions that the rest of the chapter addresses. The indicator is the change in temperature of the soil in front of each circuit between the start and the end of a test, $\Delta T = T_{\text{end}} - T_{\text{start}}$, evaluated for every sensor in front of a circuit and shown as a distribution, so that both the typical response and its variability are visible. Each sensor is assigned to the circuit whose centre is nearest to it, so that sensors near a boundary are attributed to the closer circuit; the consequences of this choice for the sensors that lie between circuits are themselves examined later, in the analysis of lateral interaction in Section 4.2.6. The near-surface sensors at $Z = 4.2$ m, which follow the air, and the far-field reference sensors are excluded. Because the undisturbed ground temperature changes over the duration of a test, the response is shown both raw and after subtraction of the change of the far-field reference C10T4 over the same period, the latter isolating the part of the response caused by the operation of the wall.

The picture that emerges is deliberately presented as it is, with its irregularities, because these irregularities define the questions pursued in the following sections. Three features are apparent at once. First, the operating modes are strongly asymmetric: the heating tests produce a clear response while the cooling tests barely register at the circuit scale. Second, the circuits respond by very different amounts, even within a single test. Third, the sensors within a single circuit disagree widely, so that each distribution is broad rather than sharp. The instrumentation is also not uniform across the circuits, either in the number of sensors or in the depths at which they are placed, which means that the distributions are not strictly like-for-like; this limitation is stated openly and is itself one of the reasons that the detailed, position-resolved analyses of the later sections are necessary.

4.2.3.1 Response during cooling operation

In the cooling tests, the buried circuits carried the warm water rejected by the heat pump, so that heat was released into the ground and the surrounding soil was expected to warm, giving a positive ΔT . Cooling Test 1 operated Circuits 1, 2, 5, and 6 in series, and Cooling Test 2 operated Circuits 2 and 6.

Figure 22 shows the raw distributions, with the far-field change marked by the dashed line, and Figure 23 the same distributions after far-field correction. The expected warming is largely absent at the circuit scale: the corrected medians lie close to zero, ranging from about $+0.2$ °C for Circuit 5 to -0.8 °C for Circuit 1 in Cooling Test 1, and the distributions are wide compared with these medians. This raises the first question of the chapter, namely why the cooling operation, which certainly rejected heat into the ground, leaves so weak an imprint on the soil temperature. Part of the answer is already suggested by the far-field line: the tests are short, each less than four days, and the seasonal background change is of the same small magnitude as the operational effect, so the two cannot be separated at this scale. Whether a clearer signal exists closer to the wall is left open here and is taken up in the penetration analysis of Section 4.2.4. Cooling Test 2 additionally shows the difficulty of relying on a single test: Circuit 6

malfunctioned during it, and its distribution accordingly cannot be interpreted as a normal response, a reminder that individual circuits and individual tests are not always representative.

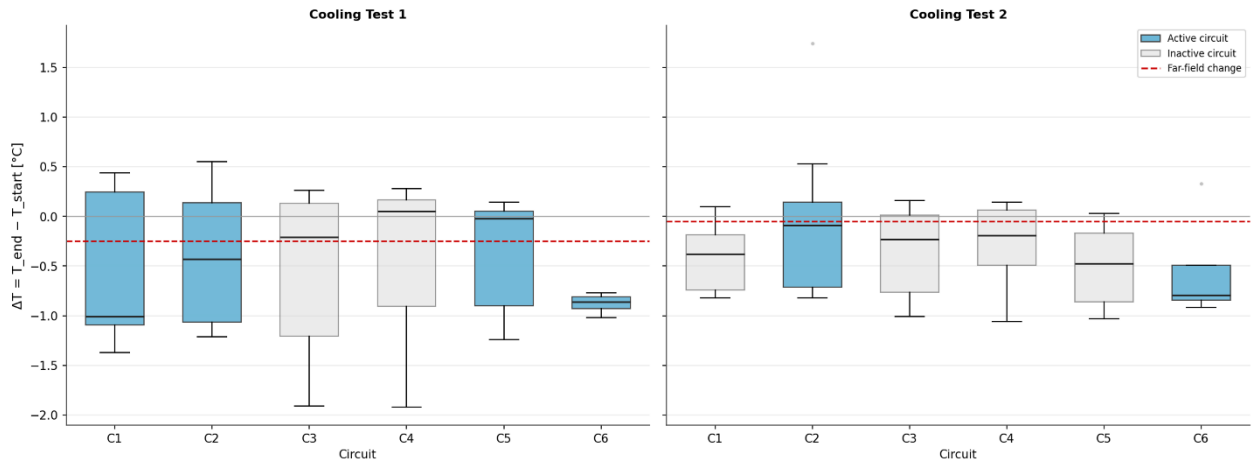


Figure 22: Distribution of the sensor temperature change $\Delta T = T_{end} - T_{start}$ in front of each circuit during the cooling tests: raw, with the dashed line marking the far-field change

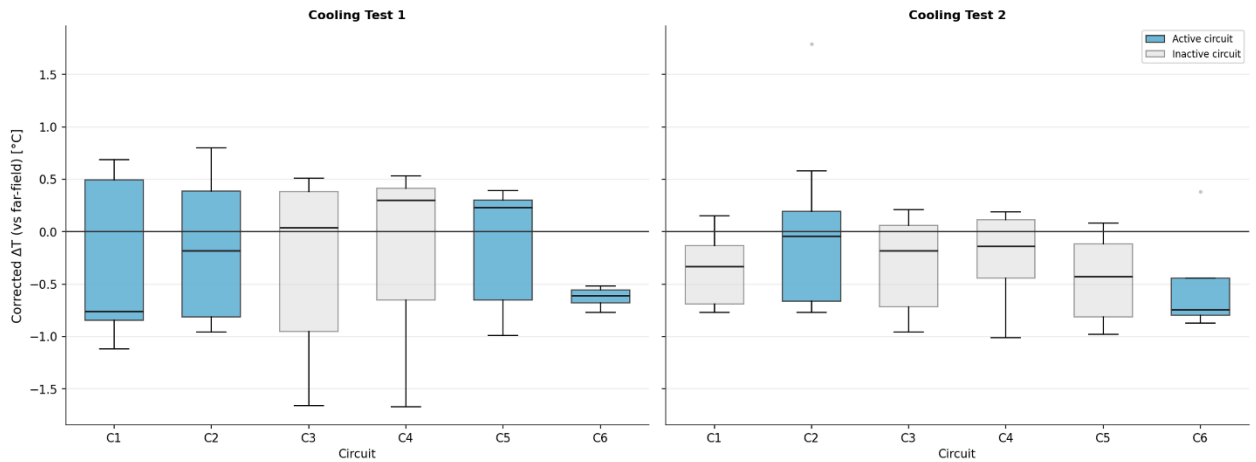


Figure 23: Distribution of the sensor temperature change $\Delta T = T_{end} - T_{start}$ in front of each circuit during the cooling tests: far-field-corrected

4.2.3.2 Heating operation

In the heating tests, the circuits extracted heat from the ground, so that the surrounding soil was expected to cool, giving a negative ΔT . Heating Test 1 operated Circuits 2 and 6 from the start and added Circuit 4 on 30 October, roughly midway through, while Heating Test 2 operated Circuits 2 and 4.

Figure 24 shows that the raw changes are large and negative, but that much of this is seasonal, since the far-field reference itself fell by $-3.7^{\circ}C$ during Heating Test 1 and by $-1.9^{\circ}C$ during Heating Test 2. Only after the far-field correction, in Figure 25, does the operational response appear in its true size. Here the heating signal is clear, and it immediately raises the second and third questions of the chapter. The circuits respond by markedly different amounts: in Heating Test 1 the corrected median cooling is about $-3.3^{\circ}C$ for Circuit 6, $-2.5^{\circ}C$ for Circuit 2, and

−1.4 °C for Circuit 4. Why should nominally similar circuits differ so much? Part of the explanation is the later activation of Circuit 4, on 30 October, which gave it less operating time, but this cannot account for all of the difference, and the possible roles of the phase-change material in front of Circuits 1 and 2, and of the position of each circuit along the wall, are left as questions for Sections 4.3 and 4.2.6. The within-circuit spread raises a further question. In Heating Test 2 the median response of Circuit 4 is close to zero, yet this is misleading, and deliberately so: the sensors directly in front of the Circuit 4 pipe cooled by about −1.1 to −2.5 °C after correction, while other sensors assigned to the same circuit, some already strongly cooled during Heating Test 1 and some lying farther from the pipe, changed very little, so that the median of the mixed population is near zero. The width of the distribution therefore encodes real differences in position and thermal history rather than mere scatter, and it is precisely this internal structure that the distance analysis of Section 4.2.4, the vertical analysis of Section 4.2.5, and the recovery analysis of Section 4.2.6 are designed to resolve.

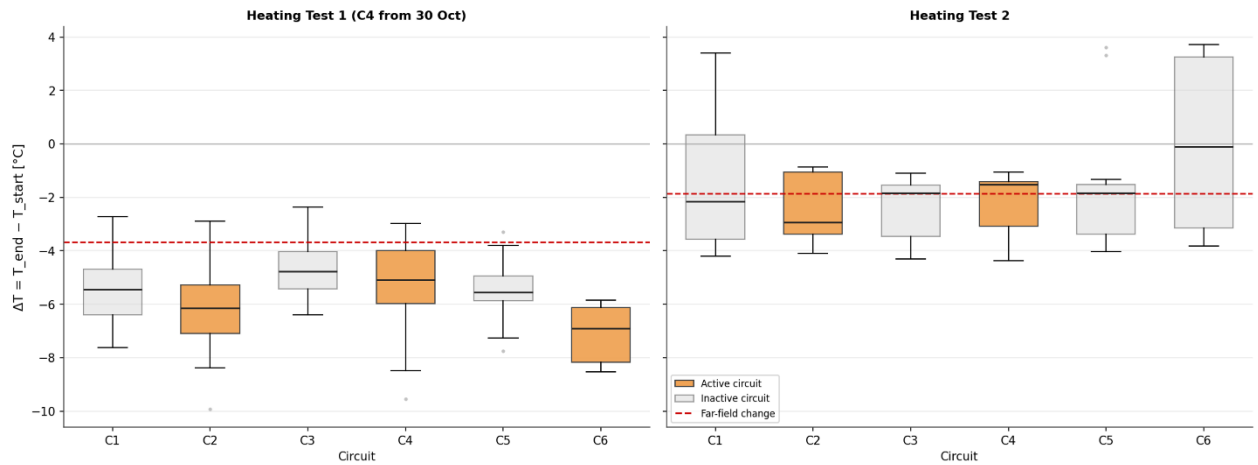


Figure 24: Distribution of the sensor temperature change during the heating tests: raw, with the dashed line marking the far-field change

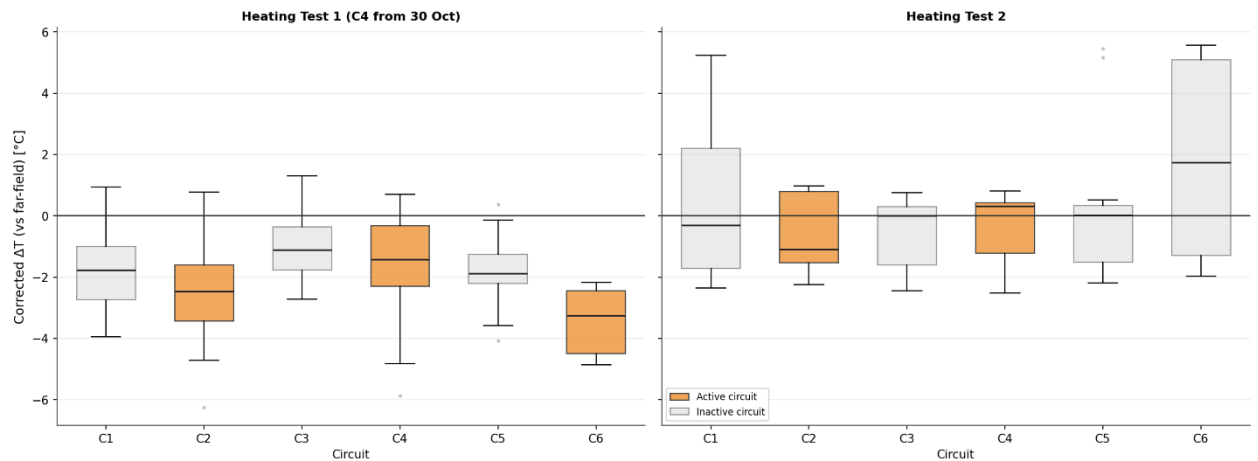


Figure 25: Distribution of the sensor temperature change during the heating tests: far-field-corrected

The two subsections establish the essential facts, that the wall responds strongly during heating and weakly during cooling, and that the response differs both between circuits and within them, while leaving open the reasons for these differences. Rather than resolving them here, this

section uses them to motivate what follows: the dependence of the response on distance from the wall is examined in Section 4.2.4, its vertical structure in Section 4.2.5, the role of the phase-change material in Section 4.3, and the lateral and recovery behaviour in Section 4.2.6. Two circuits are carried through those analyses as representative cases, Circuit 2 for the PCM part of the wall and Circuit 4 for the non-PCM part.

4.2.4 Thermal penetration into the soil

After analysing the general thermal response of the geothermal wall during the individual tests, the next step was to evaluate how the temperature disturbance propagated into the surrounding soil. This analysis was performed using the X coordinate, which represents the distance from the wall face into the soil. The objective was to characterise how the thermal effect of the active Geothermskin circuits attenuates with distance from the wall, and how this attenuation develops over time and varies with depth, rather than to assign a single quantitative influence distance.

For this reason, the analysis was restricted to sensors located in front of the circuits that were active during each test. This selection was necessary because thermal penetration is a directional phenomenon, developing from the active wall surface outward into the adjacent soil. Including sensors located in inactive circuit zones, inter-circuit regions, or separator zones would mix different spatial behaviours and would not directly represent the propagation of the thermal effect from the operating circuits. The inter-circuit sensors, which lie at the boundaries between adjacent circuits, are therefore set aside here and are examined separately in Section 4.2.6.1.

To keep the profiles clean and physically consistent, the analysis was based on single homogeneous sensor strings, formed by PT100 sensors located at the same height in front of an active circuit, rather than on averages of sensors at different heights. The presentation focuses on Heating Test 1, which was the longest test of the campaign and produced the clearest thermal signal. Section 4.2.4.1 introduces the raw temperature profiles along the strings in front of Circuits 2 and 4; Section 4.2.4.2 removes the seasonal background using the far-field reference C10T4 to isolate the local wall effect; and Section 4.2.4.3 follows the evolution of the thermal front over time and across three depths for Circuit 2. The corresponding profiles for the cooling tests, whose response is markedly weaker, are reported in the Appendix Figure 57.

4.2.4.1 Temperature profile with distance from the wall

To characterise how the thermal effect of the wall develops with distance into the soil, the temperature was examined along single homogeneous sensor strings rather than as an average of all sensors at a given distance. Averaging across sensors located at different heights combines vertical positions that respond differently and produces an irregular, non-physical profile; a single string at a fixed height avoids this. Two strings were selected, both at mid-wall height ($Z = 1.85$ m), in front of two actively operated circuits. In front of Circuit 4, the string consists of C9T1, C9T2, C9T3, C9T4, C9T5, and C9T6, located at $X = 0.3, 0.8, 1.3, 1.8, 2.3,$ and 2.8 m, respectively. In front of Circuit 2, the string consists of C19T1, C19T2, C14T1,

C19T3, and C14T2, located at $X = 0.3, 0.8, 1.3, 1.3,$ and 1.8 m, respectively. The analysis is shown for Heating Test 1, the longest test and the one with the clearest thermal signal.

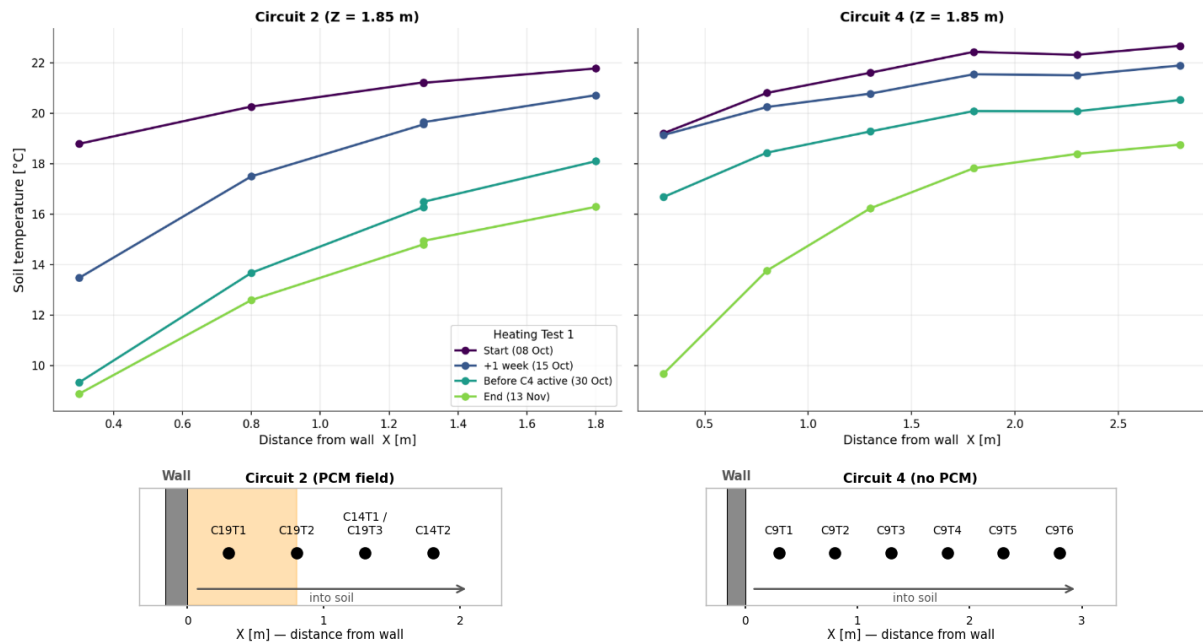


Figure 26: Raw soil temperature as a function of distance from the wall (X) along two mid-wall strings ($Z = 1.85$ m), in front of Circuit 2 (left) and Circuit 4 (right), at four stages of Heating Test 1

Figure 26 shows the raw soil temperature along the two strings at four stages of Heating Test 1: the start (8 October), one week later (15 October), immediately before the activation of Circuit 4 (30 October), and the end of the test (13 November). At the start of the test, both strings are relatively flat. For Circuit 4, the temperature rises from 19.2 °C at the wall (C9T1, $X = 0.3$ m) to 22.7 °C at $X = 2.8$ m (C9T6), a difference of about 3.5 °C; for Circuit 2 it rises from 18.8 °C at the wall (C19T1, $X = 0.3$ m) to 21.8 °C at $X = 1.8$ m (C14T2), about 3.0 °C. This gentle gradient reflects the soil condition before the circuits had imposed a significant local effect.

As the test progresses, both profiles become markedly steeper near the wall. By the end of the test the Circuit 4 sensor closest to the wall (C9T1, $X = 0.3$ m) had cooled to 9.7 °C, a decrease of 9.5 °C, while the most distant sensor (C9T6, $X = 2.8$ m) had cooled only to 18.8 °C, a decrease of 3.9 °C; the temperature difference across the string therefore grew from about 3.5 °C to about 9.1 °C. Circuit 2 shows the same behaviour: the near-wall sensor (C19T1) cooled by 9.9 °C (to 8.9 °C) while the sensor at $X = 1.8$ m (C14T2) cooled by only 5.5 °C (to 16.3 °C), and the gradient across the string increased from about 3.0 °C to about 7.4 °C. In both circuits, the cooling is therefore strongly concentrated at the sensor nearest the wall and decreases progressively with distance, which is the direct spatial signature of heat extraction localised around the active pipes.

The two circuits show consistent behaviour despite their different pipe layouts (Circuit 4 has a mainly vertical arrangement), which indicates that the observed attenuation with distance is a general feature of the wall's operation rather than a peculiarity of a single circuit. The profiles also remain monotonic at every stage, confirming that a single sensor string provides a clear

and physically consistent picture of the spatial decay. It is also evident that the largest part of the near-wall cooling develops after 30 October, in the colder part of the campaign, when the thermal demand was highest. At this stage, the temperature change still includes the natural seasonal cooling of the ground; the separation of the local wall-induced signal from this seasonal background, and the quantification of the distance over which the effect remains detectable, are addressed in Section 4.2.4.2.

4.2.4.2 Far-field-corrected temperature change and influence radius

The raw profiles in Section 4.2.4.1 still contain the natural seasonal cooling of the ground, which during Heating Test 1 was substantial: the far-field reference sensor C10T4 ($X = 3.9$ m), located far from any active circuit, cooled by about 3.7 °C over the test purely as a result of the season. To isolate the local effect of the wall from this background, each sensor is expressed relative to the far-field reference at the same instant, as $T_{\text{sensor}} - T_{\text{C10T4}}$. A value near zero indicates that the sensor behaves like the undisturbed far field, while a strongly negative value indicates local cooling caused by heat extraction at the wall.

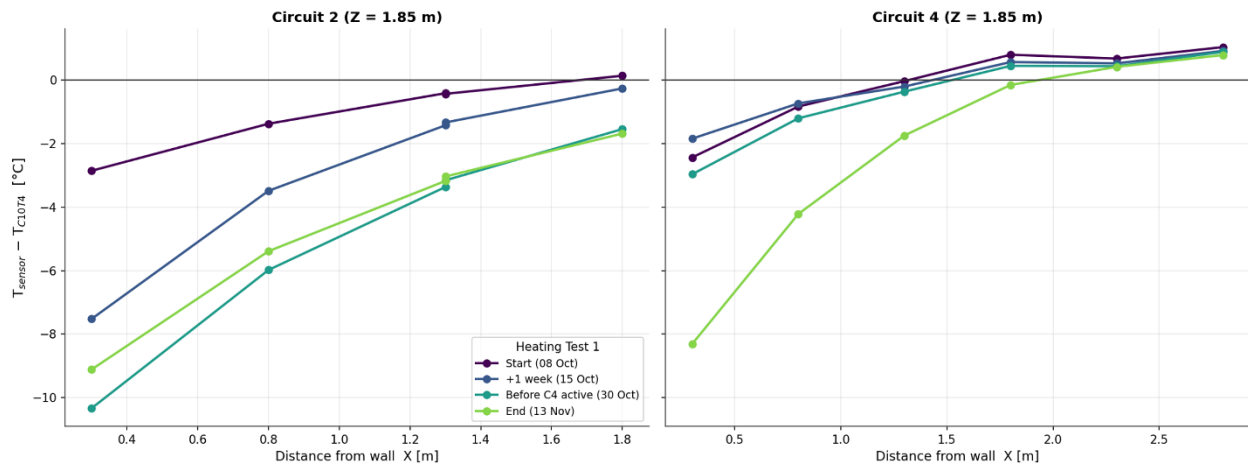


Figure 27: Far-field-corrected soil temperature ($T_{\text{sensor}} - T_{\text{C10T4}}$) as a function of distance from the wall, along two mid-wall strings ($Z = 1.85$ m) in front of Circuit 2 (left) and Circuit 4 (right), at four stages of Heating Test 1

Figure 27 shows this corrected quantity along the two mid-wall strings ($Z = 1.85$ m) at the four stages of Heating Test 1. At the start of the test, the corrected values are small at every distance, between about -2.9 °C and $+1.0$ °C, confirming that before significant operation, the soil in front of the circuits was close to the far-field condition. As the test progresses, the near-wall sensors deviate increasingly from the far field while the more distant sensors remain close to it. By the end of the test, the Circuit 4 string reaches -8.3 °C at the wall (C9T1, $X = 0.3$ m), -4.2 °C at $X = 0.8$ m (C9T2), and -1.8 °C at $X = 1.3$ m (C9T3), and then approaches the far-field condition, with -0.2 °C at $X = 1.8$ m (C9T4) and small positive values of $+0.4$ °C and $+0.8$ °C at $X = 2.3$ m and 2.8 m (C9T5 and C9T6). The Circuit 2 string behaves consistently, reaching -9.1 °C at the wall (C19T1) and decaying to -1.7 °C at $X = 1.8$ m (C14T2), the most distant sensor available for this string.

The corrected profiles therefore confirm what the raw profiles suggested: the local thermal disturbance produced by the wall is concentrated within roughly the first metre of soil and decreases steadily with distance, becoming small beyond about 1.8 m. The progressive

deepening of the near-wall values over the test, from about $-2.4\text{ }^{\circ}\text{C}$ at the start to $-8.3\text{ }^{\circ}\text{C}$ at the end for Circuit 4, reflects the accumulation of the heat-extraction effect, most of which develops after the activation of Circuit 4 on 30 October and in the colder part of the campaign.

A precise influence distance is not assigned here. The far-field-corrected values of sensors located well away from the active circuits scatter by approximately $\pm 2\text{ }^{\circ}\text{C}$, which reflects natural sensor-to-sensor differences in position rather than a wall effect. Beyond about 1.8 m, the corrected signal falls within this scatter, and the small positive values at the farthest Circuit 4 sensors are attributable to pre-existing offsets relative to C10T4 rather than to a physical response. For this reason, the distance over which the effect remains clearly detectable is described qualitatively (of the order of 1 to 2 m) rather than as a single quantitative radius; a formal definition could be introduced if required.

