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High-Temperature Subsurface Thermal Energy Storage Using Closed-Loop Geothermal Probes: The AGES Concept

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1 INTRODUCTION

The deep decarbonisation of heat systems—responsible for more than half of Europe's final energy demand—requires the deployment of flexible, dispatchable, low-carbon thermal supply solutions. While aquifer-based geothermal systems and low-temperature subsurface heat storage (ATES, BTES) are widely implemented where hydrogeological conditions allow, large-scale high-temperature subsurface heat storage (HT-TES) remains underdeveloped. Yet, HT-TES plays a key role in bridging temporal gaps between renewable energy production and heat demand, valorising industrial waste heat, and enabling large-scale decarbonisation of industrial and district heating networks.

AGES (Advanced Geothermal Energy Storage) has developed a modular HT-TES technology based on arrays of closed-loop geothermal probes, enabling controlled injection, storage, and extraction of heat over depths ranging from 30 m to more than 1 000 m. Unlike open-loop or aquifer-dependent technologies, AGES relies solely on sealed geothermal exchangers, allowing deployment in more than 95% of geological settings, independent of aquifer permeability, water chemistry, or hydrogeological constraints.

AGES has structured a portfolio of storage configurations—SES, C2SES, SESEF, and SESA—addressing a wide spectrum of temperature, operational depth, and storage capacities from 1 to more than 100 GWh. These engineered subsurface "thermal batteries" convert intermittent renewable or waste heat streams into dispatchable, secure, and local thermal supply.

This extended abstract presents (1) the AGES system architecture and variants; (2) thermo-hydro-mechanical considerations associated with HT-TES; (3) techno-economic perspectives including drilling cost reduction strategies; and (4) implications for energy-system integration and industrial decarbonisation.

2 SYSTEM ARCHITECTURE AND TECHNOLOGY PORTFOLIO

2.1 SES – Subsurface Energy Storage (Base Module)

The SES configuration forms the fundamental AGES module (Figure 1). It consists of a robust, fully sealed geothermal probe installed at depths from approximately 30 m to beyond 1 500 m. A heat-transfer fluid circulates inside the closed-loop system, exchanging heat with the rock mass. Typical operating temperatures range from 40 °C to more than 100 °C. SES probes can be implemented as single or double U-tubes, or as coaxial steel/plastic exchangers, cemented with high-conductivity grout to maximise heat transfer and ensure long-term mechanical stability. Installations are realised with conventional drilling technology and can be deployed vertically or with moderate inclination to adapt to constrained urban environments. SES offers near-universal deployability in sediments, consolidated formations, and crystalline basement; it involves no interaction with subsurface fluids, which simplifies permitting and eliminates risks of fluid leakage or chemical interactions. The concept is inherently modular: individual probes can serve single buildings, while large arrays operated with centralised hydraulics and controls can reach district-scale capacities. Thermal performance is dominated by conductive processes in the rock, leading to highly predictable behaviour that can be characterised through thermal response tests and reliably simulated over decades of operation.

