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ENERGY SIMULATION OF SHALLOW UNDERGROUND THERMAL ENERGY STORAGE TO RECOVER SOLAR ENERGY

Summary

This study evaluates a seasonal thermal energy storage using natural materials (water, sand) and a horizontal underground heat exchanger to recover low-temperature solar thermal excess energy. A dynamic numerical model (TRNSYS) and sensitivity analysis (Morris/Sobol) were used to identify the critical parameters, which were tested in three scenarios combining charge/discharge over 3 to 6 months, with fixed or real weather data. The results show that the soil thickness above the storage and insulation are decisive factors, while the heat exchanger geometry and the inlet temperatures for the charging and discharging steps require a compromise to optimise performance. Conversely, the tube internal diameter has a negligeable impact regardless of the scenario.

Keywords: Horizontal Underground Thermal Energy Storage, seasonal storage, sensitivity analysis, dynamic numerical modelling, solar thermal collectors

Field of application for the findings: 08 Thermal Energy Storage

Addressed audience:

1. Introduction

Renewable energy intermittency challenges efficiency and reliability. Thermal Energy Storage (TES) address this issue by decoupling supply and demand, mitigating variability (Rahman et al., 2020). Although water tanks are widely used for TES due to their favorable properties and cost-effectiveness (Li et al., 2018), large-scale applications require significant volumes, increasing both footprint and costs. In the agri-food sector, seasonal TES offers a promising solution by capturing surplus summer heat for use in autumn or winter, improving the efficiency of solar thermal sensors. Horizontal Underground Thermal Energy Storage (HUTES) stores excess heat underground via a heat exchanger, requiring no additional space despite the low thermal conductivity of soil.

The proposed HUTES aims to store heat for over two months, preheating water for thermal collectors. This technology is expected to reduce fossil fuel consumption, eliminate overheating risks and improve annual solar coverage. A multi-step methodology, including a literature review (Le Roux et al., 2026) was adopted to assess feasibility. This numerical work identifies influential parameters, defines operational scenarios and performes sensitivity studies to evaluate the impact of design and operational parameters.

2. Materials & Methods

2.1. Numerical model of the pilot-scale bench

An experimental bench, recently installed on a farm, has been modelled in TRNSYS. Fig. 1 shows a side view (X-Z plane) and a vertical cross-section (Y-Z plane) of the HUTES. These two views show the main dimensions.

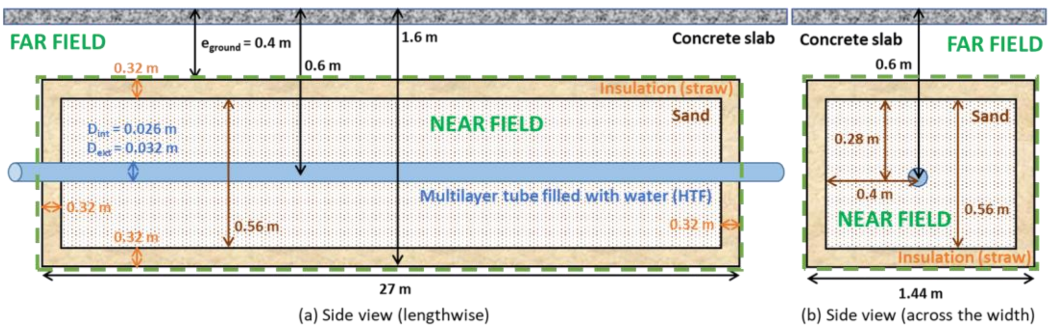

Fig. 1 : Simplified diagram of the side view (X-Z plane) (a) and vertical cross-section (Y-Z plane) (b)

The model uses TRNSYS Type 999, based on a 3D implicit finite difference method to simulate heat transfer via soil conduction and tube convection. The multi-layer structure (tubes and soil) has depth-dependent properties. Assumptions include homogeneous, isotropic and porous soil with constant properties, uniform humidity and stable Heat Transfer Fluid (HTF) and insulation properties, excluding phase change or chemical reactions. The model differentiates: **near field** (insulated and thermally active area around the tubes), and **far field** (boundary zone at constant temperature to limit edge effects). Boundary conditions are conductive with a fixed far field temperature (sides and top) and adiabatic (bottom). Initially, ground and HTF temperatures are uniformly 10°C.