4.2.4.3 Evolution of the thermal front during Heating Test 1

Sections 4.2.4.1 and 4.2.4.2 examined the penetration of the thermal disturbance at a single depth, the mid-wall level at $Z = 1.85\text{ m}$. This section extends that analysis in two ways, both of which require the long duration of Heating Test 1: it compares the penetration at three different depths, the base at $Z = 0\text{ m}$, the mid-wall at $Z = 1.85\text{ m}$, and the upper wall at $Z = 3.5\text{ m}$, and it follows the evolution of the penetration profile through five stages of the test, namely the start (8 October), one week later (15 October), immediately before the activation of Circuit 4 (30 October), shortly after it (5 November), and the end of the test (13 November). Circuit 2 is used throughout, since it remained active for the whole test and has the most complete depth coverage. In this way the section shows both how the disturbance grows in time and how its penetration into the soil differs with depth, neither of which could be seen in the single-level analysis of the preceding sections.

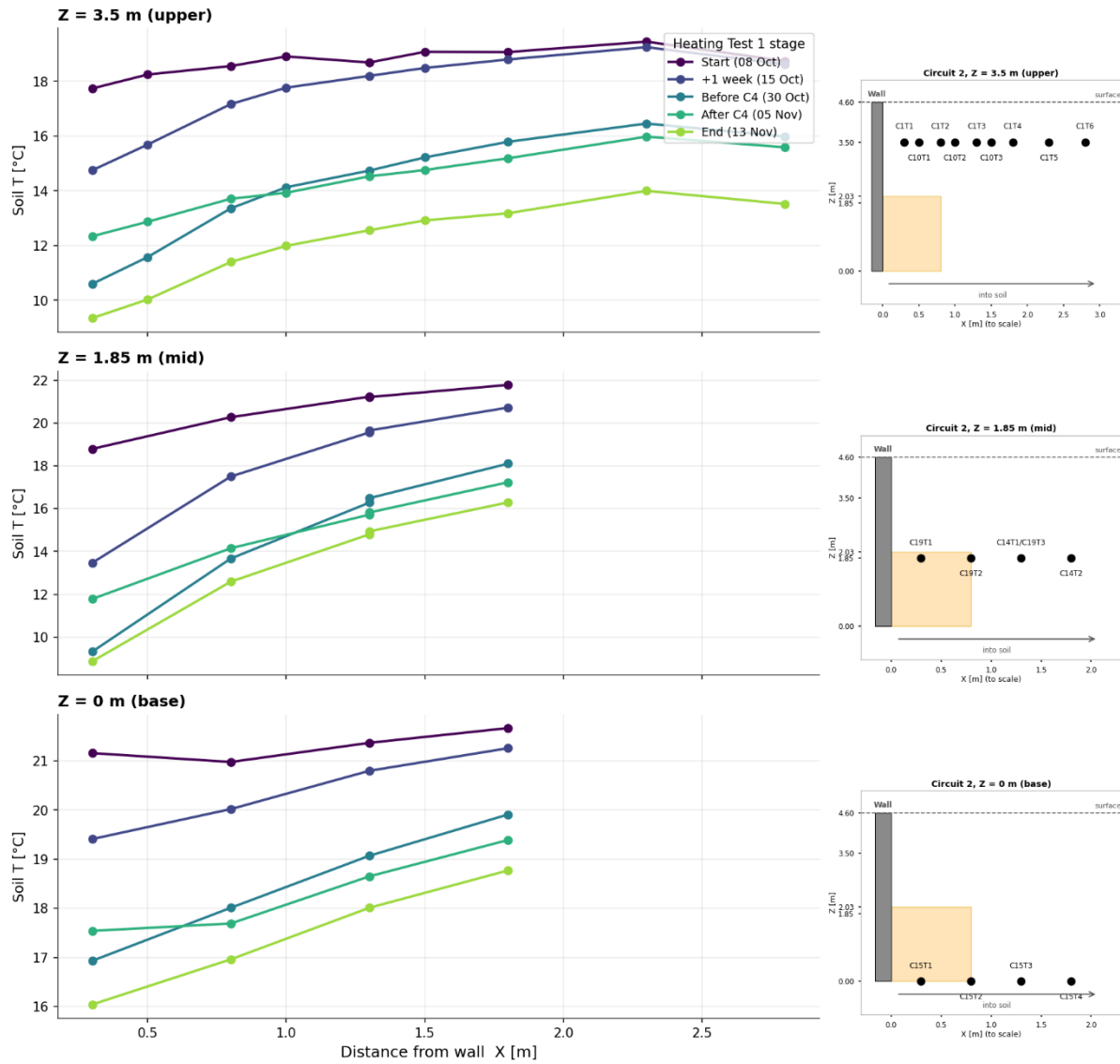


Figure 28: Raw soil temperature as a function of distance from the wall along the Circuit 2 strings at three depths ($Z = 3.5$, 1.85 , and 0 m), at five stages of Heating Test 1

Figure 28 shows the raw temperature profiles. At all three levels, the soil cools progressively over the test, and the cooling is consistently stronger near the wall than farther away. The effect is, however, clearly different between the levels. At the mid-wall level ($Z = 1.85$ m), the near-wall sensor (C19T1, $X = 0.3$ m) cooled by 9.9 °C over the test, while the most distant sensor (C14T2, $X = 1.8$ m) cooled by only 5.5 °C. At the upper level ($Z = 3.5$ m), the near-wall sensor (C1T1) cooled by 8.4 °C and the far sensor (C1T6, $X = 2.8$ m) by 5.2 °C. At the base ($Z = 0$ m), the response is markedly weaker and flatter: the near-wall sensor (C15T1) cooled by only 5.1 °C and the far sensor (C15T4) by 2.9 °C. The base level is therefore the least affected by the wall and the most thermally stable, consistent with its greater depth below the surface.

To separate the local effect of the wall from the seasonal cooling of the ground, Figure 29 shows the same profiles expressed relative to the far-field reference C10T4, as $T_{\text{sensor}} - T_{\text{C10T4}}$. After this correction, the depth dependence becomes clearer. At the base, the corrected disturbance is small at every distance, reaching only -1.9 °C at the wall (C15T1) and decaying to approximately zero by $X = 1.3$ m, which confirms that the heat extraction has little

effect at this depth. At the mid-wall level, the corrected values show a strong and localised response, from $-9.1\text{ }^{\circ}\text{C}$ at the wall (C19T1) to $-1.7\text{ }^{\circ}\text{C}$ at $X = 1.8\text{ m}$ (C14T2), with most of the disturbance contained within the first metre of soil. The progressive deepening of the near-wall values from one stage to the next, and the fact that the largest change occurs between 30 October and the end of the test, show that the thermal front develops gradually and intensifies in the colder part of the campaign.

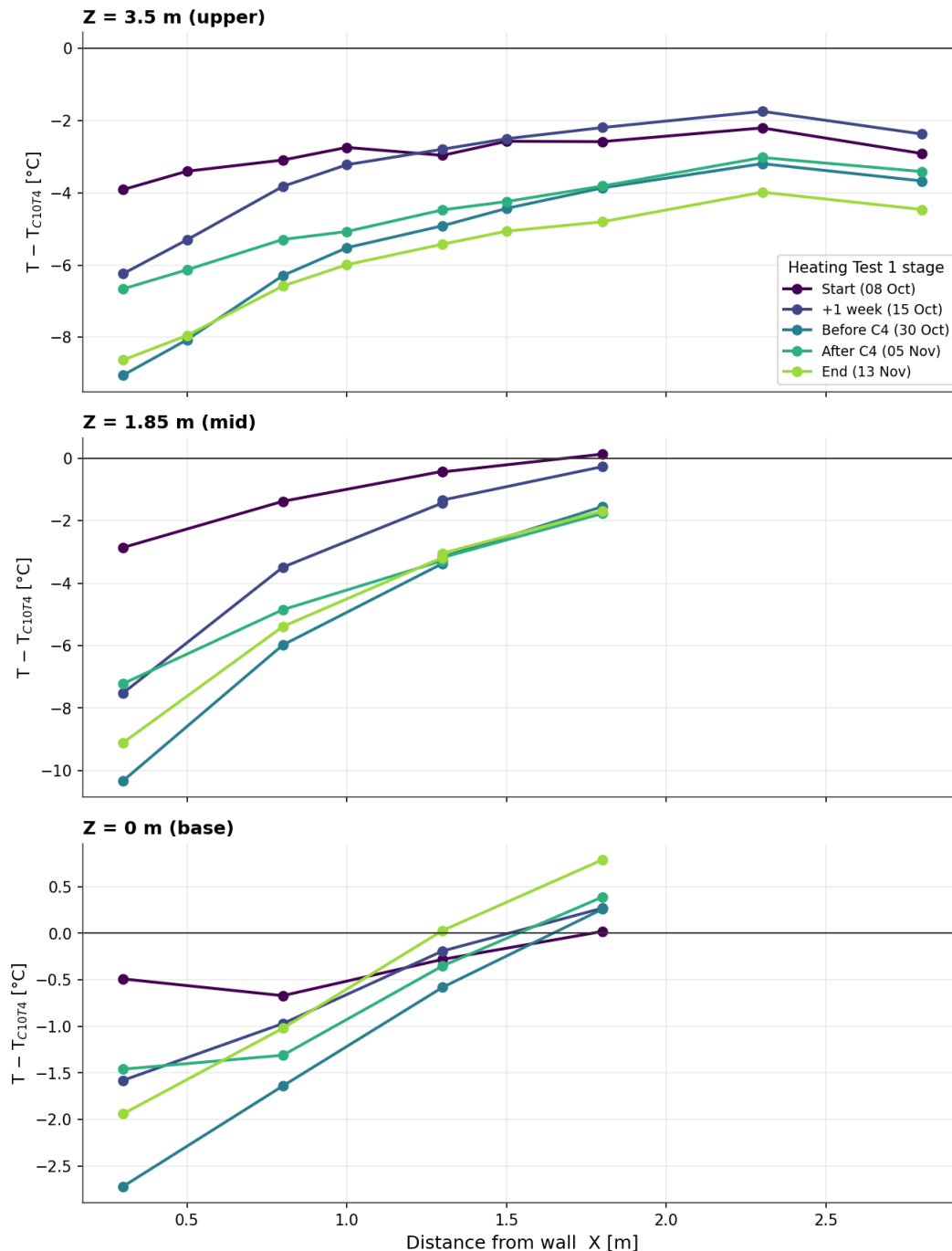


Figure 29: Corrected soil temperature as a function of distance from the wall along the Circuit 2 strings at three depths ($Z = 3.5$, 1.85 , and 0 m), at five stages of Heating Test 1

The upper level ($Z = 3.5\text{ m}$) requires a note of caution in the corrected representation. Because the far-field reference C10T4 is located at mid-depth ($Z = 1.85\text{ m}$), it does not perfectly

represent the seasonal cooling experienced by the shallower upper-wall soil, which cools more strongly under surface influence. As a result, the corrected values at $Z = 3.5$ m remain large and negative even at the farthest sensors (about -4 to -4.5 °C at $X = 2.3$ to 2.8 m) and do not decay towards zero as they do at the mid-wall level. This residual offset is a consequence of the depth mismatch of the reference rather than evidence of a wall influence extending that far, and the upper-level corrected profile should therefore be interpreted qualitatively.

Read together, the two figures show that the thermal front produced by the wall is both time-dependent and vertically non-uniform. The disturbance is strongest and most clearly localised at the mid-wall level, still significant but less cleanly resolved at the upper level, and weak at the base. The thermal penetration cannot, therefore, be described by a single representative distance or by one averaged curve; it is a spatially distributed response that depends on distance from the wall, vertical position, and the progress of the test. Since Circuits 1 and 2 are located in the PCM-enhanced portion of the wall, Section 4.3 examines whether the PCM zone modifies the thermal behaviour of the surrounding soil compared with the non-PCM circuit zones.

4.2.5 Vertical temperature distribution along the wall

The previous sections described how the thermal effect of the wall penetrates into the soil, using the horizontal distance from the wall face as the main variable. This section turns to the vertical dimension, examining how the soil temperature is distributed along the height of the wall and how this distribution changes during the tests. Whereas Section 4.2.4 treated depth only as a secondary factor modifying the horizontal penetration, here the vertical coordinate Z , measured from the base of the wall, is the subject of the analysis itself.

The analysis is carried out for Circuit 2, consistently with the previous sections, and is based on individual sensors rather than on averages, so that each value corresponds to a measured point in front of the circuit. The wall is 4.6 m high, with its base at $Z = 0$ m and the ground surface at $Z = 4.6$ m. Measurements are available at four heights, $Z = 0, 1.85, 3.5$, and 4.2 m, although the shallowest of these, lying only about 0.4 m below the surface, is found to behave differently from the rest, as discussed below. The phase change material occupies only the lower part of the wall, up to about $Z = 2.03$ m, so the two lower measurement heights lie within the PCM range and the upper ones above it.

The section is organised into three parts. Section 4.2.5.1 presents the vertical temperature profiles at representative stages of each of the four tests, showing the overall shape of the distribution and placing it in its physical context relative to the ground surface and the air temperature. Section 4.2.5.2 follows the temperature at each height continuously through the two heating tests, to show how and when the vertical structure develops over time. Section 4.2.5.3 condenses the profiles into a single vertical gradient between the base and the upper wall and examines its reversal in sign between the heating and cooling modes. Throughout, three features recur: the base of the wall is the most thermally stable level, the central part of the wall exchanges heat most strongly with the surrounding soil, and the shallowest level reflects the influence of the atmosphere rather than the operation of the wall.

4.2.5.1 Vertical temperature profiles at representative stages

Three near-wall vertical lines are considered at distances of $X = 0.3$, 0.8 , and 1.3 m from the wall face. The line at $X = 0.3$ m includes four heights, at $Z = 0$, 1.85 , 3.5 , and 4.2 m, while the lines at $X = 0.8$ m and $X = 1.3$ m include the three lower heights. The sensors that form each line are all within the Circuit 2 zone but are not perfectly aligned in the along-wall direction, varying in Y by up to about 1.5 m; they are therefore treated as an approximate vertical profile within the circuit. At the single position $X = 1.3$ m, $Z = 1.85$ m, where two Circuit 2 sensors are available, their average is used.

To place the profiles in their physical context, each figure also shows the position of the ground surface, at $Z = 4.6$ m, separating the soil below from the air above, together with the mean air temperature during the test and the band between its 25th and 75th percentiles, which indicates the range in which the air temperature spent most of the period. Because the air temperature varies strongly from day to day, this band is wide, and it is shown to help interpret the behaviour of the shallowest sensor rather than as a precise boundary condition. The vertical extent of the PCM, from $Z = 0$ to about 2.03 m, is also indicated.

In the heating tests, the profiles show the expected response to heat extraction, with the soil cooling progressively from the start of the test to its end at every height. In Heating Test 1, the near-wall line at $X = 0.3$ m cools from a fairly uniform 17 – 21 °C at the start to between about 9 and 16 °C at the end, with the strongest cooling at the mid-height levels ($Z = 1.85$ and 3.5 m) and the least at the base ($Z = 0$ m), which remains the warmest level at the end of the test, at about 16 °C. The same ordering is seen in Heating Test 2. This indicates that the base of the wall is the most thermally stable part of the profile, while the central portion of the wall exchanges heat most strongly with the surrounding soil.

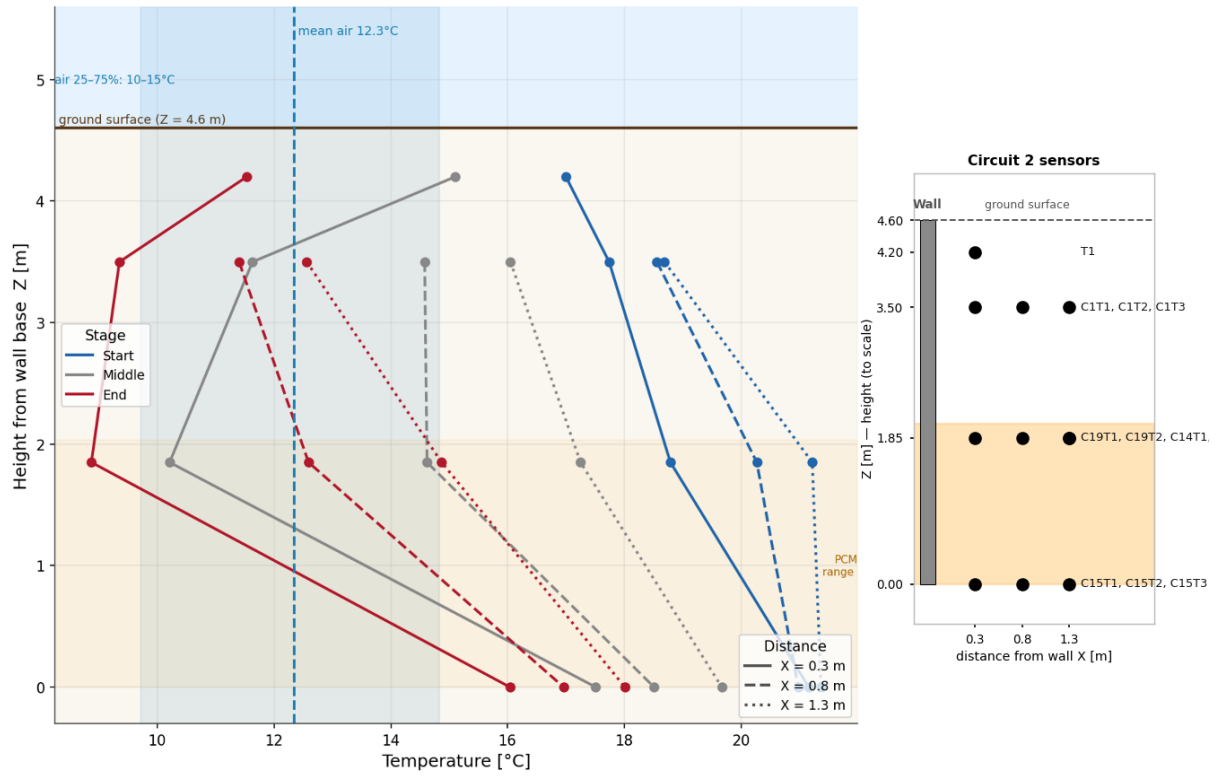


Figure 30: Vertical temperature profile for heating test 1 (temperature versus height Z) in front of Circuit 2, at three near-wall distances ($X = 0.3, 0.8$, and 1.3 m) and three stages (start, middle, and end)

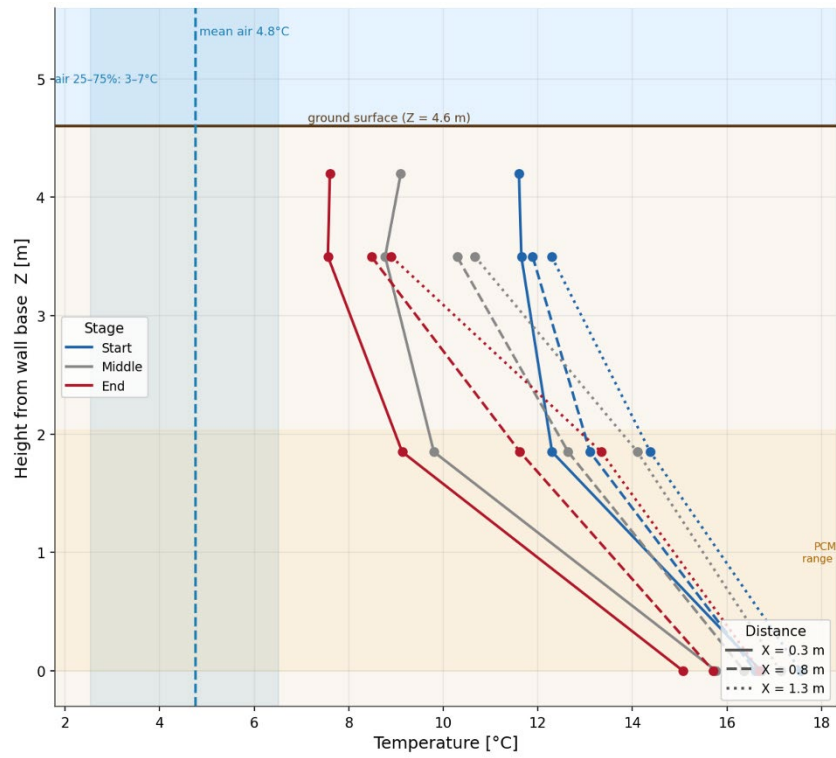


Figure 31: Vertical temperature profile for heating test 2 (temperature versus height Z) in front of Circuit 2, at three near-wall distances ($X = 0.3, 0.8$, and 1.3 m) and three stages (start, middle, and end)

The topmost level, at $Z = 4.2$ m, behaves differently from the levels below it and must be interpreted with care. This sensor lies only about 0.4 m below the ground surface and is therefore strongly influenced by the air rather than by the operation of the wall. In Heating Test 1, where the mean air temperature was 12.3 °C and the deeper active levels were cooled to about 9 °C, the shallowest sensor remained warmer, at about 11.5 °C, that is, close to the air temperature and above the actively cooled soil beneath it. Its behaviour is therefore consistent with atmospheric influence on the near-surface soil, and it marks the upper boundary of the region in which the wall, rather than the surface, controls the soil temperature. This level is based on a single sensor and is shown mainly to illustrate this surface effect.

The cooling tests, conducted in summer, show the opposite tendency, with the soil warming slightly where heat is injected, but the changes are much smaller because these tests were short, lasting fewer than four days each. In both cooling tests, the three stages nearly coincide, indicating that the soil temperature changed little over the test, and the mean air temperature, of about 21.7 °C, lies to the warm side of the soil profile. Because of their limited duration and small thermal signal, the cooling tests are reported here for completeness, but the vertical structure is much more clearly developed in the heating tests. In particular, the near-surface sensor at $Z = 4.2$ m is colder than the soil immediately below it in the summer tests, again consistent with the influence of the air, which in the early part of these tests was cooler than the heat-charged soil at depth.

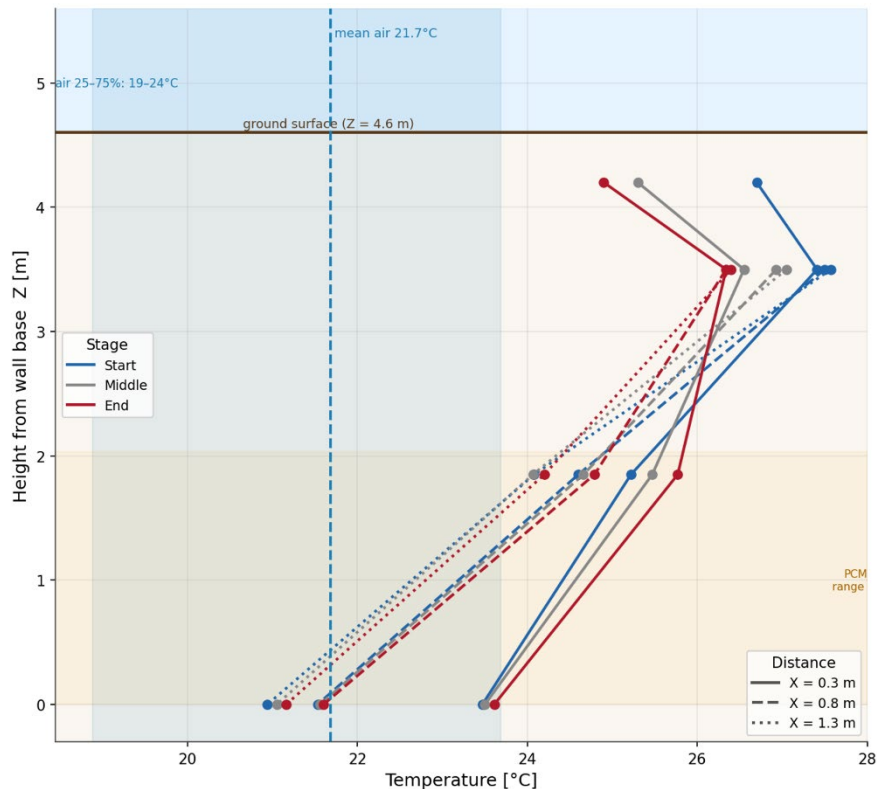


Figure 32: Vertical temperature profile for cooling test 1 (temperature versus height Z) in front of Circuit 2, at three near-wall distances ($X = 0.3$, 0.8 , and 1.3 m) and three stages (start, middle, and end)

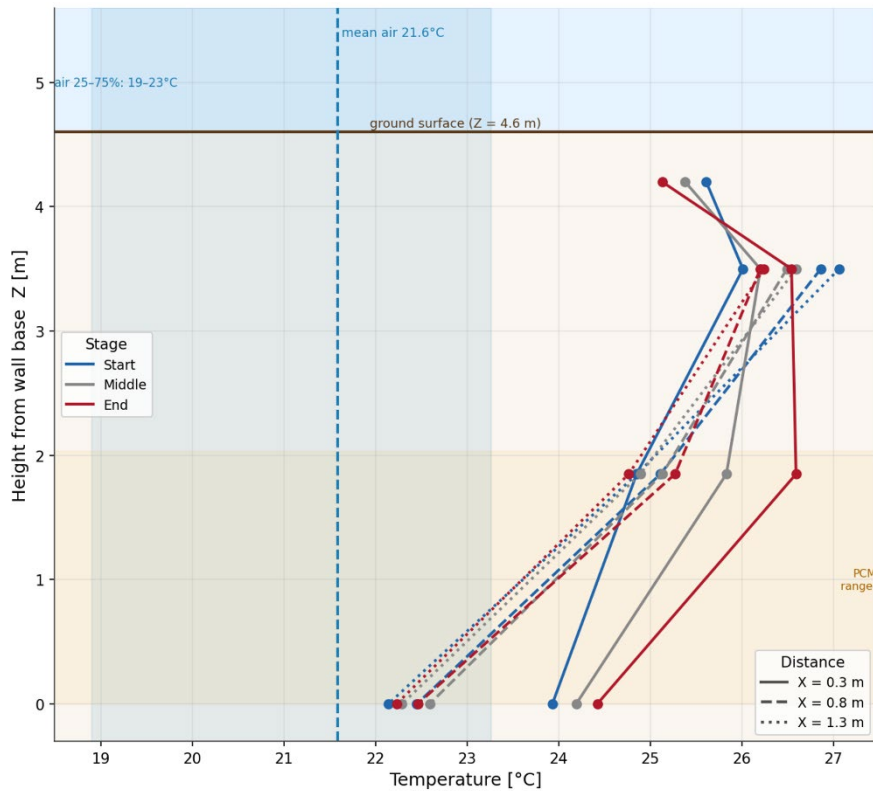


Figure 33: Vertical temperature profile for cooling test 2 (temperature versus height Z) in front of Circuit 2, at three near-wall distances ($X = 0.3, 0.8$, and 1.3 m) and three stages (start, middle, and end)

Across all four tests, the vertical profiles show that the thermal response of the wall is not uniform with height. The strongest exchange occurs in the central portion of the wall; the base remains the most stable, and the shallowest level reflects the surface and atmospheric conditions rather than the operation of the wall. This vertical non-uniformity is examined further in the following section, which follows the time evolution of the individual levels.

