EuroSun2026

REDUCING WINTER ELECTRICITY DEMAND THROUGH OVER-REGENERATION OF BOREHOLE THERMAL ENERGY STORAGE: OPERATIONAL AND GROUNDWATER INSIGHTS FROM THE OST CAMPUS DEMONSTRATOR

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Summary

Electrification of heating is expected to raise winter electricity demand, while renewable electricity is increasingly available in summer at low cost. Deliberately over-regenerating a borehole field or borehole thermal energy storage (BTES) during summer raises the winter source temperature of the heat pumps and shifts electricity use out of winter, but it also also heats the surrounding ground and groundwater. Using the OST campus Rapperswil as a demonstrator, this study combines an operational energy-system simulation with a three-dimensional subsurface and groundwater model to quantify both sides of this trade-off. Three regeneration concepts are compared: In the base case the waste heat from the existing cooling demand leads to a regeneration of only 20-30 %, full regeneration through an ambient-air heat exchanger roughly halves the required borehole field, and adding active heat-pump regeneration lowers the electricity used for heating by about 50%, at the cost of about 30% higher total consumption, while shifting demand towards summer. The groundwater model, spanning a range of flow rates and aquifer thicknesses, shows that the groundwater flow rate dominates the thermal impact and that the permissible operating envelope is narrow wherever groundwater flows through the field. Over-regeneration is therefore operationally attractive but tightly bounded by groundwater protection at such sites; a dedicated measurement campaign is proposed to characterise the site-specific flow and refine the envelope.

Keywords: Borehole thermal energy storage, seasonal thermal storage, winter electricity demand, regeneration strategies, groundwater interaction

Field of application for the findings: Heat pump systems, district and campus-scale renewable heating systems

Addressed audience: Researchers, system planners, and practitioners in seasonal thermal energy storage and renewable heating

1. Introduction

The ongoing electrification of space heating is expected to substantially increase winter electricity demand in many European countries (Prognos AG et al., 2021). Heat pumps are a central pillar of decarbonisation strategies, but their performance and electricity consumption depend strongly on the source temperature, particularly during cold periods, so winter electricity peaks are emerging as a key system challenge. At the same time, the growing share of renewable generation, in particular solar power, makes low-cost renewable electricity increasingly available during summer. Seasonal thermal energy storage (STES) decouples heat generation from demand by shifting thermal energy from periods of surplus to periods of scarcity.

Borehole thermal energy storage (BTES) is a well-established STES technology, with low surface impact, a long lifetime, and good suitability for dense urban environments (Cimmino and Bernier, 2014). Conventionally, BTES systems operate close to the natural ground temperature, where regeneration only avoids a long-term cooling of the ground. This paradigm can be deliberately relaxed (Weber and Baldini, 2018; Fiorentini et al., 2022): by actively charging the borehole field during summer to temperatures above the natural ground temperature, the source temperature of the heat pumps in winter is raised, so that less electricity is needed to cover the heating demand. The total annual electricity consumption increases, because heat has to be actively stored during summer, but the demand is shifted out of winter, which is exactly when reducing it is most valuable. The elevated ground temperature also increases the thermal interaction with the surrounding ground and groundwater.

In Switzerland, for example, groundwater protection restricts the long-term warming to about 3 K beyond 100 m from a thermal installation, which limits how high the field can be charged where groundwater flows are present. A current revision even foresees an exception based on the heated zone itself: the distance may be relaxed where a high-resolution model shows only a small part (< 10%) of the aquifer is heated to more than 16 °C. Limits differ between countries, so we report the thermal impact directly to allow adaptions to differing rules and regulations.

This contribution builds on previous work on seasonal storage and winter electricity reduction, using the OST Campus in Rapperswil as an example. We analyse two aspects: (i) the operational effect of over-regeneration on the seasonal electricity demand of the heat pump system, and (ii) the resulting thermal impact on the subsurface, assessed with a three-dimensional numerical model. Because the groundwater flow rate and the aquifer thickness are the most influential and least well-constrained parameters, we vary them together with the injection temperature and determine the operating envelope: the highest injection temperature that keeps the thermal impact within a given limit.