The functional architecture of the model (HUTES with a pump) is illustrated in Fig. 2. The model's core (yellow main block) integrates three elements: a weather file for outside temperature and solar radiation (*Data*), a circulation pump (*Pump*) and Type 999 (*HUTES*). These are managed by a central calculator (*Variables*) that consolidates key parameters, such as HUTES geometry and material properties. This setup enables Python integration to automate sensitivity studies and explore various operational scenarios. Downstream (red block), an integrator, calculator and printer process results, convert units and record data. A control subsystem (blue block) manages the six-month charge and standby steps, using solar field output data (*Data*) to control pump operation based on the following rules:

- ON if $\begin{cases} T_{out,solar\ field} - T_{out,HUTES} > 5\ K \text{ and OFF at the previous time step} \\ T_{out,solar\ field} - T_{out,HUTES} > 1\ K \text{ and ON at the previous time step} \end{cases}$, OFF otherwise

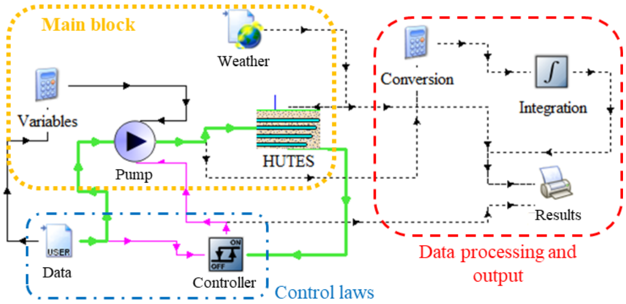

Fig. 2 : TRNSYS modelling of a HUTES (scenario 3)

Three scenarios were defined to assess the model's robustness under varying operational conditions, considering configurations with 1 to 5 parallel tubes at the same depth:

1. Charge over 3 months (8 am - 5 pm), with constant temperature and flow (0.11 kg.s^{-1}),
2. Daily charge (8 am - 5 pm) / discharge (5 pm - 8 am) over 6 months with fixed conditions (0.11 kg.s^{-1}),
3. Charge over 6 months with experimental dynamic field data (active solar field) and hourly weather file.

2.2. Sensitivity analysis

A sensitivity analysis identified the most influential parameters on the HUTES energy performance, including:

- **Internal diameter of the heat exchanger tubes (D_{int}):** 0.02 and 0.026 m,
- **Distance between the centres of the tubes on the same level (d_{tube}):** 0.15 to 1.5 m,
- **Insulation thickness (e_{ins}), and type (n_{ins}):** 0.01 to 0.35 m with 9 materials selected in (Le Roux et al., 2026),
- **Soil thickness above the top of the HUTES (e_{ground}):** 0.1 to 0.4 m,
- **Inlet temperatures during charge ($T_{in,ch}$) and discharge ($T_{in,dis}$):** 30 to 100°C and 5 to 25°C.

Two distinct and complementary methods, from Python's SALib library, were employed: **Morris** (rapid screening to identify influential parameters (linear or non-linear) and eliminate those with a negligible impact), and **Sobol** (quantitative variance analysis to assess non-linear effects and interactions between parameters).

Automated via Python scripts, these analyses generated almost 1,000 simulations per scenario, with a randomly exploration of the parameter space. The evaluation criterion is the recovered energy (E_{dis} in kWh$_{th}$), defined as:

$$E_{val} = E_{dis} - E_{pump} \cdot \eta_{pump} \qquad \text{(eq. 1)}$$

With η_{pump} the pump efficiency (90%) and E_{pump} the electrical energy (kWh$_e$) consumed by the pump.