4.2.5.2 Time evolution of the vertical temperature distribution

While the previous section examined the vertical profiles at fixed stages, this section follows the temperature of each height continuously through the two heating tests, in order to see how and when the vertical structure develops. The analysis uses the near-wall sensors of Circuit 2, at $X = 0.3$ m, at the four heights $Z = 0, 1.85, 3.5$, and 4.2 m. The air temperature is shown alongside the soil temperatures, both as an hourly series and as a 24-hour running average, to clarify the behaviour of the shallowest level. Where the air-temperature record contains gaps, the air line is interrupted rather than interpolated.

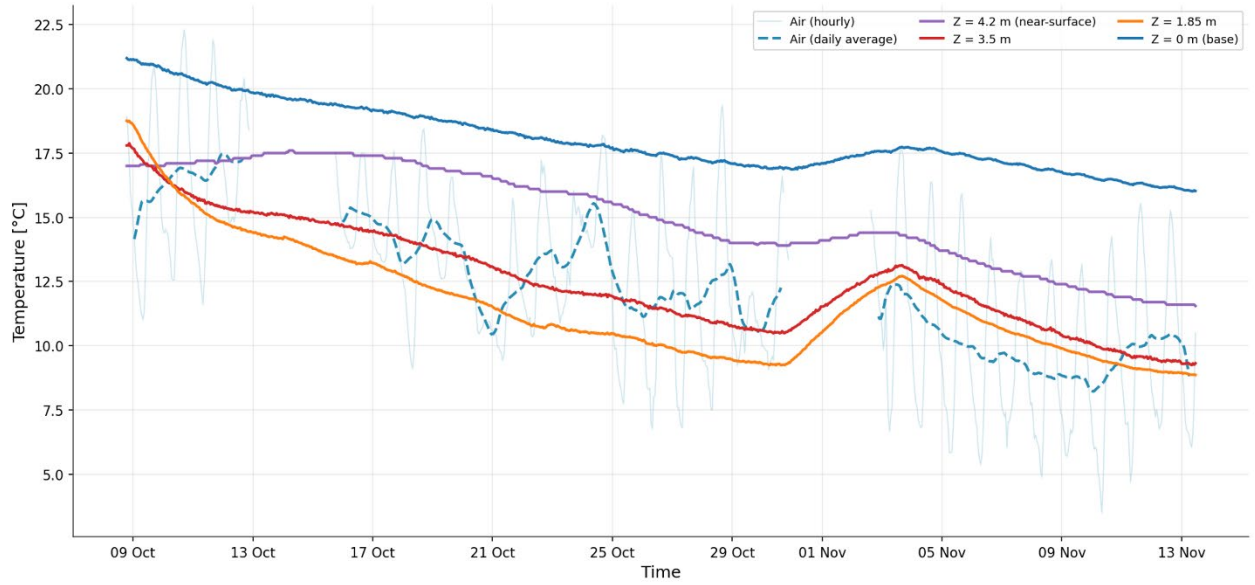


Figure 34: Time evolution of the soil temperature at four heights ($Z = 0, 1.85, 3.5$, and 4.2 m) in front of Circuit 2, at $X = 0.3$ m, during Heating Test 1

Figure 34 shows Heating Test 1. As heat is extracted, the deeper levels separate progressively from one another, and a clear vertical ordering develops. The mid-wall and upper levels ($Z = 1.85$ and 3.5 m) cool the most, falling from about 18 – 19 °C at the start to about 9 °C by the end of the test, while the base level ($Z = 0$ m) cools far less and remains the warmest part of the wall throughout, ending at about 16 °C. The vertical temperature difference between the base and the mid-wall, which is small at the beginning, grows to roughly 7 °C by the end, showing that the vertical structure is created by the operation of the wall and intensifies over time. Most of this development occurs from late October onwards, in the colder part of the test.

The shallowest level, at $Z = 4.2$ m, behaves in a distinctly different way from the soil beneath it, and its comparison with the air temperature is revealing. Rather than following the steady cooling of the deeper levels, it follows the air temperature, both in its daily fluctuations and in its slower trend. For much of the test, it lies close to the air curve, rising and falling with it, and at times it is warmer and at times colder than the levels below, depending on the air rather than on the wall. This confirms the interpretation introduced in the previous section, namely that the near-surface soil is governed by atmospheric exchange and marks the upper limit of the region controlled by the wall. The two multi-day interruptions of the air record, in mid-October and around the end of October, do not affect the continuous soil measurements.

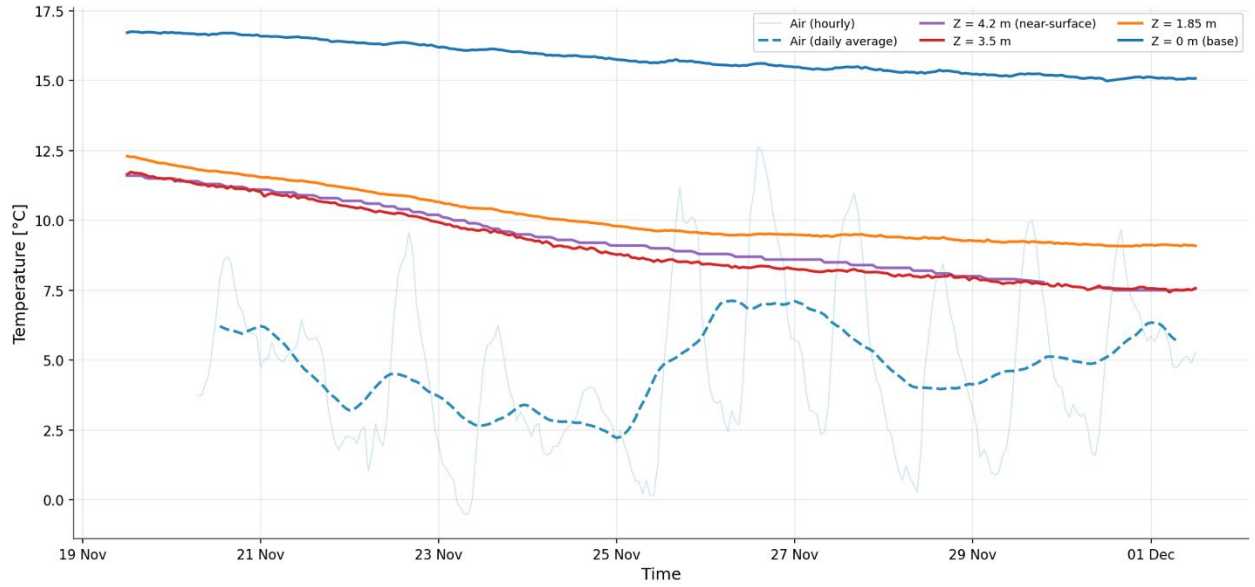


Figure 35: Time evolution of the soil temperature at four heights ($Z = 0, 1.85, 3.5$, and 4.2 m) in front of Circuit 2, at $X = 0.3$ m, during Heating Test 2

Figure 35 shows Heating Test 2 over a shorter period. The same vertical ordering is present from the start, since the soil entered this test already cooled from the previous one: the base level is the warmest, and the mid and upper levels are colder. The near-surface level again tracks the air temperature rather than the deeper soil. Because this test is shorter and the soil began in a colder state, the vertical structure changes less during the test than in Heating Test 1, but its form is consistent.

Taken together, the two tests show that the vertical structure of the soil temperature is produced by the wall and develops over time, with the central portion of the wall exchanging the most heat and the base remaining the most stable, while the shallowest level stands apart as an air-controlled boundary. The corresponding evolution during the cooling tests, whose vertical changes are much smaller, is reported in the Appendix Figure 58 and Figure 59.

4.2.5.3 Vertical temperature gradient and its reversal

The vertical profiles of the previous sections can be summarised by a single quantity, the vertical temperature difference between the base and the upper part of the wall. This is defined here as the temperature of the base level minus the temperature of the upper level, $\Delta T_{\text{vert}} = T(Z = 0 \text{ m}) - T(Z = 3.5 \text{ m})$, measured at the near-wall distance $X = 0.3$ m in front of Circuit 2. A positive value means that the base of the wall is warmer than the upper part, and a negative value means the opposite. The same two heights are used for every test, so that the values are directly comparable; the shallowest level, at $Z = 4.2$ m, is deliberately excluded from this measure, because, as shown in the previous sections, it is governed by the air rather than by the wall and would distort a gradient intended to describe the soil (Figure 36 and Figure 37).

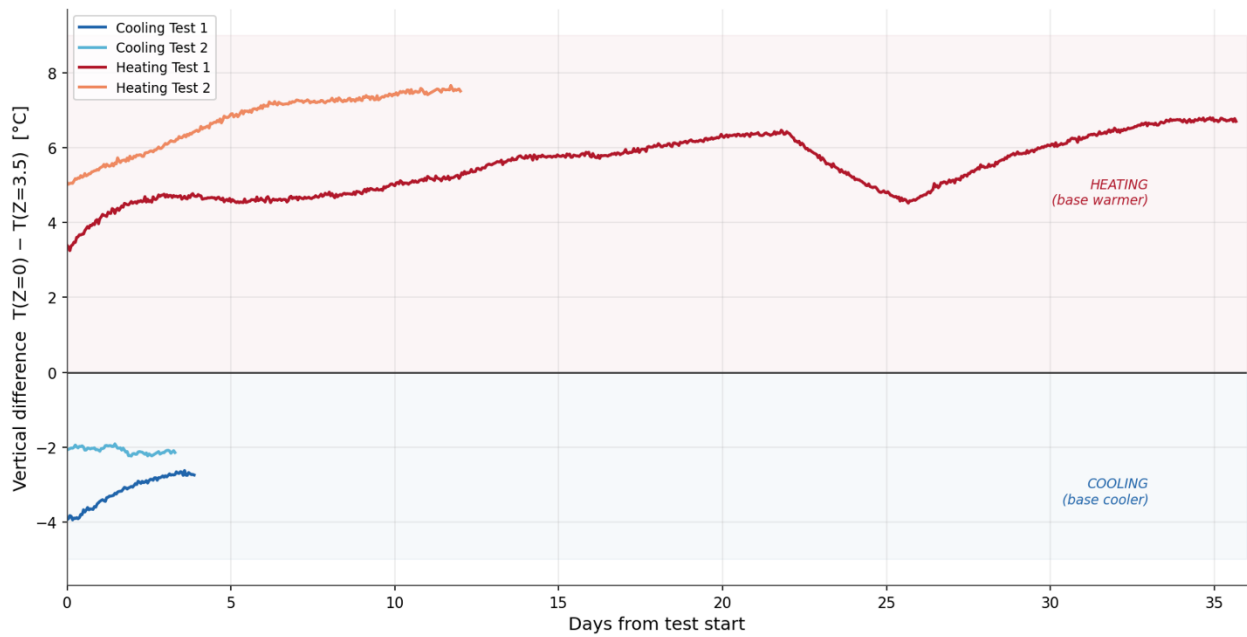


Figure 36: Vertical temperature difference between the base and upper wall, $\Delta T_{\text{vert}} = T(Z = 0 \text{ m}) - T(Z = 3.5 \text{ m})$, at $X = 0.3 \text{ m}$ in front of Circuit 2, plotted against time from the start of each test

Two features stand out, and they must be interpreted separately because they have different causes. The first is the sign of the gradient, which is opposite in the two operating modes. In both heating tests, the base is warmer than the upper soil, with ΔT_{vert} positive throughout, while in both cooling tests, the base is cooler than the upper soil, with ΔT_{vert} negative throughout. At the end of the tests, the difference reaches about $+6.7^\circ\text{C}$ and $+7.5^\circ\text{C}$ in Heating Tests 1 and 2, and about -2.7°C and -2.1°C in Cooling Tests 1 and 2. This contrast in sign is clear in both figures.

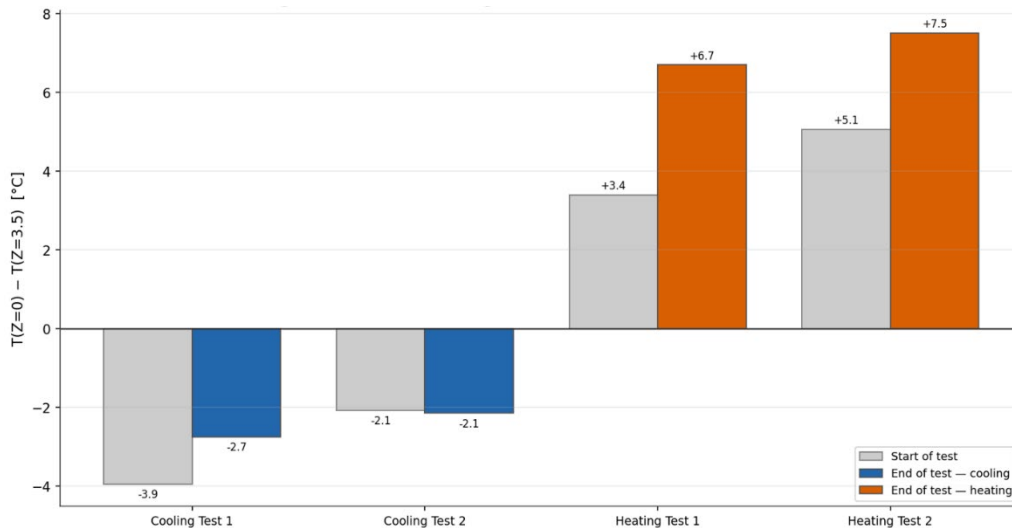


Figure 37: Vertical temperature difference between the base and upper wall at the start and end of each tests

It is important to recognise, however, that this sign reversal is largely seasonal rather than a direct product of the wall's operation. The cooling tests were performed in summer, when the shallow soil is warmed by the sun and the air, while the deeper soil remains cooler, naturally producing a profile in which the base is colder than the top. The heating tests were performed

in autumn and early winter, when the surface and shallow soil cool while the deeper soil retains the warmth of the previous season, naturally producing the opposite profile. A large part of the difference in sign therefore reflects the season in which each test happened to be carried out, and not only the direction of heat exchange at the wall. With the available instrumentation, this seasonal contribution cannot be separated numerically from the wall's own effect, because doing so would require an undisturbed reference profile measured at the same two heights far from the wall, which is not available in the sensor layout; the gradient shown here is therefore the total measured value, combining both contributions.

The second feature is the change of the gradient during each test, and this is where the effect of the wall itself is most clearly seen. In the heating tests, the gradient grows steadily over time, increasing from about $+3.4\text{ }^{\circ}\text{C}$ to $+6.7\text{ }^{\circ}\text{C}$ in Heating Test 1, and from about $+5.1\text{ }^{\circ}\text{C}$ to $+7.5\text{ }^{\circ}\text{C}$ in Heating Test 2. This growth reflects the operation of the wall: as heat is extracted, the upper levels cool faster than the well-buffered base, so the base becomes progressively warmer relative to the top. In the cooling tests, by contrast, the gradient barely changes; it remains essentially constant in Cooling Test 2 and even becomes slightly less negative in Cooling Test 1, moving from $-3.9\text{ }^{\circ}\text{C}$ towards $-2.7\text{ }^{\circ}\text{C}$. The cooling tests, therefore, do not show the symmetric, opposite evolution that might be expected if the response were a simple mirror image of heating. This asymmetry is itself informative: the heating tests were long and the heat exchange was sustained, so the wall had time to build a measurable vertical gradient, whereas the cooling tests were short, lasting fewer than four days, and their gradient stayed close to the pre-existing seasonal profile, with the modest injected-heat effect at the base tending, if anything, to reduce the seasonal gradient slightly rather than reinforce it.

In summary, the vertical gradient shows a clear difference in sign between heating and cooling that is mainly seasonal in origin, together with a growth over time that is the genuine signature of the wall's operation and that is well developed only in the longer heating tests. The base of the wall is consistently the most stable part of the profile, and the wall acts to make the base progressively warmer than the upper soil during heat extraction. This completes the description of the vertical temperature distribution, which is taken up again, together with the horizontal penetration of Section 4.2.4, in the three-dimensional view of the thermal field in Section 4.4.

4.2.6 Lateral heat transfer and recovery behaviour

The previous sections characterised the thermal response of the wall in terms of penetration into the soil and vertical structure. This section addresses two further aspects of the system's behaviour: how the circuits interact with the soil along the length of the wall, and how the soil behaves once the thermal load is removed. The first question concerns whether the thermal influence of a circuit is confined to the soil directly in front of it or extends laterally towards and beyond its boundaries with neighbouring circuits; this is examined in Section 4.2.6.1 by comparing sensors in front of the circuits with sensors at the circuit boundaries, at matched depth and distance from the wall. The analysis there also considers whether this lateral behaviour depends on height. The second question concerns the recovery of the soil during the inactive periods between tests, examined in Section 4.2.6.2 by tracking the local disturbance relative to the far-field reference and assessing whether it dissipates once operation stops.

Throughout both analyses, the observed behaviour must be separated from the strong seasonal evolution of the surrounding ground and, near the wall, from the influence of the open-top maintenance cavaedium, both of which are shown to contribute substantially to the measured temperatures between tests.

4.2.6.1 Inter-circuit thermal interaction

The preceding sections analysed the soil in front of the active circuits. This section examines the soil at the boundaries between adjacent circuits in order to assess whether the thermal influence of a circuit extends laterally to its edges and into the regions shared with its neighbours. For this purpose, the sensors are classified by their position along the wall. A sensor lying within 0.3 m of a circuit boundary is treated as an inter-circuit sensor, representing the transition region between two circuits, while a sensor nearer the centre of a circuit is treated as being in front of that circuit. Each inter-circuit sensor is then compared with a sensor in front of the same circuit, at the same height and at the nearest available distance from the wall, so that the two differ essentially only in their position along the wall. This isolates the lateral effect from the effects of depth and distance, which were treated in the previous sections.

The comparison is carried out for Circuits 2 and 4, which are the only circuits with inter-circuit sensors at all three heights and with continuous records. Circuit 2 belongs to the PCM-enhanced part of the wall and Circuit 4 to the non-PCM part, so the pair also allows a check of whether the PCM influences the lateral behaviour. The remaining circuits are more sparsely instrumented at their boundaries; in particular, Circuit 6 has only a single usable inter-circuit sensor, at $Z = 3.5$ m, and is therefore not analysed in detail here.

Figure 38 compares the front and inter-circuit temperatures over the whole monitoring period for Circuits 2 and 4 at the three heights, with the cooling and heating test periods shaded in blue and orange, respectively. In every case, the two curves remain very close to one another throughout the campaign, including through all four tests. The differences between the inter-circuit and front sensors, averaged over each test, are small: at the base and upper levels they are typically within about 0.1 to 0.5 °C, and the largest difference, at the mid-wall level of Circuit 4 during Heating Test 1, is about 1.0 °C. The small separations that do appear arise almost entirely during the active test periods, and the curves remain essentially coincident during the dormant intervals between tests. This indicates that the differences are produced by the operation of the wall rather than by static differences in the soil.

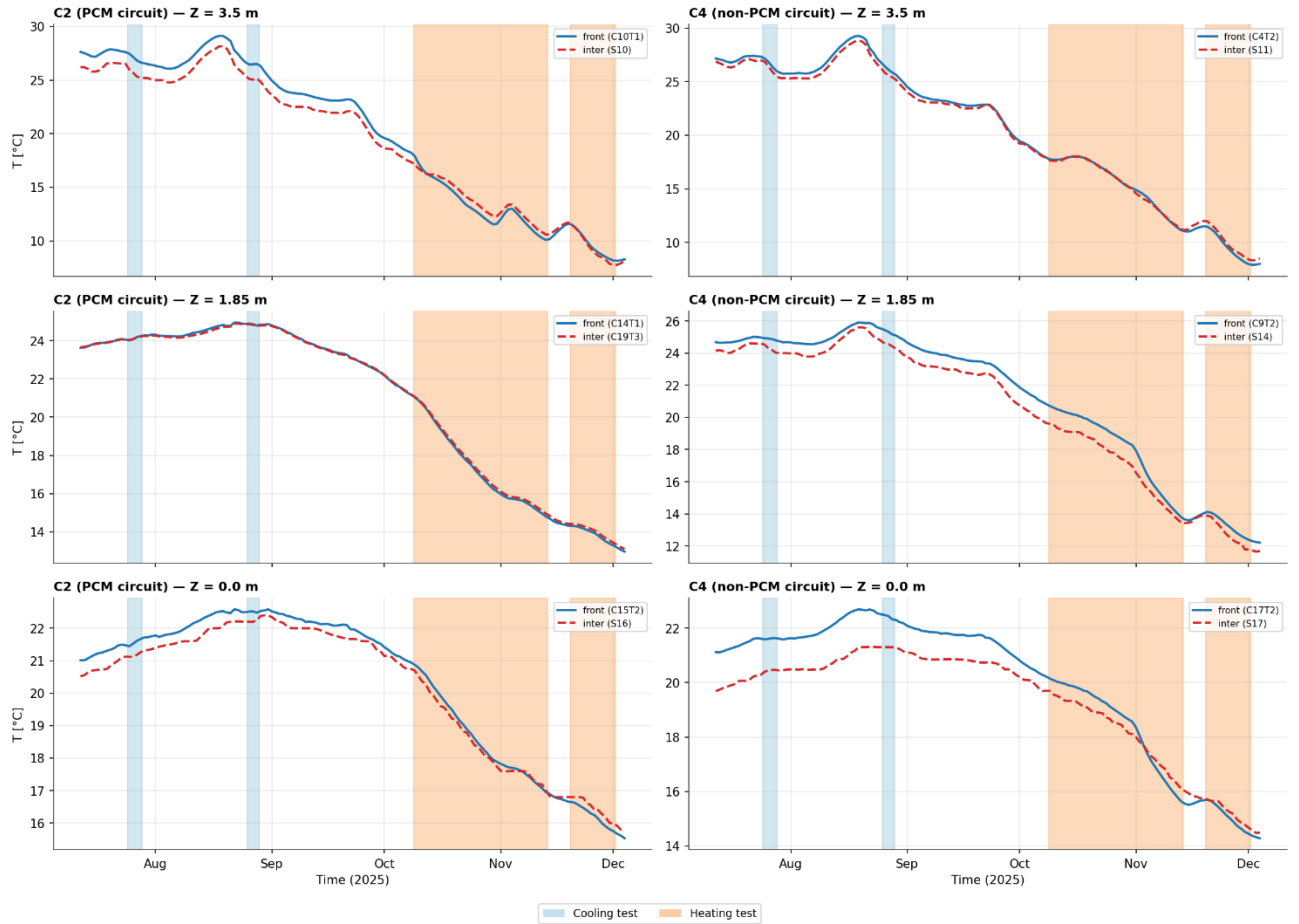


Figure 38: Front (solid blue) versus inter-circuit (dashed red) soil temperature over the monitoring period, for Circuit 2 (PCM, left) and Circuit 4 (non-PCM, right) at three heights ($Z = 3.5$, 1.85 , and 0 m)

The interpretation is that the lateral thermal continuity along the wall is strong: the soil at the boundary of a circuit responds almost in the same way as the soil directly in front of it, so the thermal influence of each circuit effectively reaches its lateral edges. The slightly larger difference at the mid-wall level of Circuit 4 is consistent with this level being the most thermally active, so that the edge there lags marginally behind the centre during the strongest extraction. The behaviour of the PCM circuit (Circuit 2) and the non-PCM circuit (Circuit 4) is very similar in this respect, indicating that the PCM does not materially change the lateral continuity of the temperature field.