2. Operational analysis of over-regeneration

This section examines the operational impact of over-regeneration of BTES based on a specific example: how the choice of regeneration strategy affects the sizing of the borehole field and the seasonal electricity demand of the heat-pump system. It also establishes the compact field layout and the over-regeneration temperature profiles that serve as input to the subsurface and groundwater analysis that follows.

2.1 Site description

The OST Rapperswil campus consists of eight buildings, most of which were constructed during the 1970s. Several of these buildings are protected as cultural heritage assets, which considerably limits the scope of envelope retrofitting and energy-efficiency measures. Seven of the buildings are currently supplied by a central fossil-fuel-based heating plant, which is planned to be replaced by a ground-source heat pump system coupled to a borehole thermal energy storage (BTES) field.

The buildings exhibit a combined annual heating demand of approximately 2.2 GWh. A preliminary feasibility study indicated sufficient space on the campus to install up to 84 boreholes with drilling depths of up to 350 m.

2.2 Energy system simulation method and assumptions

The objective of the analysis was to investigate the long-term thermal behaviour and dimensioning requirements of the BTES field. Therefore, a matlab implementation of the detailed semi-analytical borehole model developed by Cimmino (Cimmino and Bernier, 2014) was used to simulate heat extraction and regeneration processes. The borehole field consists of 84 boreholes arranged in a 4×21 configuration with a borehole spacing of 8 m. The most relevant simulation parameters were derived from a thermal response test (TRT) performed close to the project site and are summarized in Tab. 1. All other system components were represented using simplified component models to reduce computational effort.

Heating Demand: Instead of relying on standardized load profiles, measured energy consumption data from the years 2020 to 2024 were available. These five years of measured operation were used as the basis for assessing long-term thermal behaviour. To simulate a system lifetime of 50 years, the five-year measurement period was repeated ten times. The resulting demand profile exhibits peak heating loads of approximately 1.25 MW and an average annual heat demand of 2,167 MWh. Future building renovations are expected to reduce the heating demand over time. Therefore, the following reduction pathway was assumed:

Fig. 1: Top view of the OST Rapperswil campus. The buildings on the left are heritage-protected; BTES installation is possible on the highlighted area in front.

Tab. 1: Thermal and geometric parameters used for the BTES simulations.

Parameter	Value
Ground thermal conductivity	2.4 W/(m·K)
Ground density	2600 kg/m^3
Ground specific heat capacity	1000 J/(kg·K)
Borehole cover depth	1 m
Borehole radius	6.75 cm
Borehole thermal resistance	0.05 (K·m)/W
Number of horizontal layers	10

- 100% of today's demand during the first 10 years,
- 85% after year 10,
- 75% after year 20.

Since the existing heat distribution network is to remain unchanged, a constant heating supply temperature of 65 °C was assumed throughout the simulation period.

Cooling Demand: Measured cooling data from the existing chiller plant were available. However, these measurements do not fully capture the campus cooling demand because free cooling through air handling units is already used during certain operating periods. To account for this effect, the measured cooling profiles were conservatively increased by 20% based on estimates provided by the facility management team. Although this simplification does not perfectly represent the annual distribution of cooling demand, a more detailed modelling effort was considered unnecessary because cooling-induced regeneration contributes only approximately 20% of the annual heating demand. The chilled water distribution system operates at a supply temperature of 12 °C.

Heat pump: Based on a preliminary design study, a heat pump capacity of 800 kW was assumed. Heat loads exceeding this capacity are covered by the existing oil-fired boiler, which will remain available as a peak-load and backup system. These peak loads represent only approximately 1% of the annual heating demand. To quantify the impact of varying source temperatures on system performance, the coefficient of performance (COP) was dynamically adjusted throughout the simulation using a Carnot-based approach:

$$COP = \eta_{HP} \frac{T_{sink}}{T_{sink} - T_{source}} \tag{1}$$

where T_{sink} is the heating supply temperature (65 °C), T_{source} is the borehole outlet temperature, η_{HP} is the heat pump efficiency factor. A heat pump efficiency factor of $\eta_{HP} = 0.65$ was assumed. For temperature lifts below 25 K, the COP was not further increased. Operational data from the Familienheim-Genossenschaft Zürich and information provided by Walter Wettstein AG indicate that such performance levels are realistic for modern ammonia reciprocating heat pumps. The circulation pumps of the borehole field were represented by an additional electrical power demand of 2.5 kW whenever heat extraction or regeneration was active.