3. Results and discussions

The tube internal diameter had negligible impact, and was excluded from the sensitivity study per Morris method. The larger diameter was selected to reduce pressure losses. Optimal distances between tubes were identified: 0.7-0.8 m (2 tubes), 0.42 m (3 tubes), 0.3 m (4 tubes) and 0.22 m (5 tubes), aligning with HUTES dimensions. In scenario 1, the Morris and Sobol analysis highlighted three key parameters influencing HUTES performance: insulation type, insulation thickness and soil thickness above the HUTES. Fig. 3 displays the Morris indicators (σ and μ^*), where high μ^* values indicate strong influential, and high σ values suggest potential interactions. The σ/μ^* ratio (> 1 for all parameters except D_{int}) reveals significant interactions aligning with Garcia Sanchez *et al.* (Garcia Sanchez et al., 2014). Sobol indices (S1 and ST) reinforce these findings, emphasizing non-linear effects and interactions. In scenario 2, the same three parameters (n_{ins}, e_{ins} and e_{ground}) remain most influential. However, Sobol method also reveals a notable impact of inlet temperatures during charging and discharging steps. Strong interactions between parameters are confirmed by high σ/μ^* ratios (> 1) and significant differences between S1 and ST. In scenario 3, inlet temperatures for charging and discharging steps are determined by field data from thermal sensors. Findings remain consistent, with less influence from d_{tube} compared to e_{ground}, e_{ins} and n_{ins}. Minor differences from scenarios 1 and 2 include slightly weaker interactions, reflected in a lower σ/μ^* ratio.

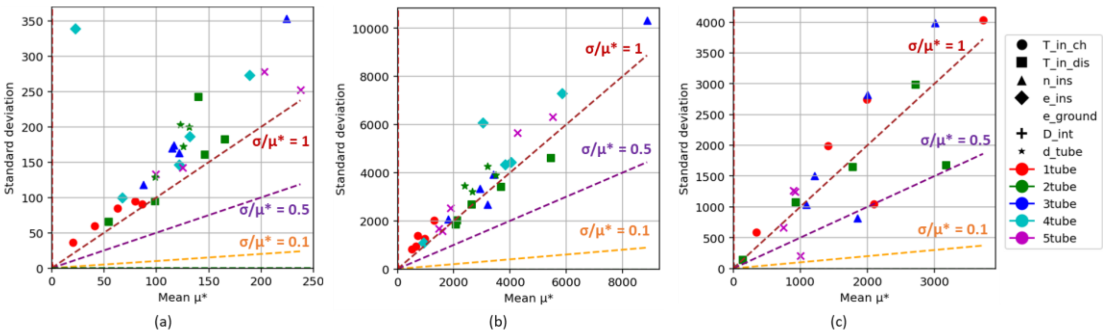

Fig. 3 : Scenarios 1 (a), 2 (b) and 3 (c) – Influence of parameters based on Morris indices

4. Conclusions

A HUTES, designed to recover heat dissipated by solar thermal collectors during the summer, was modelled using TRNSYS. A parametric study, employing Morris and Sobol methods from Python's SALib library, analysed interactions and both linear and non-linear effects. Three scenarios were simulated, combining charging and/or discharging steps over 3 to 6 months with fixed or real meteorological and operational data. The analysis, aimed at maximising the energy recovered, yielded the following recommendations for HUTES design and operation. The **internal diameter of the tube** should be maximised to minimise pressure losses. The **distance between tubes** should be carefully balanced according to the HUTES dimensions to limit thermal interactions. A **soil thickness** of 0.25 to 0.3 m above the HUTES is recommended to optimise heat transfer while minimising surface losses. For **insulation thickness**, 0.18 m is suggested for a single tube configuration, and 0.05 to 0.15 m for multi-tube configurations. Straw, extruded polystyrene, and high-density polyurethane are the **recommended insulation materials** due to their effective thermophysical properties. **Optimal operational temperatures** are suggested to be 90°C for the charge and 17- 22°C for the discharge. These results establish a robust foundation for HUTES design and optimisation, balancing energy performance, economic viability and environmental sustainability. Experimental validation on a pilot-scale test bench will confirm these findings, followed by multi-objective optimisation.

5. References

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