Figure 39 provides a complementary view, showing the temperature along the entire wall at a single time, at the end of Heating Test 1, for the two levels $Z = 3.5$ m and $Z = 1.85$ m. The circuit zones are shaded, with the central part of each zone marked as the front region and the 0.3 m strips near the boundaries as inter-circuit regions. The temperature varies smoothly along the wall, without sharp steps at the circuit boundaries, and the inter-circuit sensors fall on the same trend as the front sensors of the adjacent circuits. The active circuits of this test appear as cooler portions of the profile, but the transition between an active and a neighbouring circuit is gradual rather than abrupt, which is again consistent with a laterally continuous temperature field and with heat spreading sideways across the circuit boundaries.

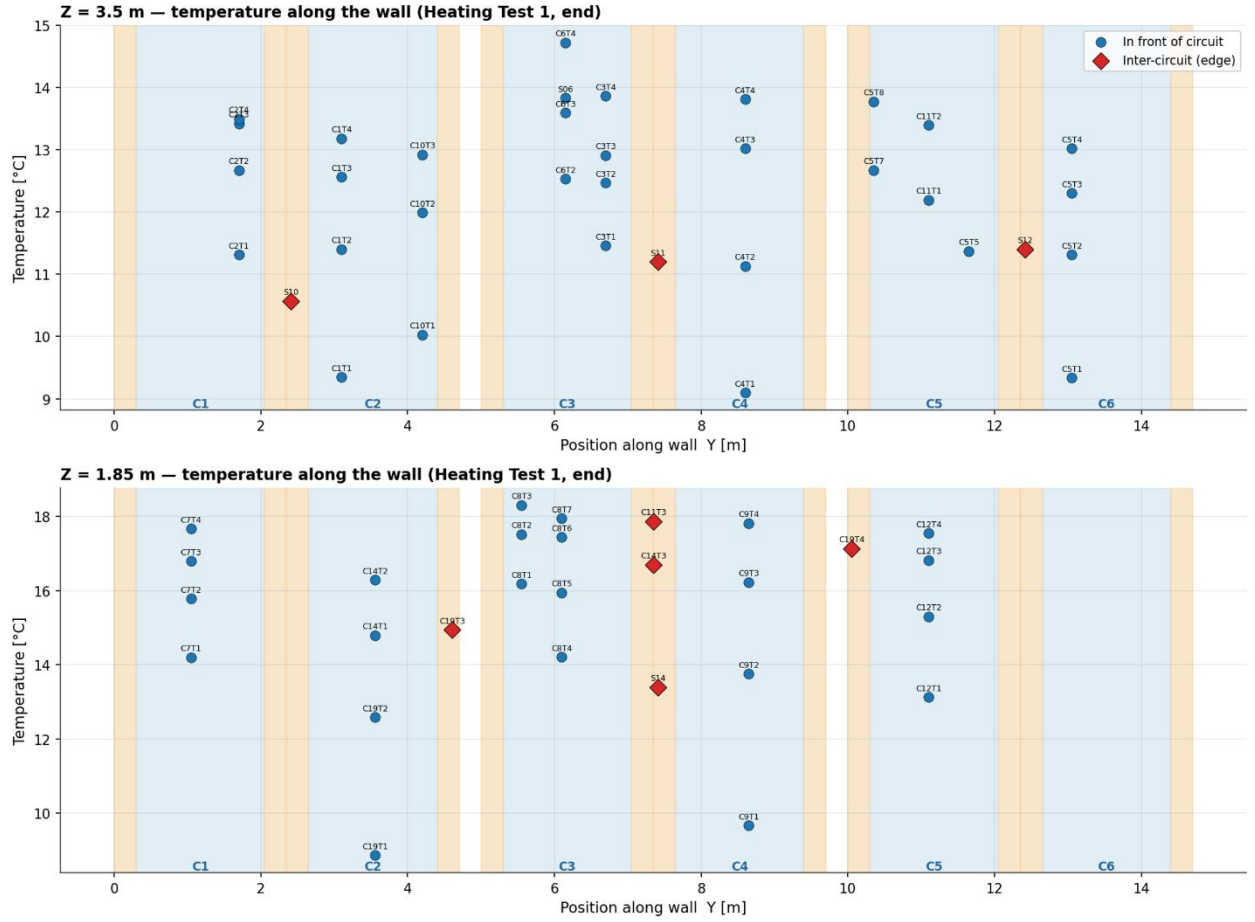


Figure 39: Temperature along the wall at the end of Heating Test 1, at $Z = 3.5$ m and $Z = 1.85$ m

Considered jointly, the two figures show that the circuits do not behave as thermally isolated segments. The soil temperature varies continuously along the wall, the boundary regions track the circuit fronts closely, and the only appreciable front-to-edge differences appear at the most active level during the strongest heat extraction, where they remain of the order of 1 °C. The lateral interaction between circuits is therefore real but modest, and the vertical dependence of this lateral diffusion is examined next.

4.2.6.2 Soil recovery between tests

The periods between the operating tests, when no circuit was active, were examined to assess whether the soil recovers towards its undisturbed condition once the thermal load is removed. Four such windows are available: after Cooling Test 1 (about 28 days), after Cooling Test 2 (about 41 days), after Heating Test 1 (about 6 days), and after Heating Test 2 (about 2 days). A direct reading of the absolute soil temperature is not a reliable measure of recovery, because the ground temperature also changes with the season; a sensor cooling during an autumn window could simply be following the seasonal decline rather than recovering from the test. To separate these two effects, the analysis uses the temperature of each sensor relative to the far-field reference C10T4. This reference is located at the same height ($Z = 1.85$ m) and at almost the same position along the wall ($Y \approx 9.3$ m) as the string of sensors in front of Circuit 4, so that the sensors and the reference differ essentially only in their distance from the wall. The quantity $T_{\text{sensor}} - T_{\text{C10T4}}$ then removes the common seasonal trend and isolates the

local disturbance caused by the operation: if this residual difference returns towards zero during a window, the soil is genuinely recovering, whereas if it stays constant, the apparent temperature change is seasonal.

Because the far-field reference lies in the plane of Circuit 4, this rigorous comparison is possible for Circuit 4 but not for the PCM-side Circuit 2, whose sensors are about six metres away along the wall; the recovery behaviour is therefore analysed on the Circuit 4 string, at distances from the wall of $X = 0.3$ to 2.8 m.

Figure 40 shows the absolute temperatures of the Circuit 4 string and the far-field reference (top), and the residual difference relative to the far field (bottom), over the whole campaign, with the test periods shaded blue and orange and the recovery windows shaded grey. During each test, the near-wall sensors deviate strongly from the far field, negatively during heating and positively during cooling, and during the recovery windows, these deviations move back towards zero. After Heating Test 1, for example, the residual difference at the wall decreases in magnitude from about -8.2 °C to -4.4 °C within six days, showing that a large part of the disturbance dissipates quickly once heat extraction stops. The recovery is incomplete for the windows that follow Heating Test 2, which lasted only about two days, too short for the soil to return to the far-field condition.

An important feature of the geometry must be taken into account when interpreting the near-wall sensor. Behind the wall, there is an open-top maintenance cavaedium, whose air is close to the outdoor air temperature. The sensor nearest the wall, at $X = 0.3$ m, is thermally coupled to this cavity and therefore partly follows the air temperature rather than the surrounding soil. This is visible in the data: during the long window after Cooling Test 2, the near-wall sensor cooled by about 5.6 °C, closely matching the 4.6 °C fall in air temperature over the same period, while the deeper soil at $X = 2.8$ m cooled by only about 2 °C; and after Heating Test 1, the near-wall sensor warmed towards the air temperature while the deeper sensors and the far-field reference continued to cool slightly. The rapid convergence of the $X = 0.3$ m sensor towards the far-field value during the recovery windows is therefore caused partly by equilibration with the cavaedium air, and not solely by the redistribution of heat into the surrounding ground. For this reason, the near-wall sensor is not used as a measure of soil recovery.

The genuine soil recovery is better judged from the sensors farther from the wall, at $X = 1.3$ to 2.8 m, which are shielded from the cavaedium by the intervening soil. At these distances, the residual difference relative to the far field is already small after the tests, of the order of 1 to 2 °C or less, and remains small and nearly constant through the windows, with the most distant sensors staying within a few tenths of a degree of the far-field condition throughout. This indicates that the operational disturbance at these distances was modest and that the soil there was never far from its undisturbed state, so that little recovery was required.

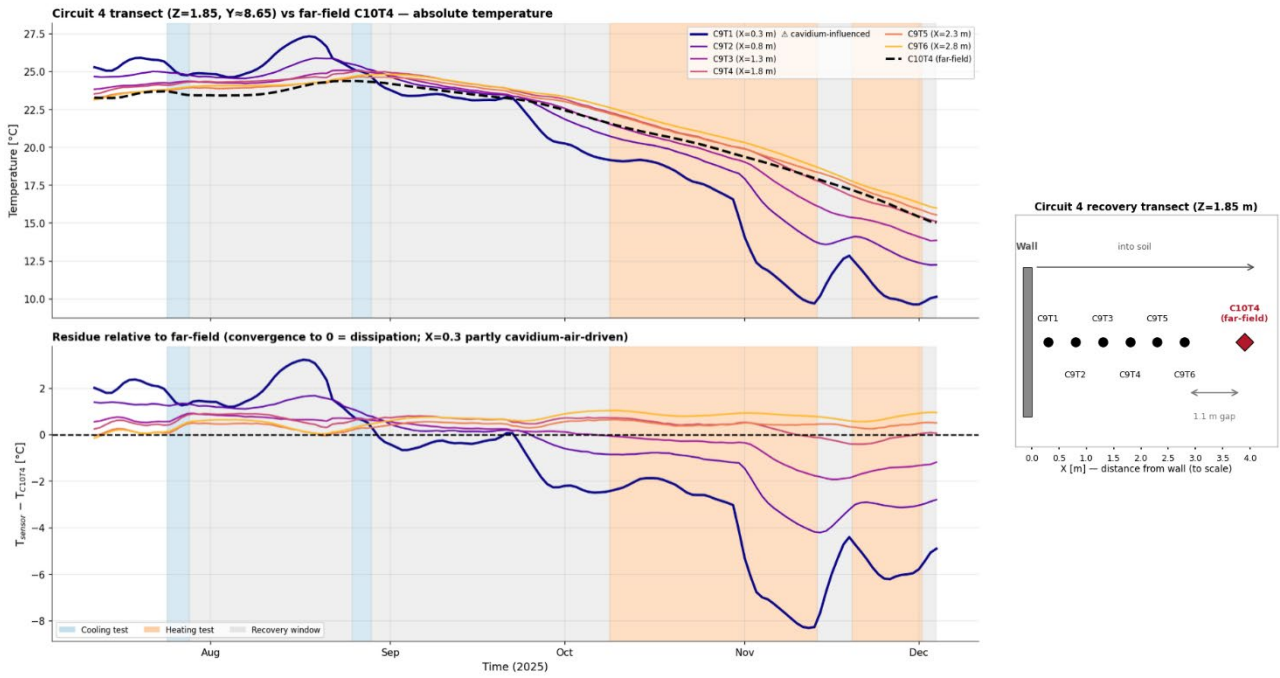


Figure 40: Soil temperature recovery between tests, for the Circuit 4 string ($Z = 1.85$ m, $Y \approx 8.65$ m) at distances $X = 0.3$ to 2.8 m from the wall, relative to the far-field reference C10T4 (same height and along-wall position, $X = 3.9$ m)

Overall, the recovery analysis shows that the soil does respond and relax once the load is removed, with the disturbance concentrated near the wall and decaying with distance, but it also shows that the inactive windows are too short, and the near-wall measurement is too influenced by the cavaedium air, to characterise a complete return to equilibrium. The clearest statement that the data supports is that the near-wall soil carries the largest operational disturbance and begins to dissipate it within days, while the soil beyond about one metre remains close to the far-field condition throughout and requires little recovery. As with the lateral analysis, the inter-test behaviour is governed by a combination of the operational residue and the seasonal and boundary conditions of the surrounding ground.

4.3 PCM thermal buffering effect

The previous section evaluated the penetration of the thermal disturbance from the active Geothermskin circuits into the soil. The present section focuses specifically on the possible contribution of the PCM installed in front of the first two circuits. Since the PCM-enhanced region is located in front of Circuits 1 and 2, the comparison was based on the thermal response of Circuit 2 as the main PCM representative.

The PCM assessment was restricted to the heating tests. This choice was made because, during the cooling tests, the macroencapsulated PCM was already melted and would not produce any relevant temperature differences in the ground (with respect to the field without PCM) through latent-heat exchange (heat stored or released during operation of the energy wall). During heating mode, the system extracts heat from the surrounding soil, and the PCM may contribute to moderating the temperature decrease by releasing stored heat or by reducing the amplitude

of temperature fluctuations. In contrast, the cooling tests were shorter and less suitable for a robust PCM/non-PCM comparison, particularly because Cooling Test 2 was affected by malfunctioning sensors in the Circuit 6 area.

Therefore, the PCM analysis was performed using Heating Test 1, the second phase of Heating Test 1, and Heating Test 2 only. Circuit 2 was used as the PCM-side reference, while Circuits 4 and 6 were used as non-PCM references depending on the active circuit configuration of each test. The results should be interpreted as a comparison between soil temperature responses around PCM and non-PCM circuit zones, rather than as a direct measurement of the PCM material itself.

4.3.1 Comparison strategy between PCM and non-PCM zones

The PCM is installed only in front of the first two circuits, within approximately $X = 0\text{--}0.8\text{ m}$, $Y = 0\text{--}4.6\text{ m}$, and $Z = 0\text{--}2.03\text{ m}$. Because the PCM occupies only the lower part of the wall height, the sensors at $Z = 0\text{ m}$ and $Z = 1.85\text{ m}$ lie within the PCM range, while the sensors at $Z = 3.5\text{ m}$ lie above it. This vertical limit is used as a consistency check: a genuine PCM effect should appear at the lower level but not at the upper level.

A second feature of the material is essential for analysis. According to the manufacturer's data, the PCM (RUBITHERM SP15) changes phase only within a narrow temperature band, with melting between 15 and $17\text{ }^{\circ}\text{C}$ and solidification between 13 and $15\text{ }^{\circ}\text{C}$, both peaking at $15\text{ }^{\circ}\text{C}$. The latent heat that produces any buffering effect is therefore available only while the surrounding soil temperature lies within this band, of roughly 13 to $17\text{ }^{\circ}\text{C}$. Once the soil has cooled well below this range, the PCM is fully solidified and behaves like an ordinary material, so no buffering should be expected. This temperature condition, rather than the simple presence of the PCM, governs where and when an effect can occur, and it is central to the interpretation that follows.

Circuit 2 was selected as the principal PCM-side circuit because Circuit 1, although also in the PCM region, was not active during the heating tests, while Circuit 2 was active in both heating tests and has the most complete sensor coverage. The analysis was restricted to the heating tests, because heat extraction provides a clearer and longer setting than the short cooling tests. It should be emphasised from the outset that the sensors measure the temperature of the soil close to the circuits, not the temperature of the PCM itself; the analysis therefore assesses whether the soil thermal response is moderated in the PCM-enhanced zone, and cannot measure the latent heat of the material directly.

The PCM-enhanced Circuit 2 is compared with two non-PCM circuits: Circuit 4 during Heating Test 2, in which the two were operated in parallel, and Circuit 6 during Heating Test 1, the longest test, where the comparison is available only at $Z = 0\text{ m}$ and $Z = 3.5\text{ m}$ because Circuit 6 has no mid-wall sensor. Both comparisons carry significant limitations that must be kept in mind. First, the circuits occupy different positions along the wall and have slightly different pipe layouts, so part of any difference may be positional. Second, and more importantly, the circuits did not share the same operating history: in Heating Test 1, Circuit 2 was active from 8 October, whereas Circuit 4 was activated only from 30 October. As a result, by the time the

parallel Heating Test 2 began, the soil around Circuit 2 had already been cooled for substantially longer than that around Circuit 4, and the two circuits entered Heating Test 2 in different thermal states. The parallel operation during Heating Test 2 therefore equalises the conditions during that test, but not the initial conditions inherited from the previous test. A within-circuit comparison by depth was also considered, but because the PCM levels are also the deeper, naturally more stable levels, it cannot separate the PCM effect from the ordinary depth effect, and it is not used as independent evidence.

Two indicators describe the soil response: the standard deviation of the soil temperature over the test period, as a measure of variability or damping, and the far-field-corrected temperature change, $\Delta T_{\text{corr}} = \Delta T_{\text{sensor}} - \Delta T_{\text{C10T4}}$, which removes the seasonal trend measured at the far-field reference C10T4. Given the small magnitude of the differences and the confounding factors described above, these indicators are interpreted with caution, and the analysis relies more on physical consistency with the phase-change behaviour of the material than on the absolute size of any single difference.

4.3.2 Temperature response of PCM and non-PCM zones

Figure 41 compares the PCM circuit (Circuit 2) with the non-PCM circuit (Circuit 6) during Heating Test 1, at the base ($Z = 0$ m) and upper ($Z = 3.5$ m) levels, using the near-wall sensors at $X = 0.3$ m in front of each circuit. At the base level, which lies within the PCM range and where the soil remained within the phase-change band of the material (around 16–21 °C, overlapping the 15–17 °C melting range), the PCM-side soil (sensor C15T1) is smoother and cooled less than the non-PCM side (sensor C20T1): its standard deviation over the test is 1.30 °C against 1.83 °C, and its far-field-corrected cooling is 1.45 °C against 3.12 °C. At the upper level, above the PCM, the two circuits behave almost identically (sensors C1T1 and C5T1, standard deviation 2.02 °C against 1.96 °C). The presence of a difference within the PCM range and its absence above it is consistent with a buffering effect, although, as discussed below, it cannot be separated with certainty from the different positions of the two circuits.

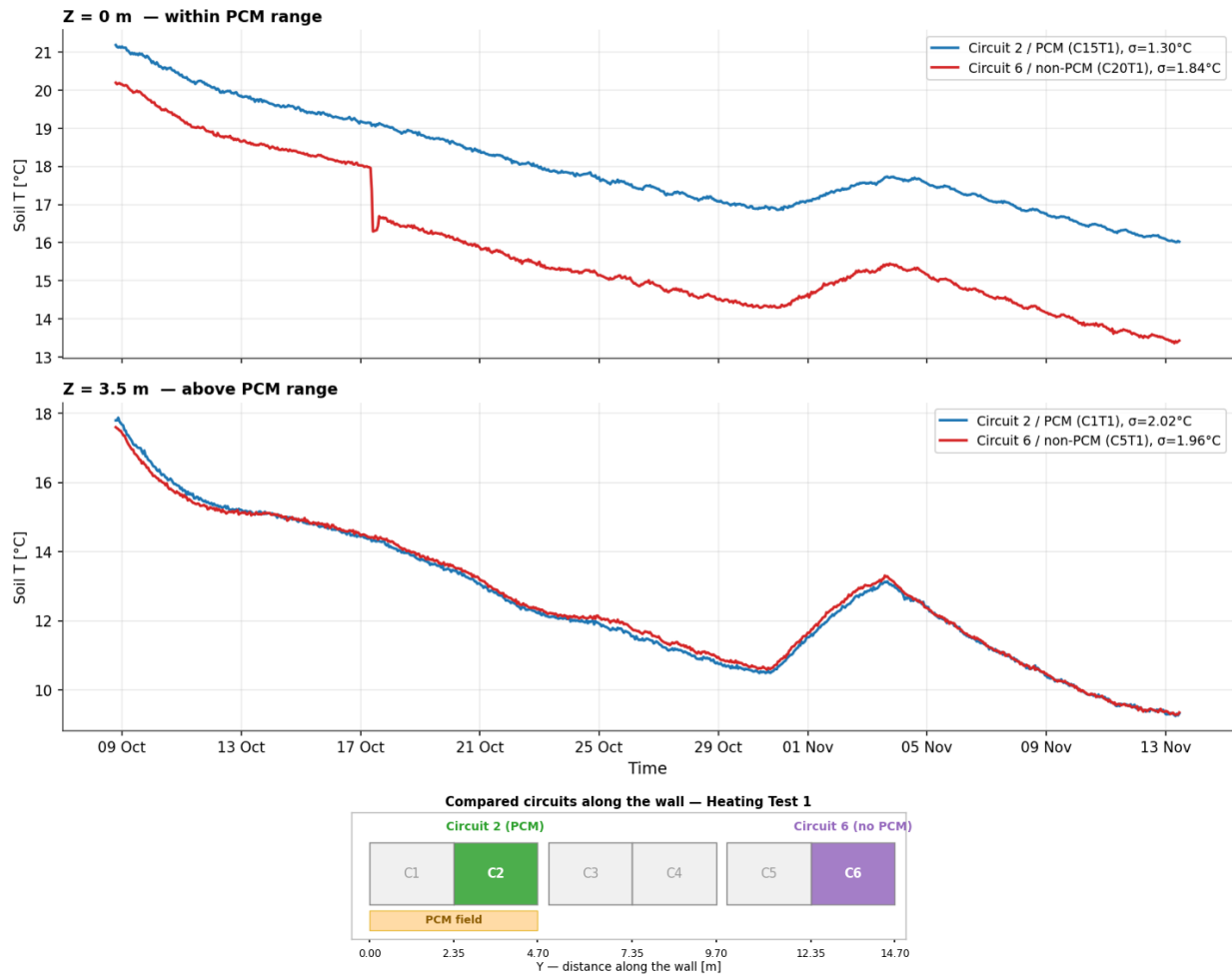


Figure 41: Near-wall soil temperature during Heating Test 1 for the PCM circuit (Circuit 2) and the non-PCM circuit (Circuit 6), at $Z = 0$ m (within the PCM range) and $Z = 3.5$ m (above it)

Figure 42 shows the comparison between Circuit 2 (in the field with PCM) and Circuit 4 (non-PCM) during Heating Test 2, when the two circuits operated in parallel. The standard deviation of the PCM side is slightly lower at all three depths (for example, 0.55°C against 0.67°C at the base, and 0.96°C against 1.01°C at the mid-wall level), but the absolute temperatures do not show a consistent buffering pattern. In particular, at the mid-wall level, the PCM-side soil is slightly colder than the non-PCM side, not warmer. This behaviour is explained by two factors identified in the comparison strategy. First, Circuit 2 had been active since the beginning of Heating Test 1, while Circuit 4 was activated only from 30 October; by the activation date, the mid-wall soil of Circuit 2 had already cooled to about 9°C , against about 17°C for Circuit 4, a difference of more than 7°C caused purely by the operating history. Circuit 2, therefore, entered Heating Test 2 in a colder state, which accounts for its lower mid-wall temperature independently of any PCM effect. Second, by Heating Test 2, the mid-wall and upper soil of the PCM zone had cooled to between 7 and 12°C , that is, below the 13 – 15°C solidification range of the material. At these temperatures, the PCM is fully solidified and no longer exchanges latent heat, so no buffering can be expected at these levels during this test. Consistently, the only level that remained within the phase-change band during Heating Test 2

was the base level ($Z = 0$ m), where the soil stayed between 15 and 17 °C throughout, and it is at this level that the PCM side again shows the lower variability.