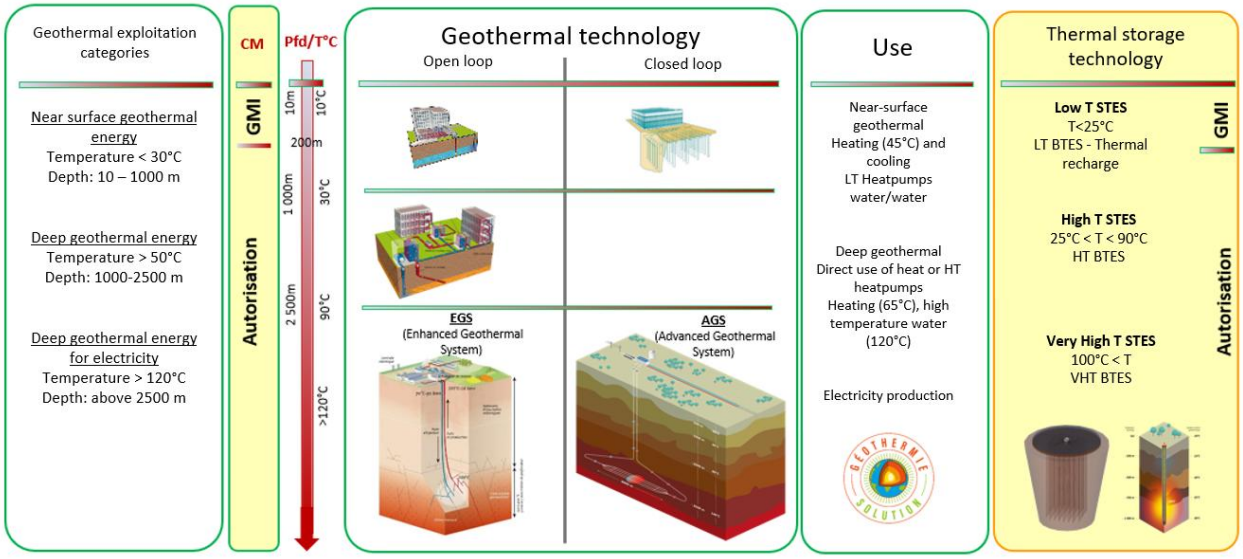


Figure 1 Technological framework for thermal storage

2.2 C2SES – Coupled Solar Thermal + Subsurface Energy Storage

C2SES, as illustrated in Figure 2, integrates solar thermal collectors with SES to store large volumes of summer solar heat for winter demand. Storage capacities typically range from 1 to 20 GWh, depending on storage geometry, collector field size and operating temperature. Flat-plate or evacuated-tube collectors, or concentrating solar fields for higher temperatures, feed a charging loop that injects heat into the SES array whenever solar production exceeds instantaneous demand. During the heating season, the same subsurface field is discharged via direct heat exchange or coupled heat pumps, providing base-load heat to buildings or district networks and freeing boilers or CHP units for peak coverage. This configuration is particularly suited for industrial sites with surplus solar production, energy communities, and district heating networks targeting high shares of renewable heat. C2SES smooths daily and seasonal fluctuations in solar output, increases the solar fraction without curtailment, and allows operators to optimise between direct use, storage, and auxiliary generation as a function of demand and electricity prices.

2.3 SESEF – Subsurface Energy Storage from Energy Fatale (Waste Heat)

SESEF enables the valorisation of industrial waste heat, often produced intermittently or continuously between 50 °C and 150 °C (Figure 3). Waste heat from processes such as furnaces, cooling water circuits, compressors, data centres or hydrogen production is captured through heat exchangers, conditioned if necessary (e.g. via intermediate loops or heat pumps), and injected into the subsurface for storage. The stored heat is later recovered either at the same site or delivered to nearby users, for instance via a district heating network. This configuration offers capacities from 1 to more than 100 GWh, making it particularly suited for industrial decarbonisation strategies, peak-shaving and seasonal flexibility, and overall energy-efficiency optimisation. SESEF transforms what is currently a lost or partially used resource into a controllable asset that can support process heat, building heating, or low-temperature industrial steps. By decoupling waste-heat generation from its end-use in time, it also allows industries to maintain stable production while responding to external signals such as electricity-market prices or district-heating load constraints. Continuous monitoring, automated control and integration into site energy-management systems ensure safe operation and maximise the avoided CO_2 emissions per unit of stored energy.

2.4 SESA – Advanced High-Temperature, Deep Storage (>100 GWh)

SESA is the most advanced AGES configuration, designed for deep installations exceeding 1 500 m and operating above 100 °C (Figure 4). It targets very large industrial hubs, high-demand urban districts, and future multi-energy infrastructures requiring long-term, high-capacity dispatchable heat. Deep borehole heat exchangers or advanced coaxial probes are installed into high-temperature geological formations, taking advantage of both injected heat and the natural geothermal gradient. Operating temperatures can be tailored to interface directly

with high-temperature district heating (4th/5th-generation DH with boosters), industrial steam cycles, or high-efficiency heat pumps. SESA fields, typically comprising dozens to hundreds of deep probes, can store several hundred GWh of heat with storage periods from weeks to multi-year cycles, effectively acting as a “geological battery” at metropolitan scale. Their design includes high-temperature materials, advanced completion concepts, and detailed thermo-mechanical modelling to guarantee integrity over decades. In integrated energy systems, SESA can be combined with large solar fields, waste-heat sources, CHP plants and electric boilers, providing system operators with a powerful lever to balance fluctuating renewable generation, secure heat supply under extreme conditions, and enable new business models around flexibility and capacity services.