Air-to-Brine Heat Exchanger: Based on manufacturer specifications, the existing dry cooler is capable of providing approximately 62 kW/K of thermal regeneration power, referenced to the temperature difference between ambient air and brine inlet temperature. A simple liner model with this coefficient was used to calculate the Heat exchanger thermal power. The electrical power consumption of the unit is 7.5 kW.

2.3 Different regeneration concepts

As a **base-case scenario**, a borehole heat exchanger field was proposed to supply the campus heating demand while simultaneously serving as a heat sink for the cooling system. This approach enables partial regeneration of the borehole field through heat rejection from cooling operation. However, the available cooling demand provides only limited regeneration potential, corresponding to a regeneration rate of 20-30%.

A large air-to-brine heat exchanger is already available as part of the existing cooling infrastructure and can be reused in the upgraded energy system. Therefore, an additional scenario was investigated in which this heat exchanger is used for borehole field regeneration whenever the ambient air temperature exceeds the average borehole field temperature by more than 3 K. This additional heat source enables full thermal regeneration of the BTES, thereby preventing long-term ground cooling and allowing for a significantly smaller borehole field design.

A third scenario investigates the use of the heat pump to further increase the regeneration rate and actively charge the subsurface to temperatures above the undisturbed ground temperature. For the simulations presented in this study, active regeneration was assumed whenever the ambient air temperature exceeded 10 °C. Under these conditions, the heat pump injects additional thermal energy into the borehole field, thereby increasing long-term ground temperatures and improving the seasonal performance of the heating system. In the initial simulations, the regeneration temperature was conservatively limited to 60 °C. In subsequent analyses, however, variable upper temperature limits were applied to better reflect the operational constraints and performance characteristics of the system.

To ensure a consistent comparison of the three regeneration concepts, the borehole field layout was kept constant at 84 boreholes arranged in a 4×21 configuration. Only the borehole length was varied between scenarios. The borehole field was sized such that the minimum allowable average borehole temperature of -1.5 °C, as specified by the Swiss standard SIA 384/6 (SIA, 2021), was not violated during the 50-year simulation period.

Tab. 2: Comparison of the three regeneration concepts.

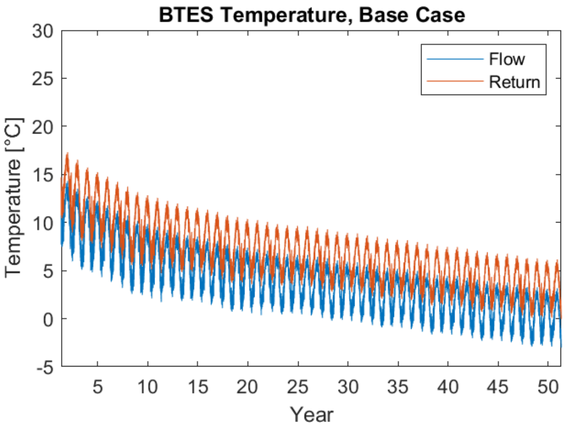
Parameter	Base Case	Air	Air & HP
Building demand reduction	100% → 85% → 75%	100% → 85% → 75%	100% → 85% → 75%
Cooling integration	Free cooling	Active cooling	Active cooling
Regeneration source	Cooling demand only	Cooling demand + air heat exchanger	Cooling demand + air heat exchanger + heat pump
Required borehole length (84 boreholes)	320 m	150 m	150 m