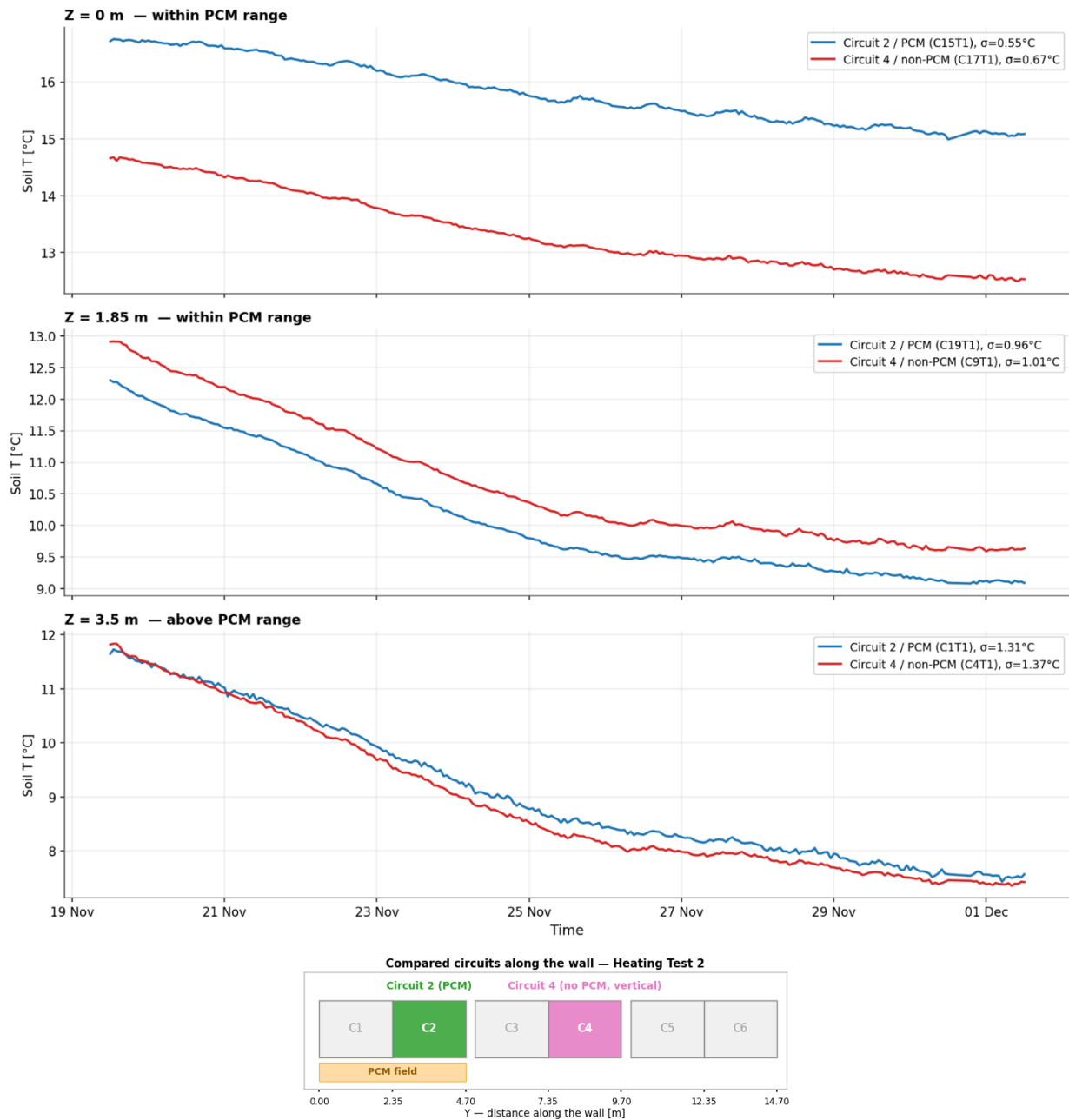


Figure 42: Near-wall soil temperature during Heating Test 2 for the PCM circuit (Circuit 2) and the non-PCM circuit (Circuit 4), operated in parallel, at $Z = 0$, 1.85, and 3.5 m

Figure 43 summarises both indicators for the two comparisons. The pattern that emerges is that the PCM side shows a lower temperature variability wherever the soil remained within the phase-change band of the material, namely at the base level in both tests, and shows little or no distinction where the soil had cooled below that band or at the level above the PCM. The far-field-corrected change follows the same tendency but more weakly.

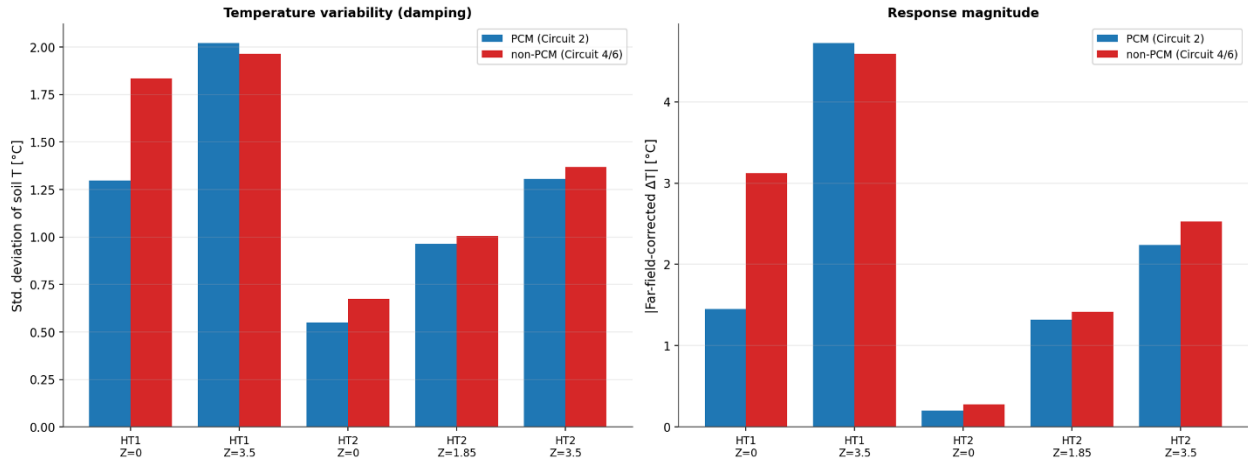


Figure 43: Summary of the two buffering indicators — standard deviation of soil temperature (left) and far-field-corrected temperature change (right) — for the PCM and non-PCM circuits in both heating tests

Overall, the soil-temperature measurements are consistent with a modest thermal buffering by the PCM, but they do not constitute a clear demonstration of it. The supporting evidence is the lower variability of the PCM-side soil at the levels and times when the soil temperature lay within the 13–17 °C phase-change band of the material, together with the absence of any distinction above the PCM and below the phase-change band, which agrees with the expected physical behaviour. Against this, the differences are small, in several cases of the order of 0.1 °C in standard deviation, and two confounding factors prevent a firm conclusion: the compared circuits occupy different positions along the wall, and they entered the parallel test with different thermal histories because of their different activation dates. The most that can be stated with confidence is that the data are compatible with the PCM acting as a thermal buffer within its phase-change temperature range, while a quantitative measurement of this effect is beyond the resolution of the soil-temperature sensors used here. Additional approaches that were examined, including a within-circuit comparison by depth and an analysis of the rate of temperature change near the phase-change temperature, were consistent with this view in some cases but did not provide independent confirmation.

4.4 Three-dimensional thermal field visualisation

The preceding sections analysed the thermal response of the Geothermskin system using time series, circuit-zone comparisons, vertical profiles, and lateral and recovery indicators, all derived from the individual sensors. These analyses quantify the behaviour of the wall, but they represent the soil temperature through discrete measurement points. To complement them, the monitoring data were also visualised as a three-dimensional field in ParaView, in which the sensor coordinates position the measurements within the wall–soil domain and the temperatures are interpolated into a continuous field. This representation does not add new measurements; its purpose is to combine the separate directions of the previous analyses, namely distance from the wall, height, and position along the wall, into a single spatial picture, and so to show the geometry of the thermal response as a whole rather than as isolated readings.

It must be stressed that the three-dimensional field is a qualitative and interpretative tool. The interpolated field depends on the spatial distribution of the sensors and on the interpolation scheme, so the fine structure visible in the images, in particular the rounded warm and cold spots, reflects the spacing of the sensors rather than the real detail of the temperature field. The visualisations are therefore used to illustrate and support the sensor-based results of Sections 4.2 to 4.7, and not to derive any independent numerical indicator. All numerical values quoted below are taken from the sensors themselves, with the images serving only to show their spatial arrangement.

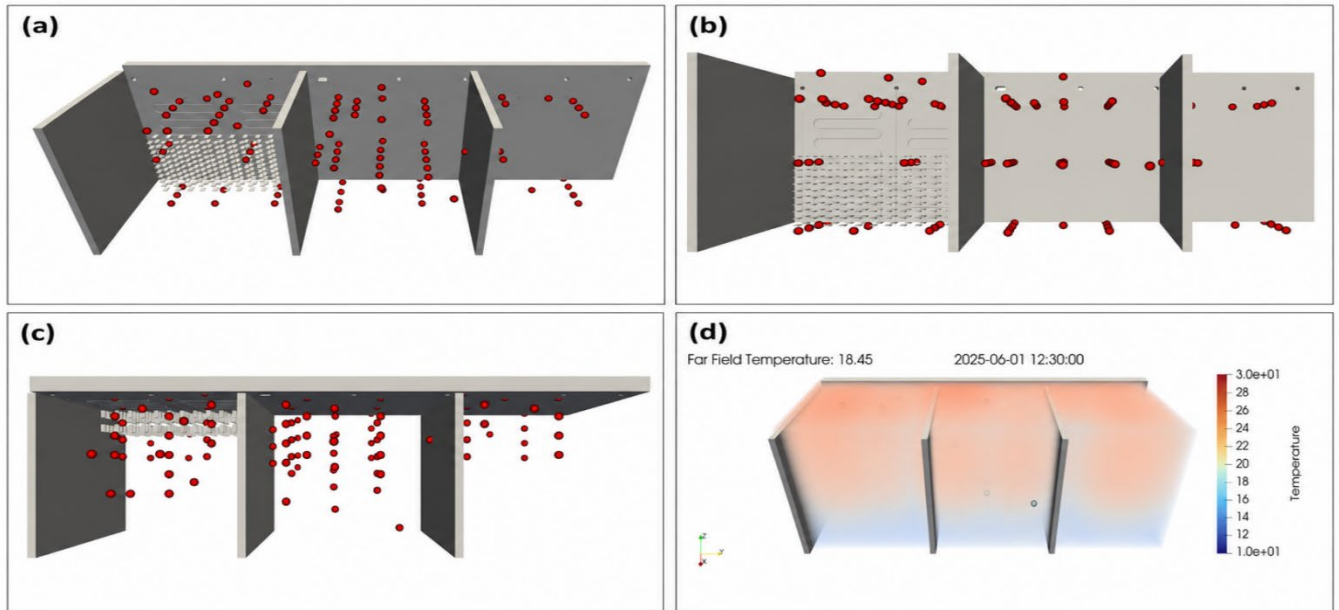


Figure 44: Representative ParaView screenshots of the Geothermskin monitoring domain

Figure 44 introduces the monitoring domain. Panels (a) to (c) show the wall segments, the embedded circuit pipework, and the distribution of the monitoring points within the soil, from several viewpoints, while panel (d) shows an example of the interpolated temperature field with its colour legend and far-field annotation. These views establish the geometry and the sensor layout that underlie all the field images that follow.

4.4.1 Spatial contrast between heating and cooling

Figure 45 shows the interpolated field over the whole domain at the end of each of the four tests. The contrast between the two modes of operation is immediate. At the end of both cooling tests the field around the wall is dominated by warm colours, and the mean temperature of the active zone is higher than the far-field reference, by $+1.6\text{ }^{\circ}\text{C}$ at the end of Cooling Test 1 (active-zone mean $25.1\text{ }^{\circ}\text{C}$ against a far-field value of $23.5\text{ }^{\circ}\text{C}$) and by $+0.7\text{ }^{\circ}\text{C}$ at the end of Cooling Test 2 ($25.1\text{ }^{\circ}\text{C}$ against $24.3\text{ }^{\circ}\text{C}$). This is the spatial signature of heat being rejected into the ground during the cooling operation. At the end of the two heating tests, the field is correspondingly colder than the reference, with the active-zone mean below the far field by $-3.7\text{ }^{\circ}\text{C}$ at the end of Heating Test 1 ($14.3\text{ }^{\circ}\text{C}$ against $18.0\text{ }^{\circ}\text{C}$) and by $-3.3\text{ }^{\circ}\text{C}$ at the end of Heating Test 2 ($12.1\text{ }^{\circ}\text{C}$ against $15.4\text{ }^{\circ}\text{C}$), the spatial signature of heat extraction. The figure

therefore renders, in a single view, the reversal between the two operating modes that was quantified throughout the previous sections.

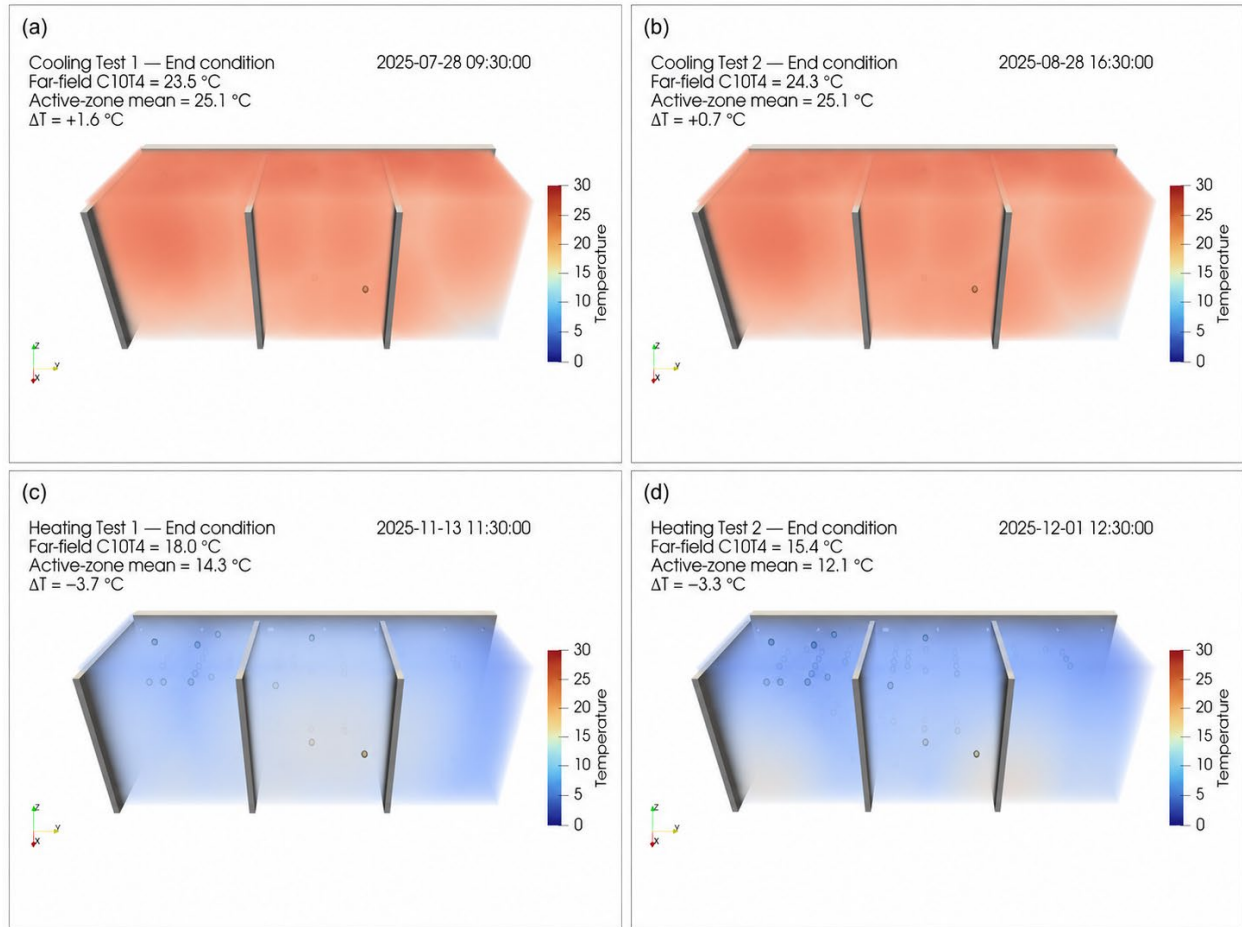


Figure 45: Three-dimensional interpolated temperature field at the end of the four operating tests

4.4.2 Near-wall field along the wall (Y-Z sections)

Figure 46 shows vertical sections taken in the plane closest to the wall, at $X = 0.3$ m, for the four test end conditions. Because this plane lies directly in front of the circuits, it reveals the structure of the near-wall field along the height and length of the wall. Two features stand out. First, the near-wall field is clearly more disturbed than the far field: during cooling the near-wall mean exceeds the far-field reference by +2.2 °C in Cooling Test 1 (25.7 °C against 23.5 °C) and by +1.7 °C in Cooling Test 2 (26.0 °C against 24.3 °C), and during heating it falls below the reference by −6.9 °C in Heating Test 1 (11.1 °C against 18.0 °C) and by −5.8 °C in Heating Test 2 (9.6 °C against 15.4 °C). These near-wall differences are markedly larger than the whole-domain differences of Figure 45, confirming that the thermal disturbance is concentrated close to the wall, as found in the penetration analysis of Section 4.2.4. Second, in the heating panels the lower part of each section is the warmest region, forming a continuous warm band along the base of the wall, which is the spatial expression of the vertical structure identified in Section 4.2.5, where the base remained the most thermally stable level while the mid and upper wall cooled. The individual circuits appear as a row of discrete spots across the

section, but neighbouring spots merge into a continuous band rather than remaining separate, which is consistent with the lateral continuity established in Section 4.2.6.

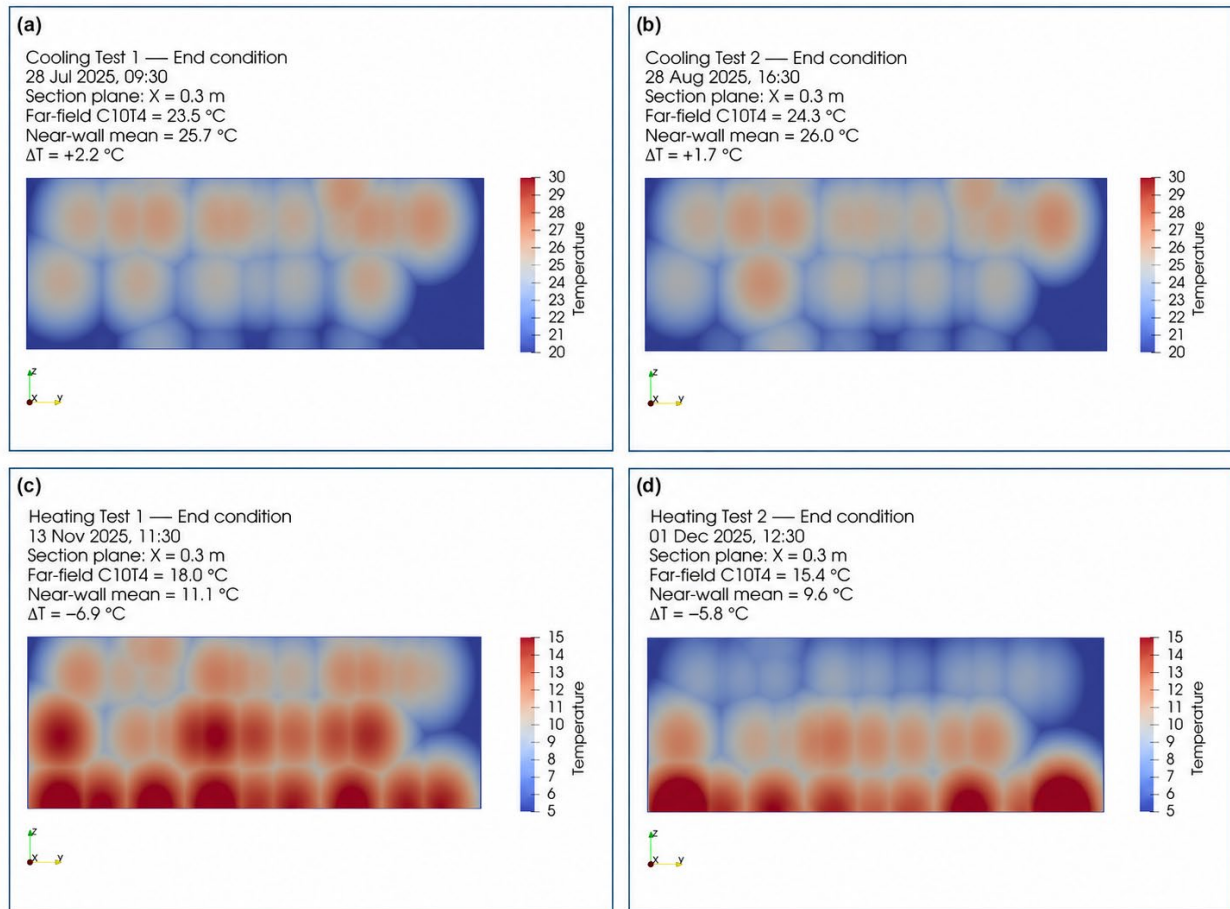
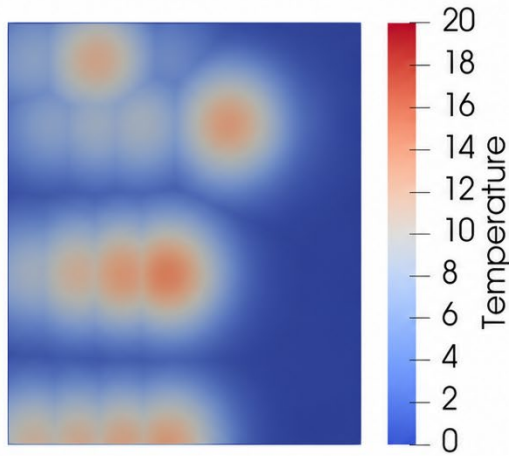


Figure 46: Y-Z near-wall sections at $X=0.3$ m for the four test end conditions

4.4.3 Penetration into the soil (X-Z sections)

Figure 47 shows sections taken perpendicular to the wall, through Circuit 2, at $Y = 3.75$ m, comparing the end of Heating Test 1 with the end of Cooling Test 2. These sections look into the soil in the direction of penetration and show that the thermal response is not confined to the wall face but reaches into the soil volume. During Cooling Test 2 the section lies within a warm range, reflecting the summer condition and heat rejection, whereas during Heating Test 1 the same section is markedly colder, showing the depleted zone that develops in front of the active circuit. Consistent with Section 4.2.4, the disturbance is strongest close to the wall and weakens with distance into the soil. The two panels are displayed on different temperature scales, appropriate to the summer and autumn conditions, so they should be read as separate fields rather than compared colour for colour; the quantitative comparison between the modes rests on the sensor values given above and in Section 4.2.4.

Heating Test 1 — End condition
13 Nov 2025, 11:30
Section plane: Y = 3.75 m (Circuit 2)



Cooling Test 2 — End condition
28 Aug 2025, 16:30
Section plane: Y = 3.75 m (Circuit 2)

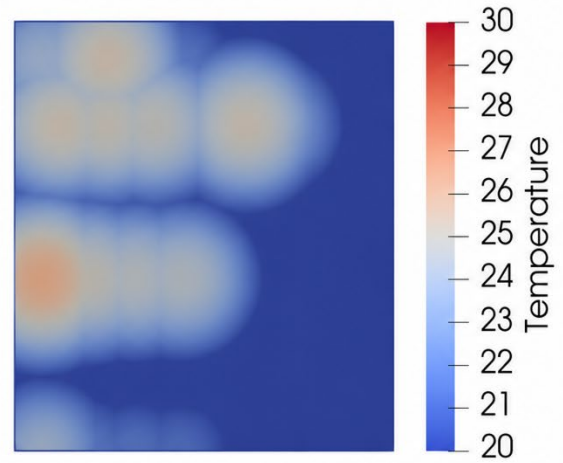


Figure 47: X-Z sections through Circuit 2 at Y=3.75 m

4.4.4 Time evolution of the near-wall field during Heating Test 1

The section planes considered so far represent the end conditions of the tests. Because Heating Test 1 was the longest and included the activation of a third circuit partway through, its development over time is shown explicitly. Figure 48 presents the near-wall section plane, at $X = 0.3$ m, at four stages of the test: the beginning (8 October), shortly before the activation of the third circuit (29 October), shortly after that activation (3 November), and the end of the test (13 November). The activation of Circuit 4 on 30 October, referred to here as the second phase of the test, divides the heating operation into an initial period with Circuits 2 and 6 active and a later period with Circuit 4 additionally in operation.

The sequence shows the near-wall soil cooling progressively as heat extraction continues. Averaged over the near-wall sensors, the temperature falls from about 19.1 °C at the beginning to 14.9 °C before the second phase, and then to 12.3 °C at the end, while the difference relative to the far-field reference deepens correspondingly from about -2.6 °C to -4.8 °C and finally to -5.7 °C. The disturbance therefore builds up steadily throughout the test rather than reaching an early steady state, consistent with the progressive development of the vertical structure described in Section 4.2.5. The effect of the second phase is visible in the panels before and after 30 October: the portion of the section in front of Circuit 4 cools by about 2 °C between 29 October and 3 November, from about 17.0 °C to 14.8 °C, as that circuit begins to extract heat, whereas the rest of the field continues its slower general decline. The images thus provide a spatial illustration of both the continuous intensification of the near-wall cooling and the localised response to the activation of an additional circuit.

