Abstract

The heating and cooling sector has been identified as a priority for meeting decarbonisation and energy efficiency targets. Transitioning to low-carbon energy systems requires innovative solutions for sustainable heating and cooling, particularly in urban environments where thermal demands are high, space is limited, and the existing building stock dominates. In this context, major renovations present a cost-effective opportunity to improve the energy performance of buildings.

Shallow geothermal energy is regarded as a reliable, renewable resource valued for its widespread availability and negligible environmental impact. Among technologies exploiting geothermal energy, energy geostructures have recently emerged as a dual-purpose solution, serving both structural and thermal energy needs. Energy walls enable transforming underground building envelopes into geothermal collectors, though their performance may be sensitive to external conditions and temperature shifts.

This Doctoral Dissertation investigates how the performance of energy walls can be enhanced by combining phase change materials (PCM) in the adjacent ground with other thermal energy sources, specifically solar thermal energy. The aim is to enable shallow underground thermal energy storage and exchange. The research is motivated by the scarcity of experimental evidence on energy geostructures for underground heat storage and by the lack of studies on their combined use with PCM under real operating conditions.

To address these gaps, a full-scale experimental site, Geothermskin, was designed, constructed, and instrumented at Politecnico di Torino. The prototype includes six thermally activated geothermal modules, arranged in pairs to form three independent experimental fields. These fields are separated by thermal insulating panels to avoid thermal interactions. In one field, macroencapsulated PCMs were distributed in the soil layers facing the energy wall to increase the ground's heat storage capacity and thermal inertia. An extensive monitoring system records ground temperature and humidity, the heat carrier fluid temperature and flow velocity, and the overall system efficiency.

A three-dimensional thermo-hydraulic numerical model was developed and validated against experimental data from the prototype. It was then used for sensitivity analyses on PCM melting temperature, distance from the wall, partially saturated soil conditions, and operating scenarios including daily and seasonal heat storage. Results show that adding PCM in the ground can improve the energy geostructure performance and thermal buffer capacity of the ground. Among the configurations examined, the most favourable PCM for both heating and cooling applications was that with the transition temperature closest to the undisturbed ground temperature and located near the energy wall. An empirical correlation was derived to estimate the exchanged thermal power as a function of effective degree of saturation. Scenario analyses indicate that winter night-time underground heat storage is the most effective strategy, with the largest performance gains achieved at higher storage inlet temperatures.

The final part of the thesis draws conclusions on the performance of shallow energy geostructures in combination with underground heat storage and the role of PCM in the ground. Experimental results confirm the main numerical trends. Underground thermal energy storage is feasible even at shallow depths and increases the thermal power exchanged by the system, with measured gains of 15.0–30.0 % compared to the operation without storage. The contribution of PCM was found to depend on the phase change's mobilisation. When latent heat exchange is not possible, the PCM locally increases thermal resistance and reduces heat exchange to the ground. Conversely, during winter operation, when PCM solidifies, the average exchanged power in the PCM field increases by up to 55.0 %. The ground stays consistently warmer at greater depths, indicating that the material exerts a thermal buffering effect. The experimental gains are consistent with numerical predictions, showing improvements of thermal energy exploitation thanks to underground heat storage and PCM.

The results provide practical engineering guidance for the integration of energy geostructures, specifically energy walls, with solar thermal systems for underground heat storage purposes. The research also offers design-oriented indications for the use of PCMs in the ground to enhance the thermal exploitation of the subsoil through energy geostructures. In particular, it highlights how the PCM's transition temperature selection should account for the intended heating and cooling operation and the underground thermohydraulic environment of the installation site. The findings show that underground heat storage through shallow earth-contact building envelopes can be considered a feasible design option for renovation projects, especially in urban areas.