BTES Temperautres

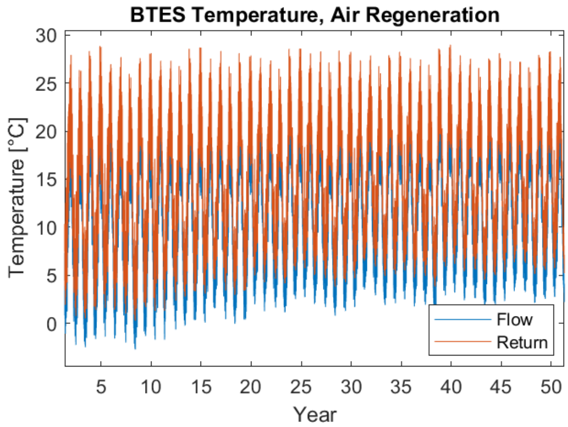
Fig.2 presents the simulated BTES inlet and outlet temperatures over a period of 50 years for three different scenarios. The base case requires significantly deeper boreholes to compensate for the long-term thermal depletion of the ground. Therefore operation starts near the undisturbed ground temperature and continuousely drops towards the limit of -1.5 °C given by the Swiss standard SIA 384/6 (SIA, 2021).

The combination of cooling demand and passive regeneration through the ambient air heat exchanger is sufficient to achieve an annual balance between extraction and regeneration. Consequently, no long-term temperature drop is observed and the required borehole depth can be reduced by approximately 50%. The minimum average borehole temperature remains above the design limit of -1.5 °C.

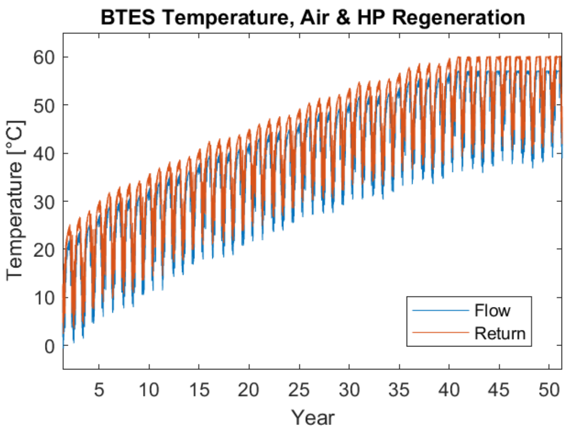
When active heat pump regeneration is additionally applied, the borehole field becomes overcharged and the ground temperature increases steadily over time. In order to fulfil the design limit during the first years of operation the same borehole length is needed. However, the heat source temperature gradually increases and largely exhibits the design rule in the later years of operation. As a consequence, the heat pump operates with continuously improving efficiency for heating.



(a) Regeneration with waste heat from actual cooling demand only.



(b) Passive regeneration using an air heat exchanger.



(c) Active regeneration using a heat pump and air heat exchanger.

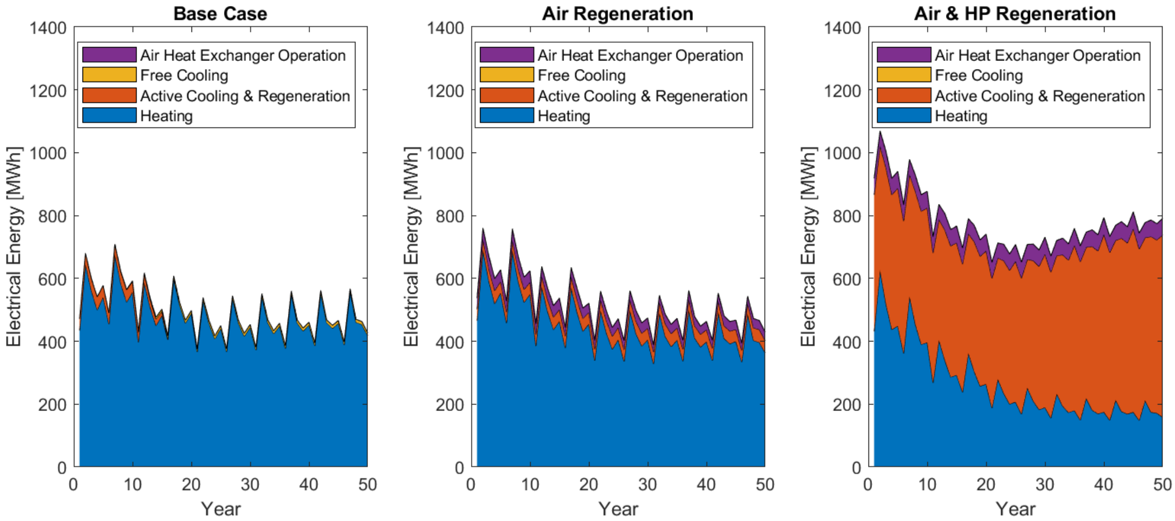
Fig. 2: Simulated BTES inlet and outlet temperatures over 50 years for three regeneration concepts.