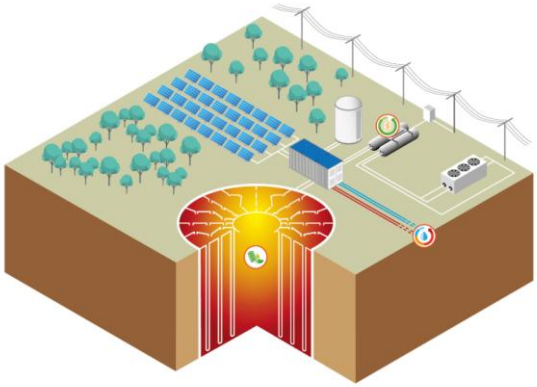


Figure 2: Coupled solar thermal and subsurface thermal battery (AGES ENERGY)

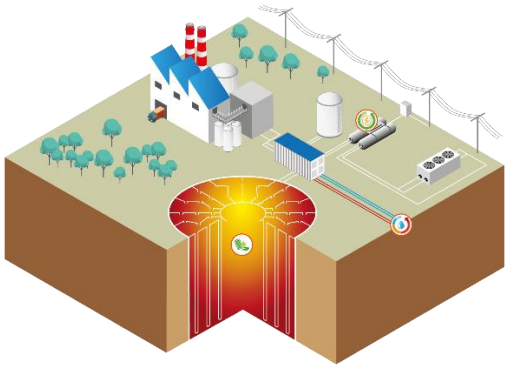


Figure 3: Subsurface Energy Storage from Energy Fatale (Waste Heat)

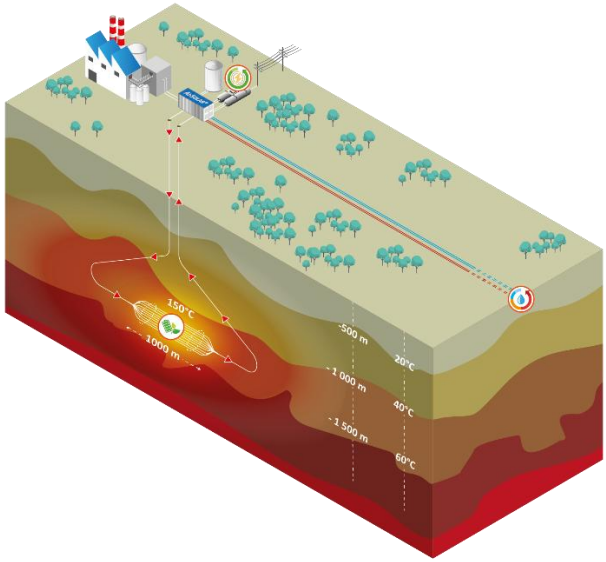


Figure 4: SESA – Advanced High-Temperature, Deep Storage (>100 GWh)

3 THERMAL AND THERMO-HYDRO-MECHANICAL BEHAVIOUR

High-temperature subsurface storage must consider both thermal and thermo-mechanical stability.

3.1 Thermal Processes

Injected heat propagates into the subsurface primarily by conduction. Key controlling factors include thermal conductivity and diffusivity of the host formation, target depth and initial geothermal gradient, storage duration, probe geometry and spacing, injection temperature and operational cycling.

Thermal envelopes evolve predictably over seasonal and multi-year cycles, achieving thermal quasi-steady states after repeated charging/discharging.