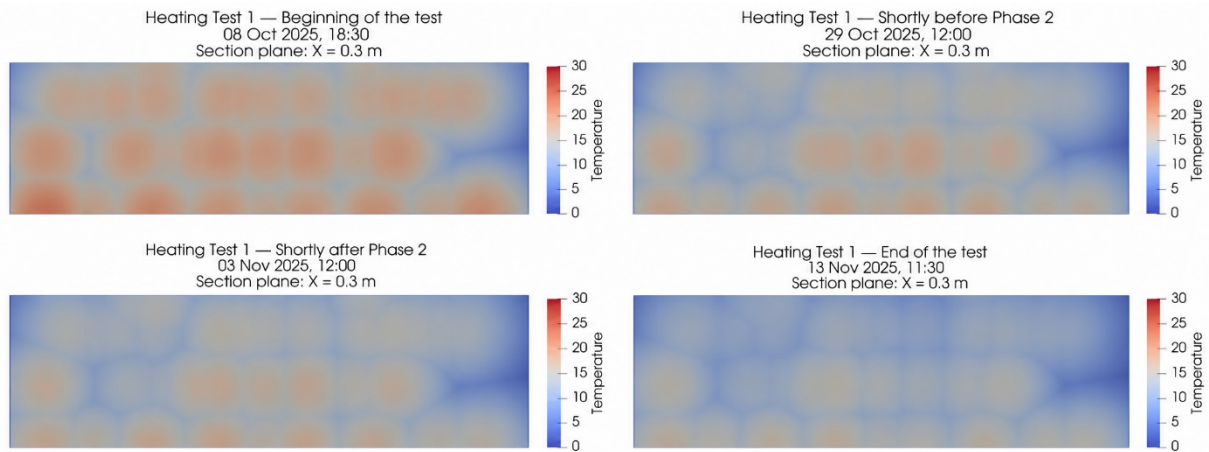


Figure 48: Evolution of the Y-Z near-wall temperature field during Heating Test 1

In combination, the visualisations provide a spatial confirmation of the main results of the chapter. Cooling operation produces a warm near-wall field and heating operation a cold one; the disturbance is concentrated within the first part of the soil and decays with distance; the base of the wall remains the most stable region; and the field is continuous along the wall rather than broken into isolated circuit cells. These images do not establish any of these findings on their own, but they make the geometry of the thermal response visible in a way that the sensor time series cannot, and in this sense, they are a valuable complement to the quantitative analysis.

4.5 Thermo-Hydro-Mechanical response

The analysis in Sections 4.2 to 4.4 treated the wall as a thermal system, using the temperature network to describe how heat penetrates, distributes, and recovers in the soil and the structure. The prototype, however, was instrumented as a coupled THM system: alongside the PT100 sensors, it carries soil humidity and water tension sensors that report the hydraulic state of the surrounding ground, and strain gauges and total pressure cells that report the mechanical state of the wall. This section examines those two additional components, with two aims: to establish whether the thermal operation of the wall produces a measurable hydraulic or mechanical response, and, where it does not, to bound the size of any such response from the data.

The scope of this section is deliberately narrower than that of the thermal analysis, for a reason that the analysis itself makes clear. As shown in Section 4.5.1, a substantial part of the hydro-mechanical instrumentation is compromised, by a mid-campaign data-acquisition event, by progressive sensor failures, and by the poor condition of the original strain gauges, so that only a reliable core of the network can support quantitative interpretation. The section is therefore organised around characterisation and bounds rather than around a full coupled model. It first documents the instrumentation and the data-quality audit that governs every subsequent choice (Section 4.5.1), then presents the hydraulic observations (Section 4.5.2) and the mechanical observations and thermo-mechanical coupling (Section 4.5.3), and closes with a synthesis of what the THM data do and do not establish (Section 4.5.4). Throughout, the guiding principle

is the same as in the rest of the chapter: seasonal and environmental signals dominate the raw records, and operational effects are identified only where they can be separated from that background.

4.5.1 THM monitoring data and interpretation

In addition to the temperature network analysed in Sections 4.2 to 4.4, the Geothermskin prototype is instrumented for the hydraulic and mechanical components of its THM behaviour. The hydraulic network comprises 15 soil humidity sensors (S01 to S18, measuring volumetric water content at depths from the wall base to approximately 0.4 m below the ground surface) and two soil water tension sensors (T1 and T3, both at $Z = 4.2$ m). The mechanical network comprises nine resistive strain gauges (BE1 to BE13) and five total pressure cells (CP1 to CP5), all installed on the wall itself ($X = 0$). The layout, shown in Figure 49a, reflects a deliberate comparative design: the gauge pairs BE10–BE11 and BE12–BE13 occupy matched heights ($Z = 0.3$ m and $Z = 2.1$ m, respectively) in Circuit 1 and Circuit 5, that is, inside and outside the PCM-equipped zone, and the pressure cells CP2 and CP1 form an analogous pair at $Z = 2.4$ m. Four of the strain gauges (BE10 to BE13) were installed or relocated during the 2024–2025 upgrade of the prototype, while BE1 to BE6 belong to the original instrumentation.

Before any interpretation, the raw data were audited, and this audit governs everything that follows. The two gauge generations differ sharply in health. The original gauges are noisy (typical in-day standard deviations of 1 to 7 $\mu\epsilon$), exhibit erratic drifts of 38 to 104 $\mu\epsilon$ over the campaign with inconsistent correlation to local temperature, and occasionally saturate at the ± 100 $\mu\epsilon$ range limit (84 samples for BE3, and 116 for BE6); BE2 additionally produced quantized readings and was effectively stuck near -11 $\mu\epsilon$ from August onward. The upgrade gauges, by contrast, are quiet (in-day standard deviations of 0.03 to 0.6 $\mu\epsilon$) and respond coherently, although BE12 proved nearly insensitive, with a total range of only 1.8 $\mu\epsilon$ in 4.5 months.

The most consequential data-quality finding is shown in Figure 49b. At 09:40 on 17 October 2025, nine days into Heating Test 1, the entire strain acquisition changed character simultaneously: BE2, BE5, BE6, and BE12 froze permanently at rounded values (-10 , -5 , -5 , and $+1$ $\mu\epsilon$, respectively), the readings of BE11 and BE13 stepped by a factor of exactly 10 (from -22.2 to -221.5 $\mu\epsilon$, and from -18.6 to -195.7 $\mu\epsilon$, respectively, with their noise floors scaling identically), and the readings of BE1 stepped by a factor of 1/10. No physical event can produce an instantaneous tenfold strain change on multiple channels; the pattern is that of a data-acquisition reconfiguration, inferred here from the data as no laboratory log of the intervention is available. Accordingly, the post-event readings of BE11, BE13, and BE1 were rescaled to restore continuity, the four frozen channels were truncated at the event, and all strain results in Section 4.5.3 are reported with this correction stated. This event also offers a plausible origin for the strain-scale inconsistencies noted in the instrumentation documentation discussed in Chapters 2 and 3.

Among the pressure cells, CP1 failed progressively, drifting from approximately -0.1 bar in June to -20 bar by August and pinning at its -50 bar range limit by November, a physically impossible value for earth pressure at 2.4 m height on the wall (Figure 49c); it is excluded from

the analysis. The remaining cells, CP2 to CP5, read within approximately ± 0.2 bar of zero throughout the campaign. Finally, the meteorological rain gauge recorded a total of 2.14 mm over the six-month campaign, which is incompatible with the local climate, so precipitation cannot be used as an explanatory variable; soil water tension is used instead as the indicator of wetting and drying.

Given these constraints, the interpretation method for this section is deliberately conservative: the analysis is restricted to the healthy instruments (the upgrade gauges, the cells CP2 to CP5, and the hydraulic network), it works with changes over defined windows rather than absolute values, and it aims to characterise and bound the THM response rather than to quantify coupling coefficients that the data cannot support.

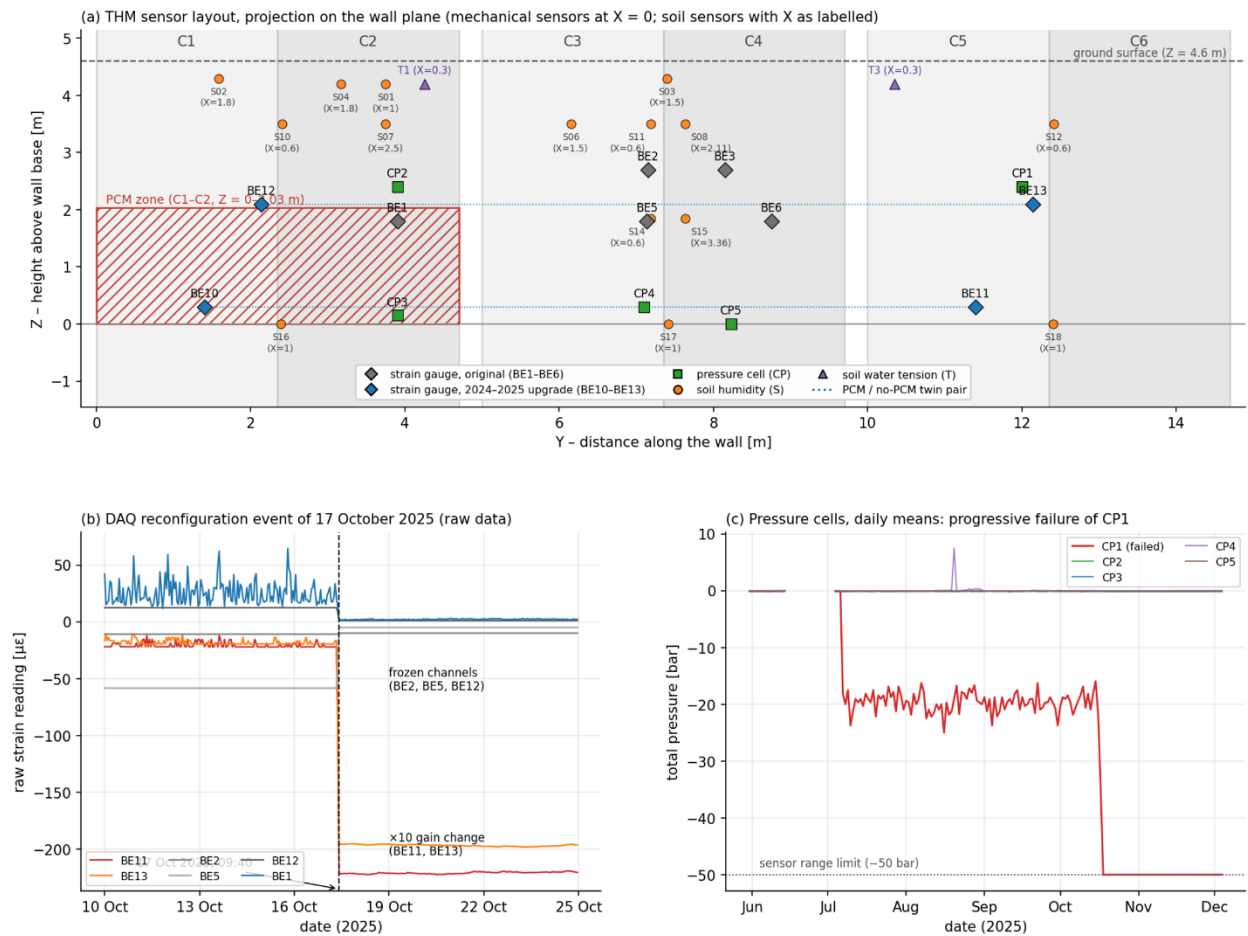


Figure 49: THM instrumentation and data quality. (a) Sensor layout projected on the wall plane, with strain gauges (BE), pressure cells (CP), soil humidity sensors (S), and soil water tension sensors (T); mechanical sensors are installed on the wall ($X = 0$), while the soil sensors are placed in the ground at the horizontal distances X labelled next to each marker, and the hatched area marks the PCM zone (circuits C1–C2, $Z = 0$ –2.03 m). (b) DAQ reconfiguration event of 17 October 2025 (raw strain readings), showing the channels that froze (BE2, BE5, BE6, BE12) and those affected by a $\times 10$ gain change (BE11, BE13). (c) Daily-mean total pressure, showing the progressive failure of cell CP1, which drifts to its -50 bar range limit, while cells CP2 to CP5 remain near zero.

4.5.2 Hydro-thermal response

The soil moisture field is organised primarily by depth and season, not by wall operation. Figure 50a shows the volumetric water content at four representative depths. The near-surface and upper sensors ($Z = 4.2$ m and $Z = 3.5$ m) are dynamic, tracking the seasonal moisture cycle

with variations of several percentage points, whereas the mid-height and base sensors are nearly constant: over the entire six-month campaign the two $Z = 1.85$ m sensors varied by only 0.18% and 0.25%, and the base sensors ($Z = 0$ m) by 0.8% to 1.9% (the exception, S16, is discussed below). The soil at and below mid-height is therefore hydraulically stable throughout, which is consistent with the depth being decoupled from surface infiltration and evaporation.

Critically, no moisture response to wall operation is detectable at depth. Aggregating the five sensors at $Z \leq 1.85$ m over each test window, the mean absolute change in water content was 0.03% during Cooling Test 1, 0.01% during Cooling Test 2, 0.17% during Heating Test 1, and 0.05% during Heating Test 2, with a single-sensor maximum of 0.48% during the 36-day Heating Test 1. These changes are at the level of sensor noise and an order of magnitude smaller than the seasonal variations seen near the surface. The near-surface sensors do change appreciably during the tests (for example, S01 dried by 5.8% across Heating Test 1), but this reflects the seasonal autumn transition rather than an operational signal, as it is present at the surface and absent at depth. In short, the thermal loads applied in these tests did not measurably redistribute soil moisture.

The soil water tension record in Figure 50b confirms the seasonal reading and adds temporal detail. Both tensiometers describe a coherent annual cycle: progressive summer drying (T1 rising from about 47 cBar in early June to 58 cBar by mid-July, T3 peaking near 60 cBar in late August), an abrupt rewetting in early September (T3 collapsing to essentially 0 cBar), and a gradual autumn re-drying back toward 40 to 48 cBar by late November. The September rewetting is the single largest hydraulic event of the campaign, yet it cannot be attributed to a measured cause: the meteorological rain gauge is inoperative (Section 4.5.1), so precipitation cannot be quantified, and the event is seasonal in character and unrelated to any test window.

Two localised features are noted for completeness but not interpreted further. First, sensor S16 (base, Field 1) shows a larger range (4.2%) than the other base sensors, and the shallow Field 1 sensors (S02, S04) display a sustained summer wetting trend, with S02 rising from about 12% to 27% between May and October, that no other field exhibits. Second, a sharp localised wetting occurred in Field 1 on the evening of 24 July, with S02 rising by 7.7% and S10 by 4.7% within about one hour while all other sensors moved by less than 0.1%. Both features are confined to Field 1 and near the surface; their origin is undocumented and, in the absence of precipitation and irrigation records, they are reported as localised infiltration of unconfirmed source rather than assigned a mechanism.

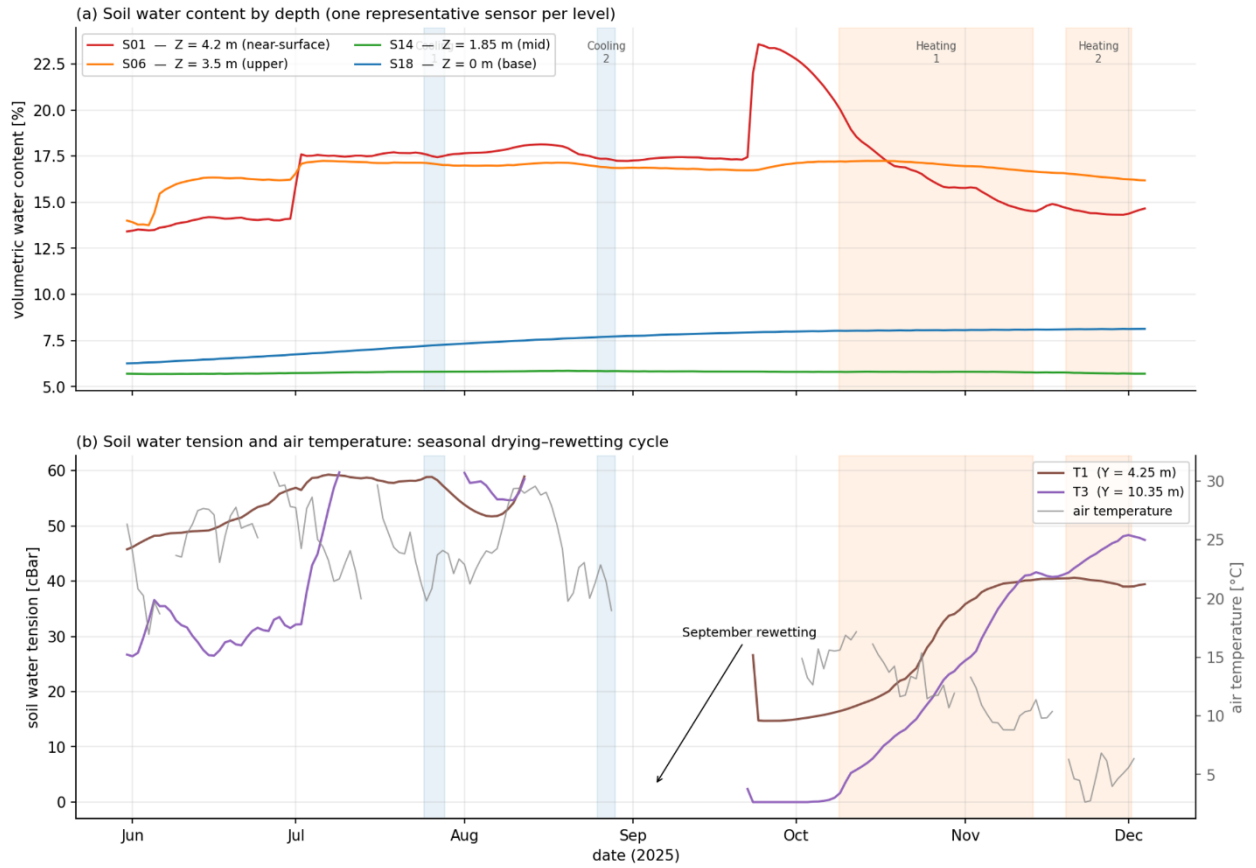


Figure 50: Hydro-thermal observations. (a) Volumetric water content at four representative depths (daily means), with test windows shaded (blue for cooling, orange for heating); the mid-height and base sensors are nearly flat while the near-surface sensors follow the seasonal moisture cycle. (b) Soil water tension recorded by the two tensiometers (T1 and T3), showing progressive summer drying, an abrupt rewetting in early September, and a gradual autumn re-drying.

4.5.3 Mechanical response and coupling effects

The mechanical analysis is confined to the reliable core defined in Section 4.5.1, namely the four upgrade strain gauges and, for the pressure cells, CP2 to CP5. The seasonal behaviour of the healthy gauges is shown in Figure 51a. The dominant signal is a slow, seasonal thermal strain: BE10, the best-conditioned gauge, extended by about $+28 \mu\epsilon$ between early June and early September as the wall warmed, and the other upgrade gauges followed the same sign with smaller amplitudes (BE13 by $+7.5 \mu\epsilon$, BE11 by $+2.3 \mu\epsilon$). These magnitudes, of order tens of microstrain over the season, set the scale of the wall's mechanical response and confirm that the upgrade gauges resolve it well above their noise floor.

The thermo-mechanical coupling can be quantified for BE10. Regressing its daily strain against the nearest near-wall soil temperature over the warming phase (June to mid-October, before the acquisition event) gives a slope of $4.8 \mu\epsilon/^\circ\text{C}$ with a correlation of $r = 0.64$ (Figure 51c). This apparent thermal-expansion coefficient is roughly half the free thermal strain of the concrete (of the order of $10 \mu\epsilon/^\circ\text{C}$), which is the expected signature of a wall that is partially restrained by its foundation and the retained soil: it can expand and contract with temperature, but not freely. The relationship is specific to the warming phase; over the full campaign the correlation breaks down ($r = -0.13$), because in autumn the near-surface soil temperature and

the deeper wall strain decouple, so the coefficient is reported as a warming-phase value rather than a campaign-wide constant.

The clearest operational signal in the entire mechanical dataset is the response of BE10 to Cooling Test 1 (Figure 51b). Over the test the gauge extended by $+7.7\ \mu\epsilon$, with a gradual onset in the hours following activation and a partial reversal after shutdown (returning to within about $4\ \mu\epsilon$ of its pre-test value by 2 August). This is the behaviour expected of a restrained wall receiving warm rejected water: gentle thermal expansion during operation, relaxation afterward. Its Field 5 twin BE11, active in the same series test but outside the PCM zone, moved by only $+1.1\ \mu\epsilon$. It is tempting to read the difference as a PCM effect, but it cannot be attributed as such: the localised Field 1 wetting of 24 July (Section 4.5.2) coincided with this test, so a moisture-driven contribution to the BE10 response cannot be separated from the thermal one. The twin difference is real but its cause is not identifiable from these data.

For the remaining tests, the operational strain response could not be measured, and the reason is instrumental rather than physical. In both heating tests the only active circuits (2, 4, and 6) contained no healthy gauge: the upgrade gauges all sit in the inactive Circuits 1 and 5, where they registered changes of at most $2.4\ \mu\epsilon$ despite paired near-wall cooling of up to $6.7\ ^\circ\text{C}$, while the one gauge in a continuously active circuit, BE1 in Circuit 2, is among the unreliable originals and additionally straddles the 17 October acquisition event. No quantitative statement about the heating-mode mechanical response is therefore supportable.

The earth-pressure record is a clean null result. Across all four tests the healthy cells CP2 to CP5 changed by at most 0.09 bar, at or below their resolution and well under the geostatic stresses of order 0.2 to 0.4 bar expected at their positions (the failed cell CP1 is excluded, Section 4.5.1). No operational change in total earth pressure on the wall is detectable.

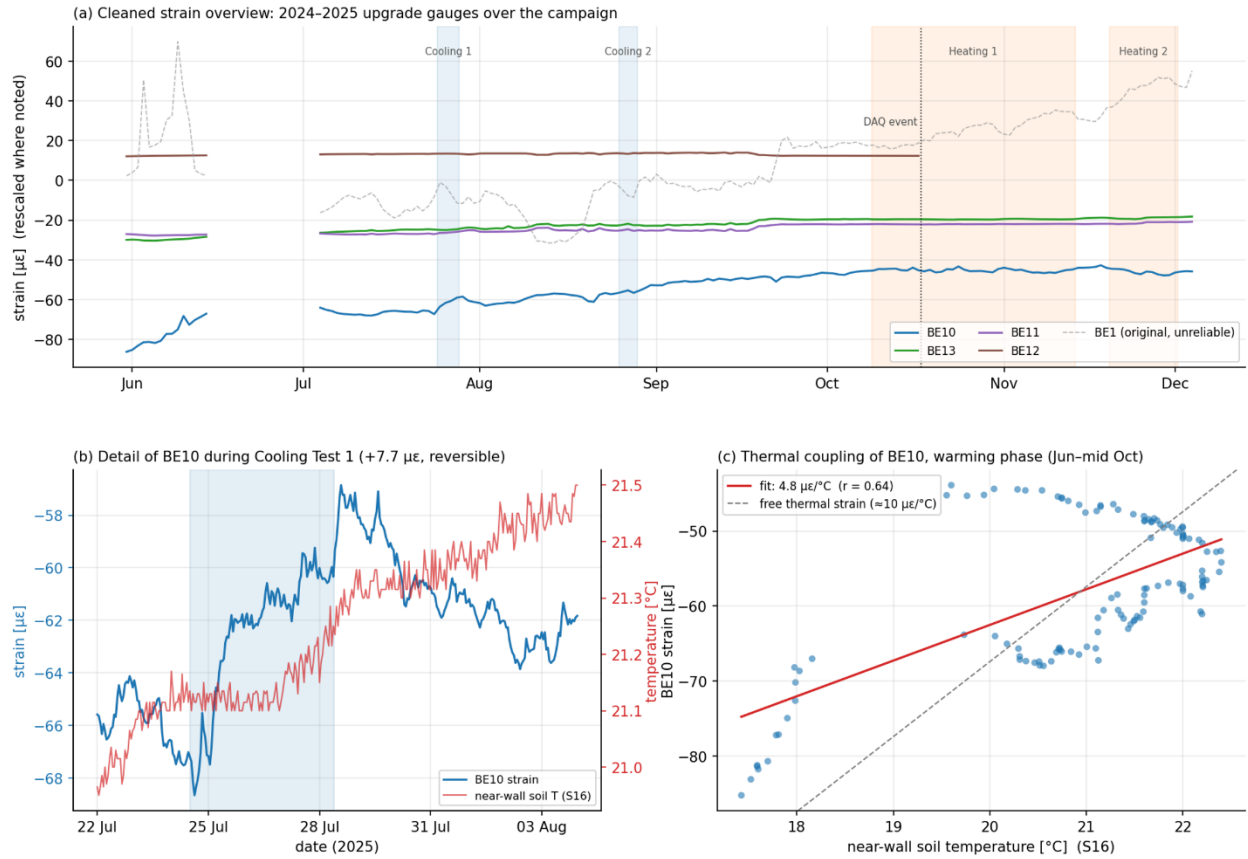


Figure 51: Mechanical observations. (a) Daily mean strain of the four 2024–2025 upgrade gauges over the campaign, with test windows shaded and the 17 October acquisition event marked; BE1 is shown dashed for reference as an unreliable original gauge. (b) Detail of BE10 during Cooling Test 1, showing the reversible $+7.7 \mu\epsilon$ extension (left axis) against the near-wall soil temperature (right axis). (c) BE10 strain against near-wall soil temperature over the warming phase, giving an apparent thermal coefficient of $4.8 \mu\epsilon/^\circ\text{C}$, about half the unrestrained value of roughly $10 \mu\epsilon/^\circ\text{C}$ shown for comparison

4.5.4 Summary of THM observations

The thermo-hydro-mechanical instrumentation of the prototype was examined to determine whether the thermal operation of the wall produces measurable hydraulic and mechanical effects, and to bound those effects where they could not be resolved. Three conclusions emerge, consistent in character with the seasonal-dominance theme of the preceding sections.