Electricity demand

Fig. 3 compares the annual electricity consumption of the three investigated regeneration strategies. In the base case, dropping source temperatures reduce the heat pump COP over time. However, this effect is largely compensated by the assumed reduction in building heating demand resulting from future renovation measures. The passive regeneration scenario requires additional electricity for operation of the air heat exchanger. Due to the more compact borehole design, the system approaches the minimum permissible source temperature already during the first years of operation. As a result, the heat pump operates at a similar efficiency level throughout the entire simulation period. Although the electricity demand is slightly higher during the first years, it converges towards the base case despite requiring only half the borehole length.

Active regeneration using the heat pump requires substantially more electricity than passive regeneration. However, the continuously increasing source temperatures reduce the electricity demand for heating by more than 50% compared to the other system configurations. This benefit comes at the expense of an approximately 30% higher total electricity consumption. Fig. 4 illustrates the monthly distribution of electricity consumption for the active regeneration scenario during years 2, 12, 22, and 42.

During the early years, electricity demand is dominated by winter heating operation. As the BTES field temperature increases due to continuous active regeneration, the distribution gradually shifts towards a more balanced year-round electricity demand. The share of the electricity used during summer operation for thermal charging of the storage becomes more important than the electricity used for heating. This behaviour improves



(a) Base case (cooling-only regeneration)

(b) Air regeneration

(c) Air and heat-pump regeneration

Fig. 3: Annual electricity consumption of the investigated regeneration concepts over a 50-year simulation period: (a) base case, (b) air regeneration, and (c) air and heat-pump regeneration.

utilization of renewable summer electricity generation and can contribute to reducing winter peak electricity demand.

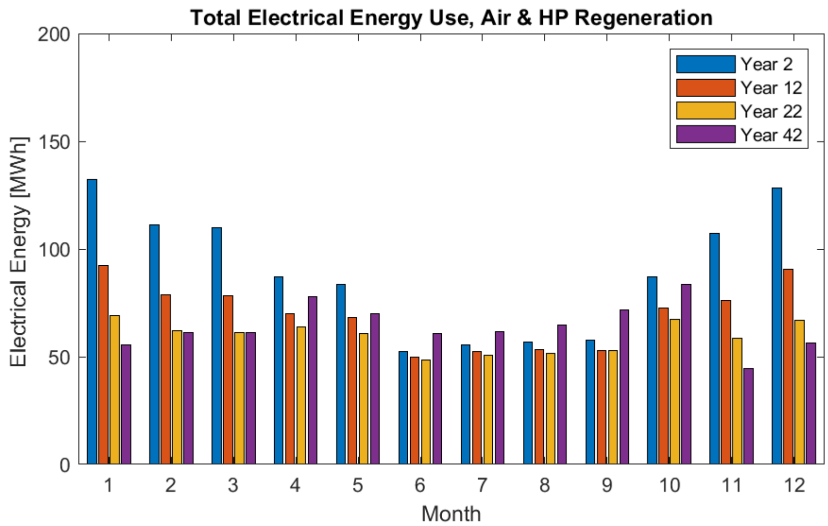


Fig. 4: Monthly electricity consumption in years 2, 12, 22, and 42 for the active regeneration scenario, illustrating the transition from winter-dominated heat pump operation towards year-round energy use.