3.2 Thermo-Elastic and Mechanical Effects

Temperature variations induce thermo-elastic stresses in the rock mass. AGES integrates laboratory measurements of thermal expansion and mechanical properties, 2D–3D thermo-hydro-mechanical (THM) numerical modelling, in-situ monitoring (deformation sensors, microseismic arrays). Key results from AGES' internal studies show thermal stresses remain localised (<1–3 m around probes), negligible risk of fracture propagation under operating conditions, no pore-pressure perturbation due to closed-loop operation, reducing geomechanical risk. This ensures stability over multiple decades of cyclic operation.

4 TECHNO-ECONOMIC FRAMEWORK

4.1 Drilling-Cost Dominance

Drilling costs represent the main capital expenditure for closed-loop HT-TES systems. Cost reduction is therefore essential to scaling the technology. AGES targets a factor ≥3 reduction in drilling costs for wells deeper than 500 m via optimised drilling diameters and materials, simplified casing strategies, standardised probe manufacturing, modular, repetitive installation workflows, and adoption of lower-cost drilling techniques for shallow and mid-depth probes.

4.2 LCOE Performance

Preliminary LCOE calculations show that AGES systems become cost-competitive when waste heat streams are available for charging (SESEF), solar thermal curtailment is significant (C2SES), carbon prices strongly penalise fossil-based heating, storage is deployed at scale (≥20 GWh). SES, C2SES, SESEF and SESA provide a continuum of options enabling incremental investments ("pay-as-you-grow").

5 APPLICATIONS AND INTEGRATION INTO ENERGY SYSTEMS

AGES high-temperature thermal energy storage (HT-TES) solutions support industrial decarbonisation by capturing, upgrading and storing waste heat from furnaces, kilns or data centres, thereby reducing fossil fuel use, enabling fuel-switching to electricity or low-carbon heat sources, and providing seasonal load shifting so that heat-intensive industries can operate flexibly without drawing peak-load gas or power. At the urban scale, AGES can be coupled to district heating and cooling networks to increase winter resilience: the subsurface reservoir acts as a large thermal buffer and inertia, smoothing demand spikes during cold spells, stabilising supply temperatures, and allowing operators to integrate more variable or low-temperature renewable heat sources (solar thermal, ambient heat, wastewater, low-enthalpy geothermal) without compromising service quality. By storing large volumes of excess solar- or wind-powered heat when production is high and demand is low, AGES directly addresses the intermittency challenge of renewables, turning curtailed or stranded energy into a controllable, dispatchable heat resource. In this way, AGES positions HT-TES as a backbone of future geo-smart multi-energy grids, enabling coordinated management of heat pumps, solar collector fields, industrial waste heat streams, geothermal gradients and district networks under a single optimisation framework. For illustration, a metropolitan industrial cluster could feed surplus high-temperature waste heat from a glass factory into an AGES borehole field in summer, store it in the subsurface at 100–200 °C, and later recover it via heat exchangers to support the nearby district heating network on cold winter mornings, while heat pumps dynamically top up temperatures and the control system arbitrages between electricity prices, industrial production schedules and district heating demand.

6 DISCUSSION AND PERSPECTIVES

Closed-loop HT-TES presents a set of unique advantages: applicability in >95% of geological environments, no reliance on aquifer permeability, minimal environmental impact, predictable thermal behaviour, strong modularity enabling incremental scaling.

Challenges that remain include achieving targeted drilling cost reductions, demonstration of very large-scale installations (>100 GWh), deeper integration with digital tools for predictive operation and optimisation, broader adoption by industrial end-users.

HT-TES is emerging as a key enabling technology for the European heat transition, with strong potential for cross-sector deployment.

AGES delivers a fully modular and widely deployable high-temperature thermal energy storage solution based exclusively on closed-loop geothermal probes. By using the subsurface as a stable and high-capacity thermal reservoir, AGES systems (SES, C2SES, SESEF, SESA) enable seasonal balancing, industrial waste-heat valorisation, and high-temperature dispatchable heat supply. Large-scale deployment depends primarily on drilling cost optimisation and continued integration into renewable and industrial ecosystems. With the increasing need for decarbonised, flexible, and secure heat infrastructures, AGES has the potential to become a cornerstone of future low-carbon multi-energy systems.