First, the hydraulic response to operation is below detection. Soil moisture is organised by depth and season rather than by the tests: it is dynamic near the surface and effectively constant at and below mid-height, where the sensors varied by less than 0.3% over six months, and the mean change at depth during any test did not exceed sensor noise. The tensiometers trace a clear summer-drying to autumn-rewetting cycle, dominated by an unquantified September rewetting, that is unrelated to any test window. At the power levels tested, the wall does not measurably redistribute soil water.

Second, the mechanical response is small, and dominated by seasonal thermal strain. The best-conditioned gauge, BE10, extended by about $28 \mu\epsilon$ over the warming season and yielded an apparent thermal coefficient of $4.8 \mu\epsilon/^\circ\text{C}$, roughly half the free thermal strain of the concrete, which is the expected signature of a partially restrained wall. The single clear operational signal was a reversible $+7.7 \mu\epsilon$ extension of the same gauge during Cooling Test 1, consistent with

thermal expansion under warm-water injection but confounded by a coincident wetting event and therefore not attributable to the PCM. Earth-pressure changes stayed below 0.1 bar throughout, a clean null result.

Third, and most important for the interpretation of this section, the measurement was limited by instrumentation rather than by the physics of the wall. A data-acquisition event on 17 October 2025 truncated or rescaled most strain channels, one pressure cell failed progressively, the original strain gauges proved unreliable, and the healthy upgrade gauges were located in circuits that were inactive during both heating tests. As a consequence the heating-mode mechanical response could not be quantified at all, and the mechanical conclusions rest on the cooling tests and the seasonal signal.

4.6 System-level performance indicators

The analysis so far has described the thermal behaviour of the wall and the surrounding soil in detail, from the penetration and vertical structure of the temperature field to the lateral interaction and recovery of the ground. These descriptions, however, are based almost entirely on the soil-side measurements. This section complements them with the fluid side of the system, quantifying the thermal energy and power that the wall actually exchanged with the ground during each test, and then relating these system-level indicators back to the soil response established earlier. The performance quantities are obtained from the ground-side energy metering of the installation, with the exchanged power defined as the exchanged energy divided by the effective operating time, that is the time during which the heat pump was actually running, and normalised by the activated wall area, taken as 11.5 m² for each active circuit, so that tests activating different numbers of circuits can be compared on a common basis. The section is organised in two parts: Section 4.6.1 presents the energy, the operating regime, and the normalised performance of each test and each circuit, while Section 4.6.2 brings the fluid-side performance together with the soil-side response of the preceding sections into a combined interpretation.

4.6.1 Energy, operating regime, and normalised performance

The performance indicators for the four tests are summarised in Table 7. The tests differ greatly in duration, from about four days for the cooling tests to more than five weeks for Heating Test 1, and in operating regime, so that the raw exchanged energy is not, on its own, a meaningful basis for comparison. Heating Test 1 exchanged 801.2 kWh, roughly an order of magnitude more than any other test, but this is almost entirely a consequence of its length and of its near-continuous operation, rather than of any superior exchange capability: it ran for 855.75 active hours at an active cycle of 99.86%, whereas Heating Test 2, for example, ran for only 101.8 active hours at an active cycle of 35.31%. For this reason the analysis focuses on power, and in particular on power per unit of activated wall area, as the fair performance indicator.

Table 7: System-level performance indicators for the four tests

Test code	Cooling test 1	Cooling test 2	Heating test 1	Heating test 2
Total Test Duration [h]	93.52	78.88	856.93	288.28
Total Active Time [h]	67.96	50.4	855.75	101.8
Active Cycle [%]	72.67	63.89	99.86	35.31
Average ΔT	1.4	0.9	2.28	0.5
Total Exchanged Energy [kWh]	68.83	49.9	801.2	44.6
Energy/Circuit [kWh]	17.2075	24.95	267.07	22.3
Total Exchanged Power [kW]	1.01	0.99	0.94	0.44
Average exchanged power per active wall area [W/m ²]	22.02	43.05	27.14	19.05

Figure 52 shows, for each test, the power per active wall area as bars and the total exchanged power as a line, with the average fluid temperature difference and the active cycle annotated. Two points emerge. First, the total power and the normalised power rank the tests differently. Cooling Test 1 has the highest total power, at 1.01 kW, yet the lowest normalised power among the cooling and heating tests that exchanged heat effectively, at 22.02 W/m². This is a direct consequence of its hydraulic configuration: its four circuits were connected in series, so that a single fluid stream passed through them in sequence and gave up its heat progressively, spread over the full 46 m² of four activated circuits, rather than each circuit receiving fresh fluid as in the parallel tests. The series configuration therefore produces a large total exchange but a low intensity per unit area. Second, among the parallel tests, the normalised power is governed largely by the fluid temperature difference. Cooling Test 2, with an average ΔT of 0.9 °C over two parallel circuits, reaches 43.05 W/m², the highest of all the tests, whereas Heating Test 2, with an average ΔT of only 0.5 °C, falls to 19.05 W/m², the lowest. Since the exchanged power is proportional to the temperature difference between the fluid and the returning flow, the small ΔT of Heating Test 2, combined with its low active cycle of 35.31%, accounts directly for its modest performance. Heating Test 1, at 27.14 W/m² for the whole test, lies between these, reflecting its higher ΔT of 2.28 °C but also the mid-test activation of a third circuit, which increased the activated area from 23 m² to 34.5 m² partway through and so lowered the whole-test average intensity.

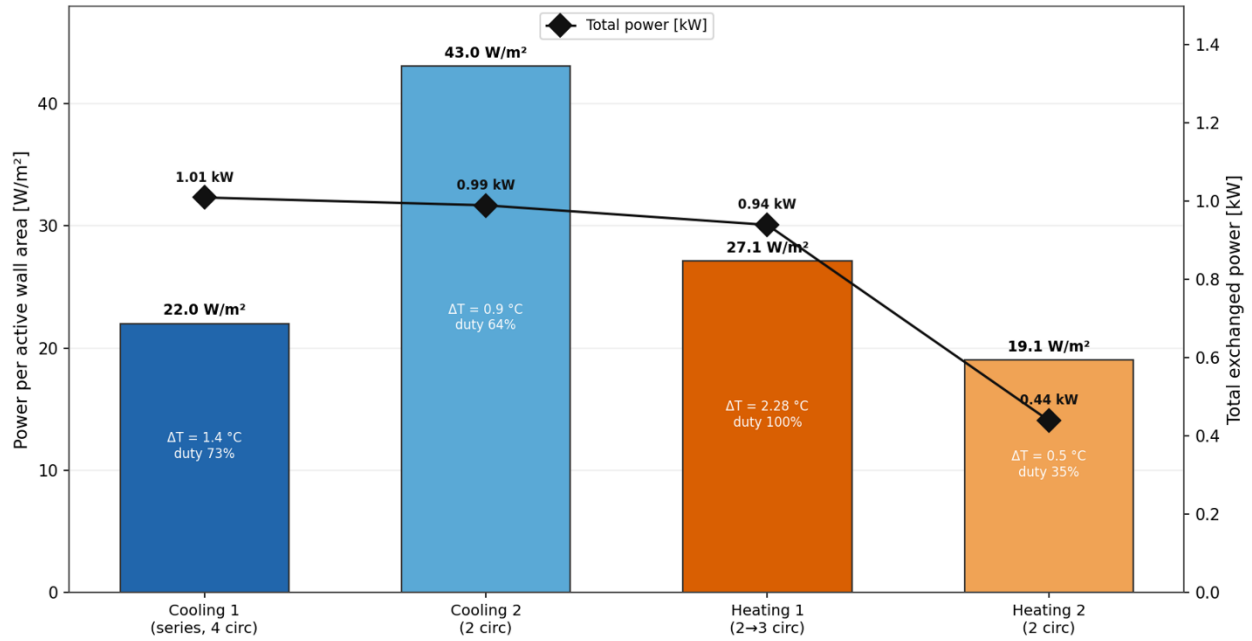


Figure 52: Normalised and total power for the four tests. The bars show the mean power per active wall area, the line shows the total exchanged power, and the average fluid temperature difference and active cycle are annotated on each test

The performance can also be resolved by individual circuit, for the parallel tests in which the circuits could be metered separately; the series configuration of Cooling Test 1 does not allow this, because its circuits shared a single fluid stream (i.e. series hydraulic connection) and cannot be distinguished.

Table 8: Individual circuit performances during each test

Test code	Cooling test 2		Heating test 1			Heating test 2	
By Circuit	Circuit 2	Circuit 6	Circuit 2	Circuit 6	Circuit 4	Circuit 2	Circuit 4
Total Test Duration [h]	78.88	78.88	856.93	856.93	332.08	288.28	288.28
Total Active Time [h]	48.7	57.2	855.8	855.65	332.08	101.75	102.1
Active Cycle [%]	61.74	72.52	99.87	99.85	100.00	35.30	35.42
Average ΔT	0.7	1.5	2.05	3.49	2	0.4	0.48
Total Exchanged Energy [kWh]	20	49.6	332.8	390.7	125	22.2	24
Total Exchanged Power [kW]	0.41	0.87	0.39	0.46	0.38	0.22	0.24
Average exchanged power per active wall area [W/m²]	35.71	75.40	33.82	39.71	32.73	18.97	20.44

Table 8 and Figure 53 shows the power per active wall area for each circuit. The most striking value is that of Circuit 6 during Cooling Test 2, which reached 75.4 W/m², nearly double that of any other circuit in any test, driven by its comparatively high average ΔT of 1.5 °C. More generally, a consistent pattern appears in the comparison of Circuit 2, which is backed by the phase-change material, with Circuit 6, which is not: in both tests where the two operated together, Circuit 6 exchanged more power per unit area than Circuit 2, by 75.4 against 35.7 W/m² in Cooling Test 2, and by 39.7 against 33.8 W/m² in Heating Test 1. Circuit 4, which is

the only vertically-aligned circuit and is not backed by phase-change material, showed the lowest normalised performance in both tests in which it operated, at 32.7 W/m² in Heating Test 1 and 20.4 W/m² in Heating Test 2. Its lower values should, however, be interpreted with caution, since Circuit 4 differs from the others in three respects at once, namely its later activation, its vertical alignment, and the absence of phase-change material, so that its behaviour cannot be attributed to any single one of these. The comparison between cooling and heating circuits should likewise be read within each mode rather than across the two, since heat rejection and heat extraction are different processes; the meaningful comparisons here are those between circuits operating in the same test.

The small discrepancy between the total exchanged energy and the sum of the circuit-level values is mainly attributed to the different measurement locations and interpretation procedures. The total value is derived from the main ground-circuit headers, whereas the circuit-level values are evaluated at the individual circuit headers and are used primarily for comparative performance assessment. In addition, the circuit-level results are normalised with respect to active area and effective compressor operating time, so they should not be interpreted as directly additive over the full test duration.

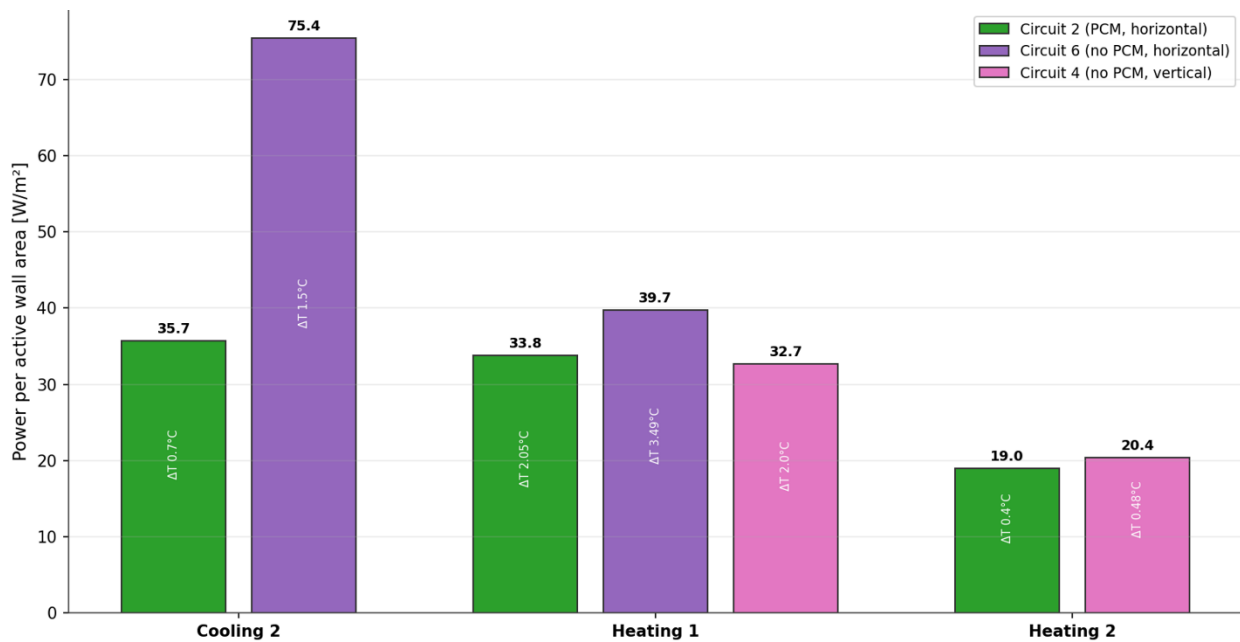


Figure 53: Power per active wall area resolved by individual circuits

4.6.2 Relation between system performance and soil response

The preceding subsection quantified the performance of the system from the fluid side, using the energy metered at the ground circuits. That measurement is entirely independent of the soil-temperature measurements analysed in Sections 4.2 to 4.4, which were obtained from the buried PT100 sensors. Bringing the two together provides both a physical consistency check, since energy extracted from the ground must appear as a cooling of the soil, and a deeper interpretation of the results of the whole chapter. This subsection therefore relates the per-circuit exchanged energy to the per-circuit soil response, examines the dynamics of the coupling in time, and then uses the combined picture to revisit the main findings of the chapter.

The central result is shown in Figure 54 and Figure 55. The energy exchanged by each circuit and the cooling of the soil in front of it, the latter taken as the far-field-corrected temperature change of Section 4.2.3, are strongly and positively related. In Heating Test 1, the three active circuits rank identically on the two independent measurements: Circuit 6 exchanged the most energy, 390.7 kWh, and produced the largest soil cooling, $-3.3\text{ }^{\circ}\text{C}$; Circuit 2 follows, with 332.8 kWh and $-2.5\text{ }^{\circ}\text{C}$; and Circuit 4 is lowest, with 125 kWh and $-1.4\text{ }^{\circ}\text{C}$. The correlation between exchanged energy and soil-cooling magnitude is very high, with a coefficient of about 0.98 for Heating Test 1 and 0.92 across all the metered circuits. This agreement between the fluid-side energy metering and the soil-side PT100 sensors, two entirely separate measurement systems, is a strong internal validation of both: the heat that the meters record leaving the ground is the same heat whose absence the PT100 sensors record as cooling. The dependence on the fluid temperature difference is equally consistent, and is reported in the Appendix Figure 60, where the per-circuit soil cooling is shown to follow the fluid ΔT with a correlation of about 0.89.

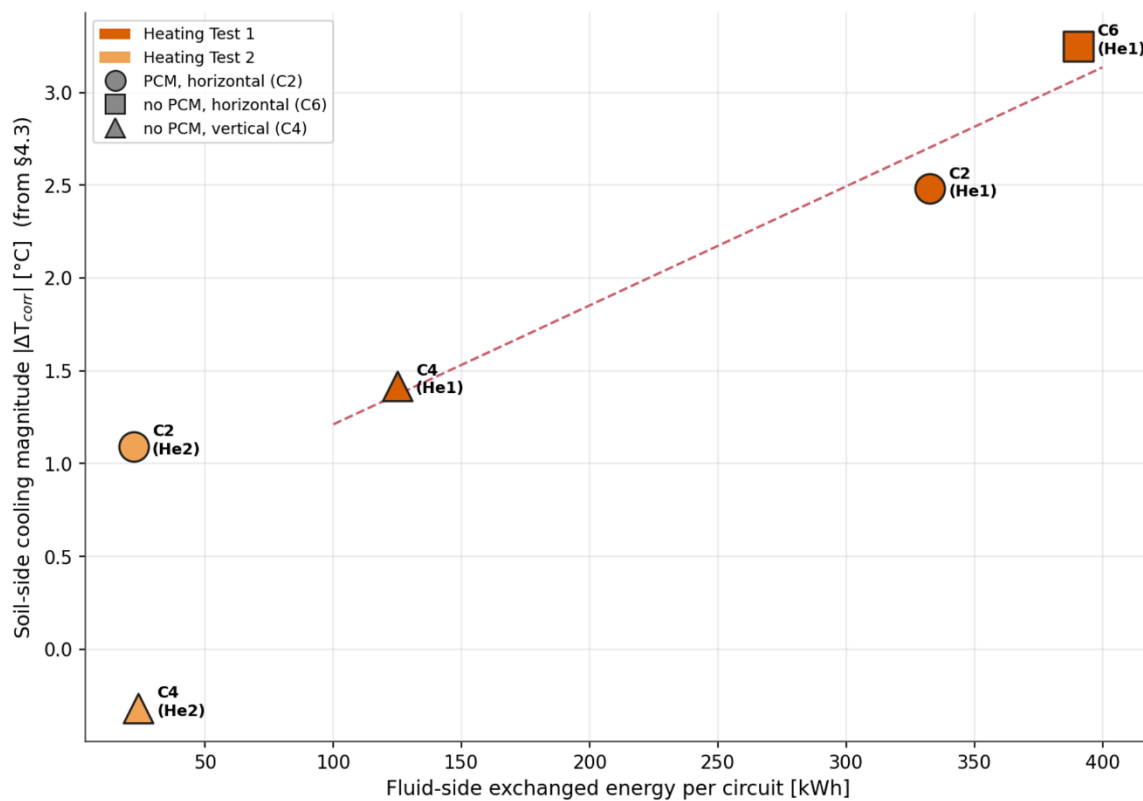


Figure 54: Relation between the fluid-side exchanged energy and the soil-side thermal response, per circuit

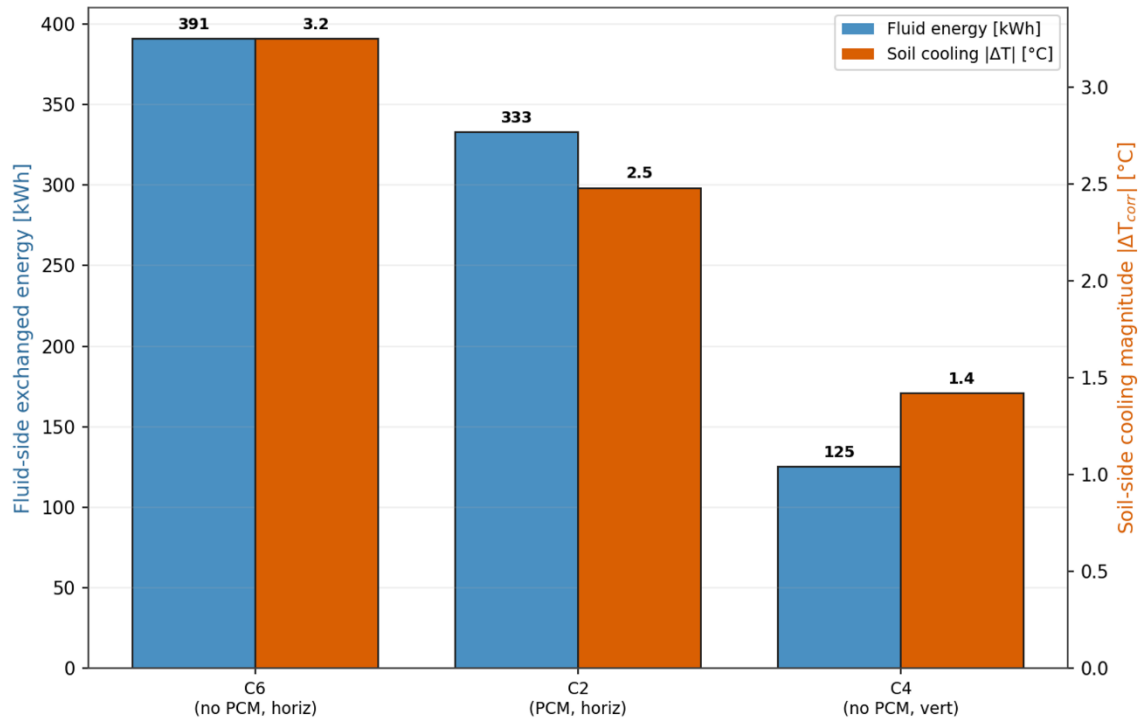


Figure 55: Matched fluid-side and soil-side rankings of the circuits for Heating Test 1. The left bars show the exchanged energy of each circuit, and the right bars show the magnitude of the corresponding soil cooling from Section 4.2.3

The coupling can also be followed in time. Figure 56 shows, for Circuit 2 over Heating Test 1, the evolution of the fluid thermal power and temperature difference together with the near-wall soil temperature. As heat extraction proceeds, the near-wall soil cools steadily, falling from about 18.7 °C at the start of the test to about 9.0 °C at the end, and so approaches the temperature of the cold fluid supplied to the circuit, the difference between them narrowing from about 12.5 °C to about 7.8 °C. Over the same period the far-field soil temperature is almost unchanged, confirming that the effect is local to the wall. The fluid power falls gradually as the test progresses, from roughly 420 W to 290 W, which is consistent with this narrowing temperature difference: as the near-wall soil cools towards the fluid, the gradient available to drive heat exchange diminishes and the exchanged power declines. Part of the change coincides with the activation of Circuit 4 on 30 October, which redistributed flow between the circuits, so the decline should be read as consistent with progressive soil depletion rather than as an isolated proof of it; nonetheless, the joint behaviour of the falling power and the cooling near-wall soil gives a clear picture of the coupled exchange between the circuit and the ground.

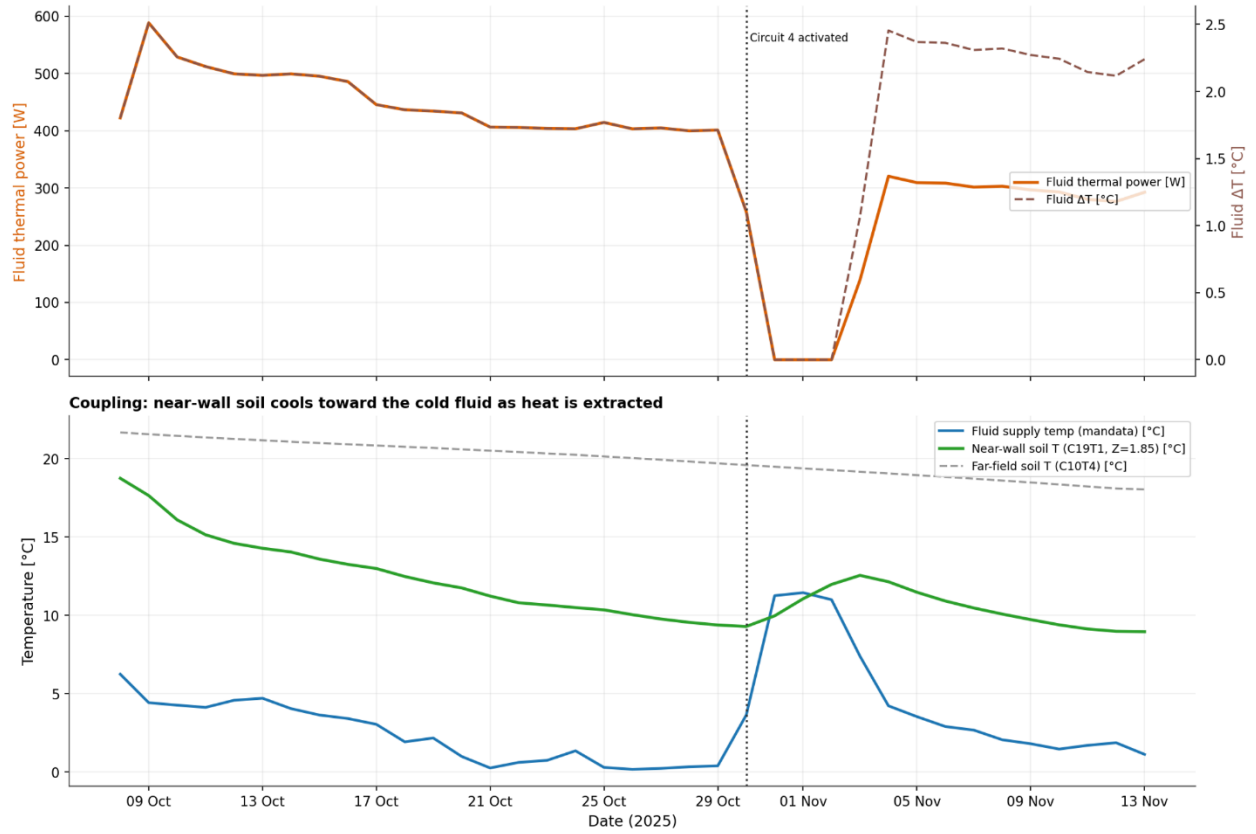


Figure 56: Time evolution of the coupling between the circuit and the ground, for Circuit 2 during Heating Test 1. The upper panel shows the fluid thermal power and the fluid temperature difference, and the lower panel shows the near-wall soil temperature together

The combined picture also sharpens several of the interpretations reached earlier. The comparison of the phase-change-backed Circuit 2 with the non-PCM Circuit 6 is the clearest example. On both the fluid and the soil side, Circuit 6 exceeded Circuit 2: it exchanged more energy and it cooled its surrounding soil more. This is consistent with the discussion of Section 4.3, where the phase-change material was expected to buffer the thermal response of Circuit 2. A buffered circuit should both moderate the soil-temperature swing, as suggested there, and, because the buffering limits the temperature difference available to drive exchange, be associated with a somewhat lower energy throughput, as seen here. The data are therefore compatible, on both sides of the system, with the buffering role of the phase-change material, although, as in Section 4.3, the comparison is confounded by the different positions of the circuits and cannot on its own prove the effect.