2.4 Borehole Field Proposal for Groundwater Investigation

As the comparison of the three regeneration scenarios showed that both the air-only regeneration and the combined air and heat pump regeneration concepts required the same total borehole length of 12,600 m (84 × 150 m), the subsequent analyses focused on concepts with full regeneration. Furthermore, a more compact borehole field layout was selected for further investigation (Fig. 5). The field consists of 12 × 5 boreholes with a spacing of 6 m. To satisfy the SIA criterion of a long-term mean ground temperature $> -1.5\,°C$, a borehole depth of 220 m was required with this new compact field.

Compared to the elongated field used in the initial concept comparison, the more compact layout resulted in a slightly faster increase in subsurface temperature. To generalize the analysis of high-temperature borehole fields under groundwater influence, the maximum regeneration temperature was varied. Fig. 6 shows the inlet temperatures of the BTES resulting from different regeneration temperature limits. These temperature profiles

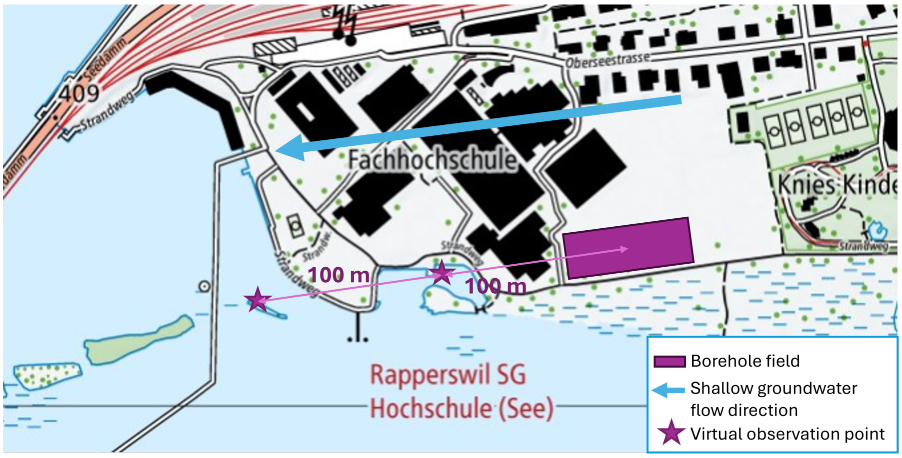


Fig. 5: The modelled borehole field on the OST campus in Rapperswil. Shallow groundwater flows from the field towards the lake; the thermal impact is evaluated at two virtual observation points 100 m and 200 m downstream.

were subsequently used as boundary conditions for the detailed groundwater analyses presented in the following section.

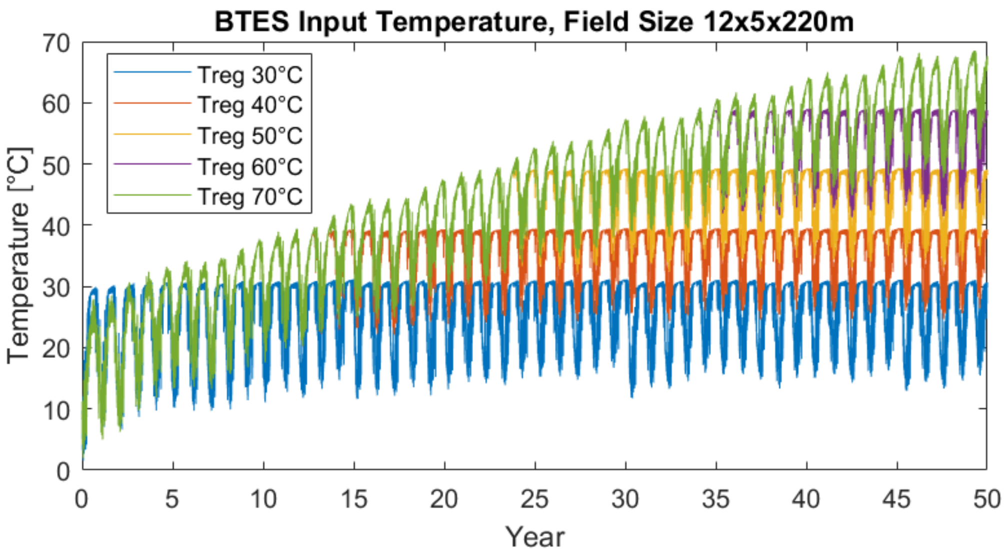


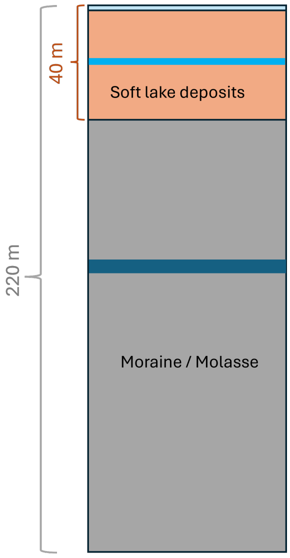
Fig. 6: BTES input temperature for a field of 12×5×220 m and different regeneration temperature limits.

3. Subsurface and groundwater model

3.1 Model description

The groundwater analysis is carried out for the compact field proposed above (60 boreholes on a 12×5 grid, 6 m spacing, 220 m depth). The over-regeneration temperature profiles of Fig. 6 set the range of injection temperatures studied here.

The subsurface is represented by a horizontally layered ground model (Fig. 7). It is based on the geology of the campus but kept representative of the Swiss Plateau, so that the results are not tied to one specific site. The model reaches a depth of 220 m and consists of topsoil and soft lake deposits near the surface, underlain by a thick moraine and molasse body. Groundwater is carried by two aquifers: a shallow one within the soft deposits and a deeper one within the molasse. The thermal conductivity, porosity, heat capacity, and density of each layer are given in Fig. 7. Both aquifers lie within the depth range of the boreholes and are therefore heated by borehole regeneration. We present the results for the shallow aquifer, because the near-surface aquifers are of primary concern for groundwater use.



Layer	Thermal conductivity λ ($\mathrm{W\,m^{-1}\,K^{-1}}$)	Porosity ϕ (–)	Heat capacity c_p ($\mathrm{J\,kg^{-1}\,K^{-1}}$)	Density ρ ($\mathrm{kg\,m^{-3}}$)
Topsoil	2.0	0.32	900	1830
Soft lake deposits	2.0	0.40	900	1890
Shallow aquifer	2.3	0.30	900	1990
Moraine / molasse	2.9	0.18	850	2350
Deep aquifer	2.0	0.15	900	2350

Fig. 7: Layered ground model (left) and the thermal and physical properties of each layer (right). The profile reaches 220 m depth; groundwater flows only through the shallow and deep aquifers.

The borehole field and the surrounding ground are simulated with the finite element software COMSOL Multiphysics, as a three-dimensional transient model over a horizon of 50 years (Fig. 8). The domain measures 600×220 m in the horizontal plane and 220 m in depth, large enough that the outer boundaries do not affect the temperatures around the field. The field consists of 60 boreholes on a rectangular grid with 6 m spacing, each 220 m deep and equipped with a single U-tube of 0.152 m diameter through which water circulates at 6 $\mathrm{dm^3/min}$. The boreholes are modelled with the Pipe Flow interface and are thermally coupled to the ground, which is described by the Heat Transfer in Porous Media interface, so that the circulating fluid, the borehole walls, and the ground temperatures are solved together.