The behaviour of Circuit 4 illustrates the value of combining the two views while also showing the limits of interpretation. Circuit 4 was lowest on both measures, but it differs from the other circuits in three respects simultaneously: it was activated later, roughly midway through Heating Test 1; it is the only vertically-aligned circuit; and it is not backed by phase-change material. Its lower energy and smaller soil response cannot be attributed to any single one of these, and the consistency of the fluid and soil measurements does not resolve the ambiguity, since both are affected by the same three factors. What the combined view does confirm is that the reduced energy throughput and the reduced soil cooling are two expressions of the same underlying behaviour, rather than independent effects.

The penetration analysis of Section 4.2.4 showed that the thermal disturbance is confined to the soil within roughly one to two metres of the wall, and the vertical and three-dimensional analyses of Sections 4.2.5 and 4.4 showed that it is concentrated near the wall and structured with depth. Relating the metered energy to this disturbed volume, as reported in the Appendix (Figure 61), gives an energy density of the order of 20 kWh/m³ for the more active heating circuits, confirming that the several hundred kilowatt-hours exchanged per circuit over the long heating test are deposited into a relatively thin and well-defined volume of soil close to the wall, which is why the near-wall temperature changes are large while the far-field remains almost unaffected. The fluid-side energy and the soil-side temperature field are thus two consistent descriptions of the same localised exchange.

Finally, the combined view resolves the apparent weakness of the cooling response noted in Section 4.2.3. The cooling tests did exchange real energy with the ground, 44.9 kWh in Cooling Test 2 for example, yet the soil in front of the circuits barely registered a warming at the circuit scale. This is not a contradiction: the cooling tests were short, less than four days, so that the exchanged energy, though real, was delivered over a brief period and, being distributed through the near-wall soil against a background of comparable seasonal change, produced only a small and hard-to-detect temperature signature. The recovery of the soil during the inactive periods between tests, examined in Section 4.2.6, is consistent with the same energy view: the short inter-test windows allowed only a small fraction of the extracted heat to be restored to the near-wall soil, which is why the recovery was found to be incomplete. The fluid side confirms that heat was genuinely exchanged; the soil side shows how, and over what time, that heat accumulated or dissipated.

5 Conclusions

This thesis set out to analyse the experimental monitoring data from the Geothermskin energy wall at the Politecnico di Torino Energy Center, across four operating tests carried out in 2025, and to establish, from the measurements alone, how such a wall exchanges heat with the ground and how the surrounding soil responds. The prototype is a full-scale installation rather than a controlled laboratory system. As a result, the analysis had to account for several site-related factors: seasonal ground temperature variation, instrumentation of uneven quality, tests with different durations and configuration, and boundary conditions specific to the site. Much of the interpretation therefore involved distinguishing the thermal response of the wall from concurrent changes in the surrounding ground. This closing chapter draws the findings together, discusses what data could and could not demonstrate, and summarises what the prototype indicates about the performance of the wall as an energy geostructure.

The main methodological conclusion is that the seasonal evolution of the ground affects the raw measurements, and that soil-temperature data cannot be interpreted reliably unless this background is removed. Over the long autumn heating test the undisturbed far-field soil cooled by nearly 4 °C independently of wall operation. This change was larger than the operational effect of the wall in several locations, making the raw temperature changes misleading in magnitude and, for the cooling tests, in some cases even in sign. The far-field correction adopted throughout the analysis, in which the change of an undisturbed reference is subtracted over the same period, was therefore necessary for interpretation rather than a simple refinement. This issue appears throughout the results and explains why some initially weak or unexpected responses, particularly during cooling, turned out on closer inspection to be consistent and explicable rather than contradictory.

Against this background, the thermal response of the wall emerged clearly and consistently. During heating, when the circuits extracted heat from the ground, the soil in front of the wall cooled measurably, by two to three degrees at the circuit scale after correction and more immediately at the wall face. During cooling, when the circuits rejected heat into the ground, the response was weak and, at the circuit scale, barely distinguishable from the seasonal background, a consequence of the short duration of the cooling tests rather than of any absence of exchange. This asymmetry between the strong, well-resolved heating response and the faint cooling response is one of the defining features of the campaign, and it reflects the tests themselves, the heating tests being far longer and more nearly continuous, as much as any property of the wall.

Where the wall has a measurable effect, its influence is strongly localised. The thermal disturbance is concentrated in the soil within roughly 1 to 2 m of the wall face and decreases with distance, so that the near-wall sensors register large changes while the far field remains almost undisturbed. In the vertical direction the response is structured rather than uniform: the base of the wall remains the most stable region, the central part exchanges heat most strongly, and the shallowest soil is controlled mainly by atmospheric conditions rather than by wall operation. The vertical temperature gradient reverses sign between heating and cooling, but this reversal is largely seasonal. The clearer operational signature is the growth of the gradient

over the course of a test, well developed only in the long heating tests. Along the wall, the circuits do not behave as isolated segments: the temperature field is laterally continuous, the soil at the boundary of a circuit responding almost as strongly as the soil directly in front of it, so that the influence of each circuit reaches its edges with only modest attenuation.

Two questions addressed by the prototype could not be answered conclusively. The buffering effect of the phase-change material, expected in front of the two circuits where it is installed, could not be demonstrated quantitatively. The material can provide buffering only when the surrounding soil lies within its narrow phase-change band, and for much of the testing the soil was outside it. Where a comparison was possible, the circuit backed by the material did show a smaller and more moderated response, but this was affected by differences in circuit position and operating history, and therefore cannot be treated as definitive evidence of the material's effect. The recovery of the soil between tests was similarly real but not fully characterised: the near-wall disturbance began to dissipate within days of a test ending, but the inactive windows were short. In addition, the near-wall measurement was affected by the open-top maintenance cavaedium behind the wall, whose air temperature remains close to the outdoor temperature and influences the nearest sensors toward it. The soil beyond approximately 1 m from the wall remained close to its undisturbed state throughout the tests, and therefore required limited recovery.

The thermo-hydro-mechanical analysis was constrained above all by the quality of the mechanical instrumentation. The pressure cells were largely unusable, and several of the strain gauges were unreliable, so that the mechanical interpretation had to rely on a reduced set of instruments. Within that subset, the deformation of the wall was found to follow the thermal cycles in a physically sensible way, contracting as the ground cooled and expanding as it warmed. However, as in the thermal analysis, part of this response is associated with seasonal variation. The data therefore support a qualitative interpretation of the thermo-mechanical behaviour. The hydraulic measurements from the humidity sensors added a consistent, although secondary, indication of the moisture response. The overall message of this part of the work is that the wall responds mechanically to its thermal operation in the expected sense, but that a rigorous quantification would require better mechanical instrumentation than was available.

The combined interpretation of the fluid-side and soil-side measurements represents one of the main outcomes of the study. The energy metered at the ground circuits and the temperature changes recorded by the buried PT100 sensors are entirely independent measurements, and they agree: the energy exchanged by each circuit tracks, almost exactly, the cooling it produces in the surrounding soil, with a correlation of about 0.98 in the long heating test and an identical ranking of the circuits on the two systems. This agreement validates both measurement chains at once, and it allows the whole chapter to be read as a single consistent account. The exchanged power was of the order of 1 kW, with specific rates of approximately 20–40 W/m² of activated wall area. The thermal response is concentrated within the near-wall soil volume identified by the penetration-depth analysis. Within this limited volume, the resulting energy density is of the order of 20 kWh/m³, which explains the relatively large temperature variations recorded close to the wall and the limited disturbance observed in the far field. The same interpretation accounts for the weaker response observed during the cooling tests: although measurable

energy was exchanged, the shorter duration of the tests and the superposition of a strong seasonal temperature trend limited the observable thermal signal. The lower performance of the vertically aligned circuit and of the phase-change-material-backed circuit is also consistently reflected in both the fluid-side energy data and the soil-side temperature measurements.

Taken as a whole, the work shows that the Geothermskin wall functions as intended as a heat exchanger with the ground. It exchanges heat measurably and predictably, with an intensity governed principally by the temperature difference of the circulating fluid and by the hydraulic configuration, concentrated in a well-defined near-wall region, structured with depth, and continuous along its length; and its fluid-side performance and soil-side response tell one coherent and mutually consistent story. The prototype's cooling performance is less clearly demonstrated than its heating performance, but this reflects the brevity of the cooling tests rather than a limitation of the wall. From an engineering perspective, the prototype demonstrates that an energy retaining wall of this kind can serve as an effective ground heat exchanger at the scale of tens of W/m^2 of activated area, and that its behaviour is well described by the measurements once the seasonal background is properly accounted for.

The principal limitations of the study point directly to the work that would extend it. The dominant influence of the seasonal signal suggests the need for longer-duration tests, particularly cooling tests of comparable duration to the heating tests, in order to characterise summer operation with similar reliability. The phase change material should be assessed through dedicated tests conducted under thermal conditions that maintain the adjacent soil within the relevant phase-change temperature range, allowing its buffering capacity to be evaluated directly. Also, the influence of external conditions (i.e. cavaedium temperature) on the near-wall sensors should be determined or removed, since it presently limits the interpretation of the recovery phase. These limitations do not alter the principal findings. The prototype demonstrates, through two independent and mutually consistent measurement systems, that this energy wall configuration exchanges heat with the ground in a measurable, localised, and predictable manner. The results also show that reliable interpretation of field-scale thermal data requires explicit treatment of the seasonal ground-temperature background.

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Appendix A - Supplementary results

This appendix contains supplementary figures that support the interpretation of the experimental results presented in Chapter 4. These figures are not essential to the main discussion but provide additional detail on cooling-test temperature evolution, fluid-side and soil-side response, and normalised energy indicators.

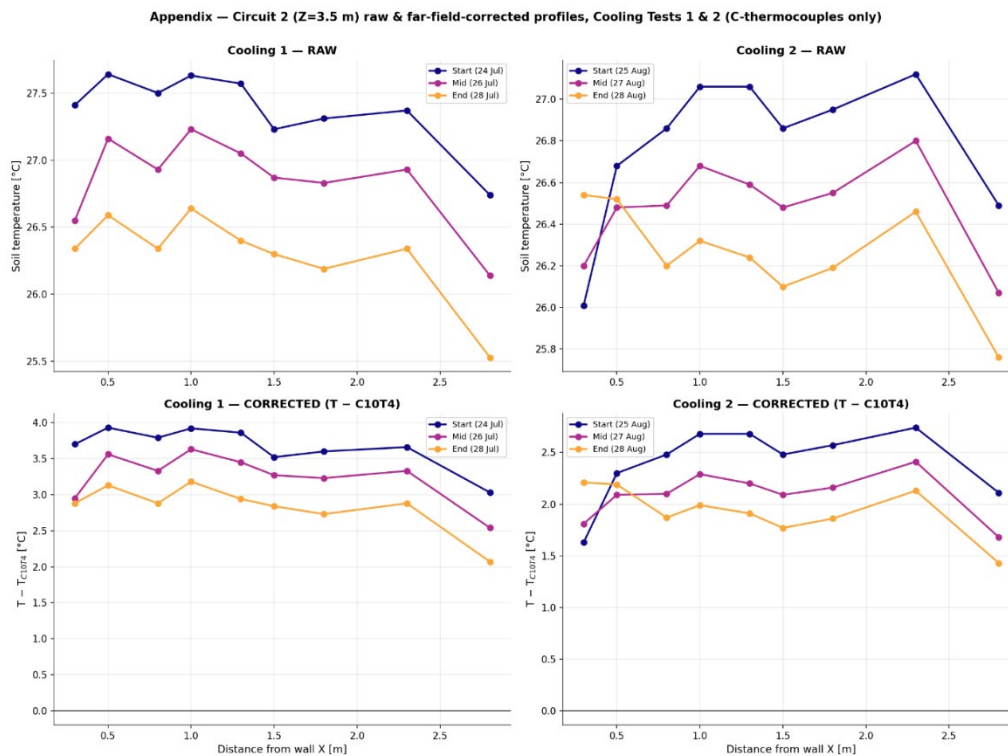


Figure 57: Soil temperature in front of Circuit 2 at the upper-wall level ($Z = 3.5$ m) during Cooling Tests 1 and 2

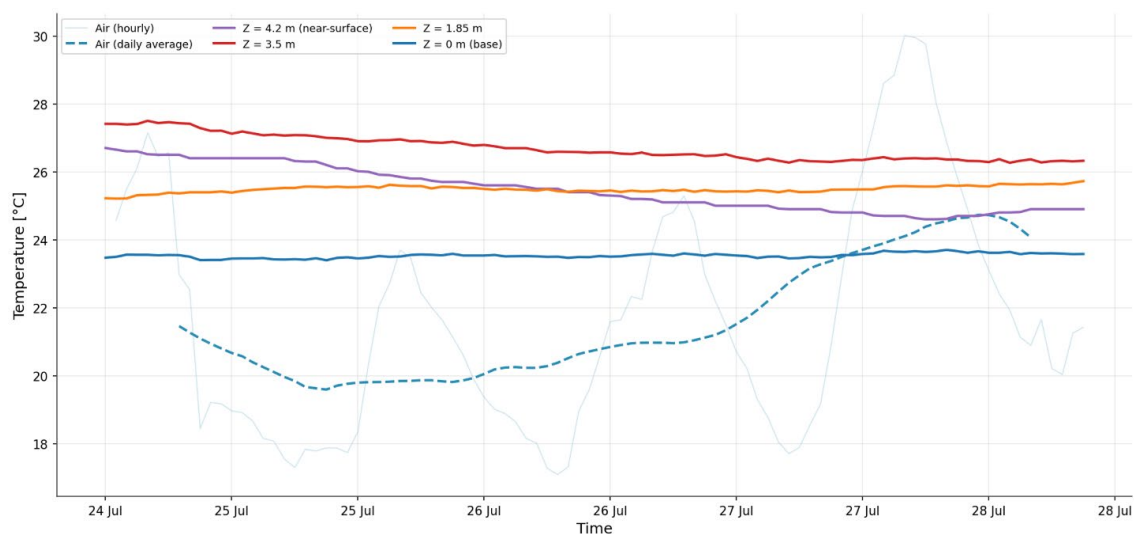


Figure 58: Time evolution of the soil temperature at four heights ($Z = 0, 1.85, 3.5,$ and 4.2 m) in front of Circuit 2, at $X = 0.3$ m, during Cooling Test 1

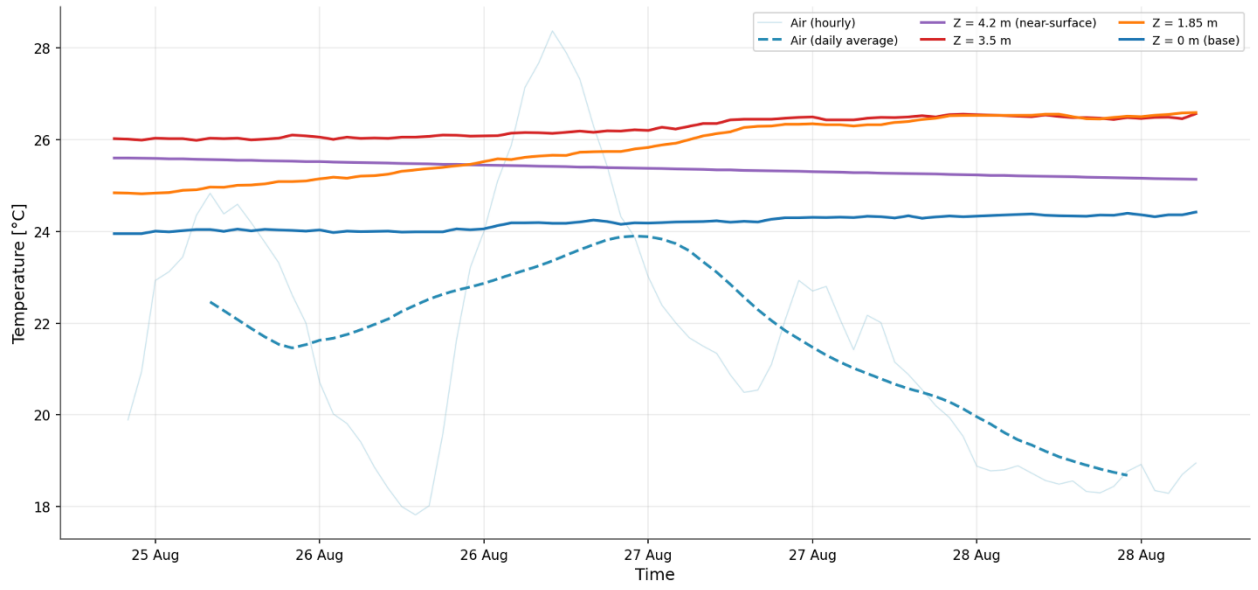


Figure 59: Time evolution of the soil temperature at four heights ($Z = 0, 1.85, 3.5$, and 4.2 m) in front of Circuit 2, at $X = 0.3$ m, during Cooling Test 2

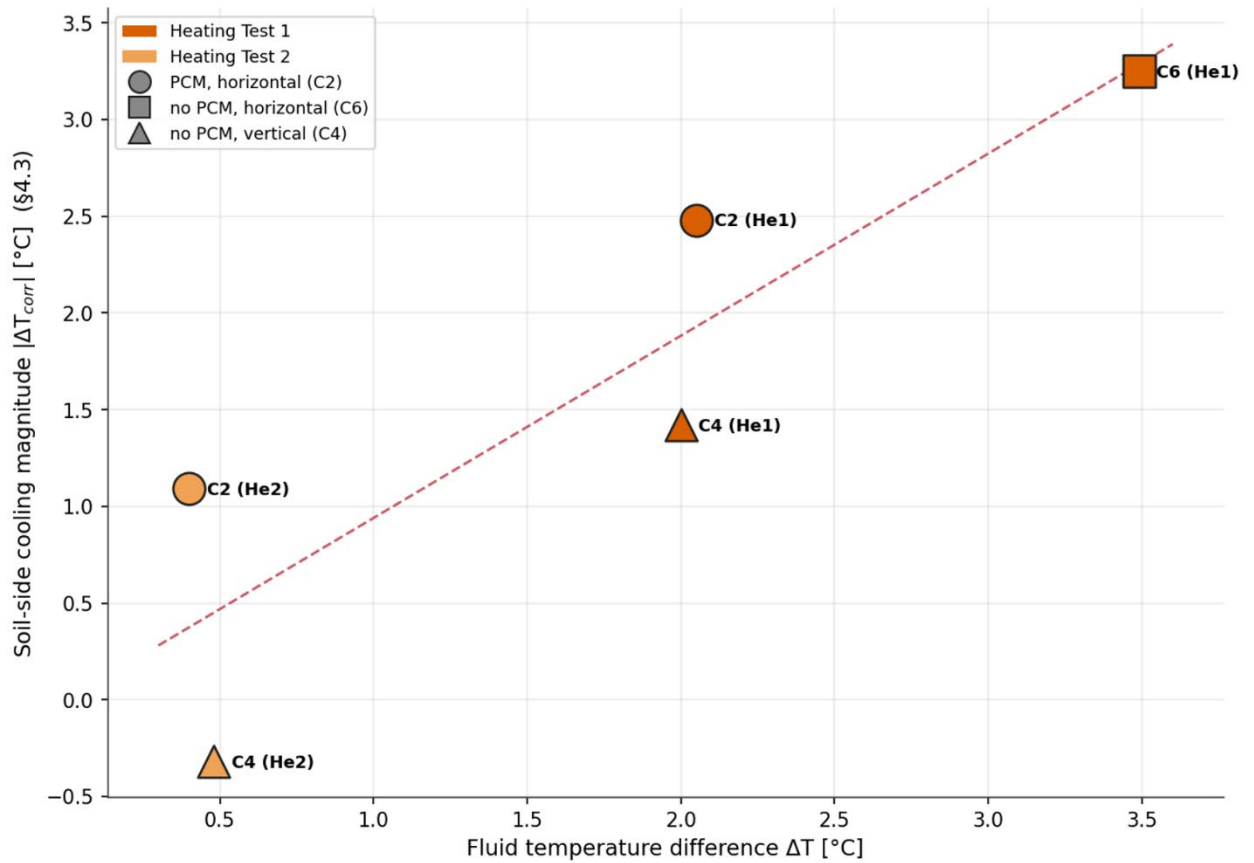


Figure 60: Relation between the fluid temperature difference and the soil-side thermal response, per circuit, for the heating tests. The magnitude of the far-field-corrected soil cooling follows the fluid temperature difference, with a correlation of about 0.89

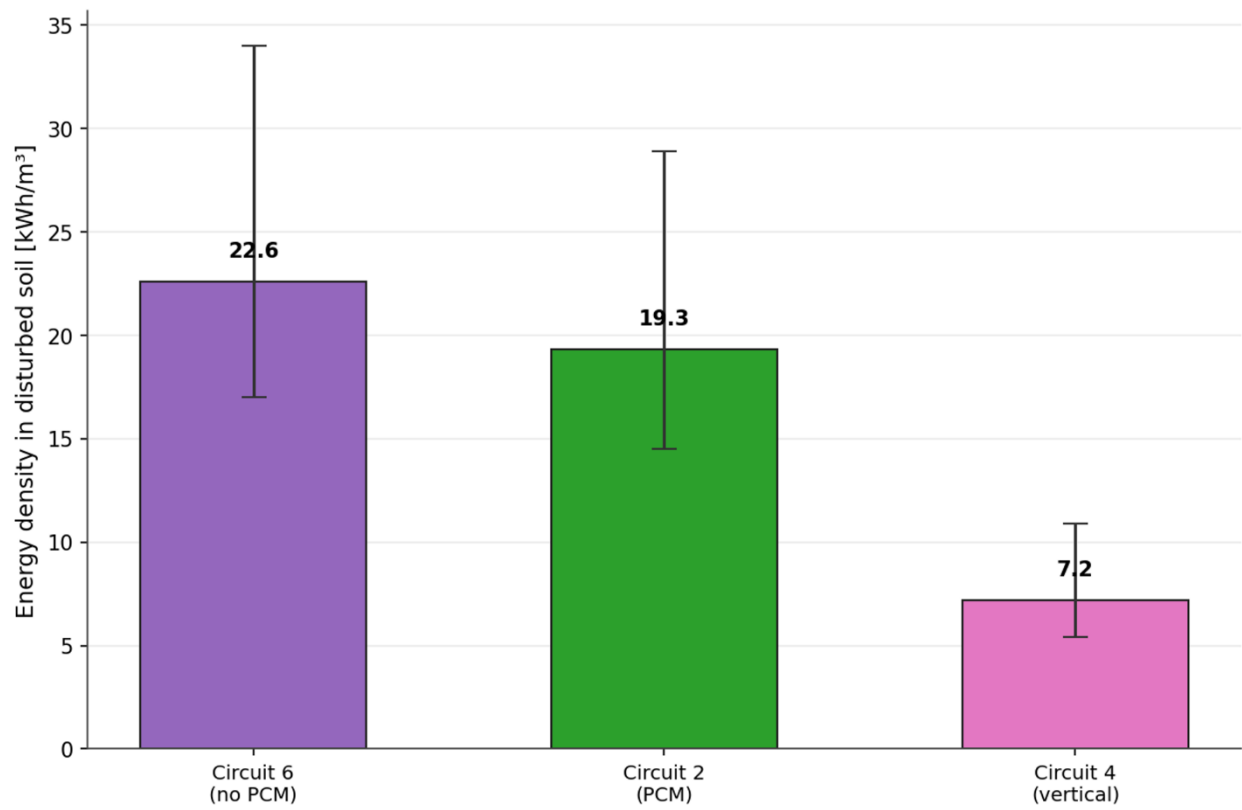


Figure 61: Exchanged energy per unit of disturbed soil volume for the active circuits of Heating Test 1. The disturbed volume is estimated as the activated wall area of each circuit multiplied by the penetration depth of Section 4.2.4