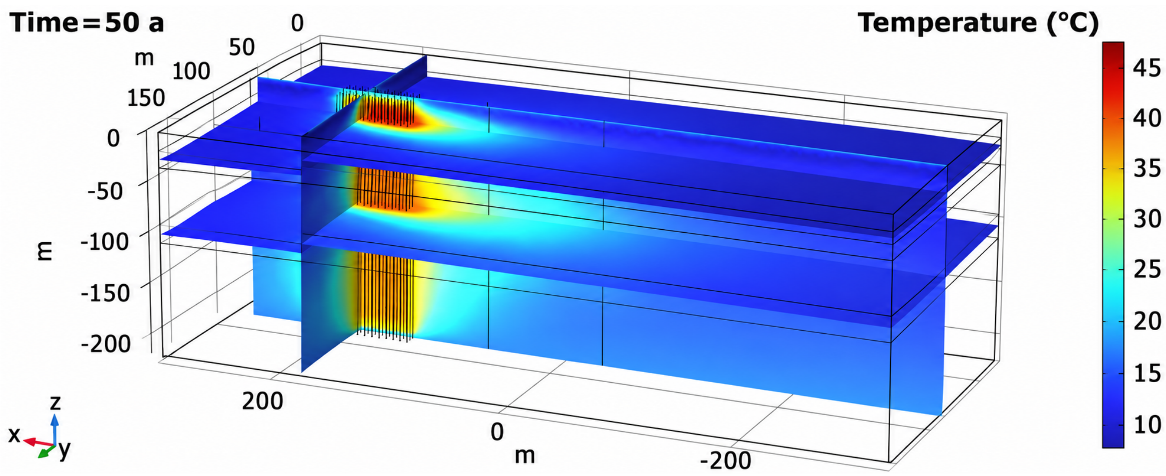


Fig. 8: Simulated 3-D temperature field after 50 years for medium aquifer, medium flow, at 50 °C injection.

Groundwater is included as a horizontal Darcy velocity through the two aquifers, while the other layers are impermeable. The field is operated as a seasonal store: in summer the fluid enters the boreholes at an elevated injection temperature and charges the ground, and in winter heat is extracted for the heat pumps. Three quantities are varied in the study. Two of them, the groundwater flow rate and the aquifer thickness, are properties of the site that are usually not well known. The third, the injection temperature, is an operating choice: the aim is to determine how high it can be set, for a given flow and aquifer thickness, without exceeding regulatory limits. We consider three flow rates, three aquifer thicknesses, and five injection temperatures between 30 and 70 °C (Tab. 3), which together give 45 simulated cases. In the following, the flow rates and aquifer thicknesses are referred to as low, medium, and high, and as thin, medium, and thick.

Tab. 3: Parameters varied in the simulations. Their combination yields 45 cases.

Parameter	Unit	Values
Groundwater flow (Darcy velocity)	$\mathrm{m\,s^{-1}}$	5×10^{-8} (low), 2.75×10^{-7} (medium), 1.5×10^{-6} (high)
Aquifer thickness (shallow / deep)	m	5 / 10 (thin), 10 / 20 (medium), 15 / 30 (thick)
Injection temperature	°C	30, 40, 50, 60, 70

The initial condition is the undisturbed ground temperature. A constant temperature is prescribed at the surface, the groundwater enters the aquifers at the undisturbed temperature at the upstream boundary, and the remaining boundaries are insulated. The domain is discretised with a tetrahedral mesh, refined around the boreholes and within the aquifers. The thermal impact is evaluated in the shallow aquifer, both as the temperature field around the field and as the temperature at observation points 100 m and 200 m downstream.

3.2 Thermal spreading in the aquifer

Over-regeneration raises the ground temperature around the field, and the groundwater carries part of that heat downstream. How far it spreads, and in which shape, decides how much of the surrounding aquifer is affected. We map the extent of the heated zone in the shallow aquifer, the near-surface layer most relevant to groundwater protection.

Swiss groundwater protection limits the temperature change in shallow groundwater to 3 K above the natural state within 100 m of the point of heat input (Swiss Federal Council, 1998, Annex 2, No. 21). A revision will allow an exception to the 100 m distance for installations of high thermal power, provided a high-resolution model shows that less than 10 % of the groundwater-fauna habitat is heated above 16 °C. The 16 °C threshold is therefore the regulatory marker for the edge of the heated zone, and we follow its contour through the results. Because the 16 °C / 10 % rule is specific to Switzerland and its outcome depends on the size of the reference aquifer, we map how far the 16 °C zone reaches, in metres, rather than as a percentage of the habitat, so that this or any other national limit can be read against it.

The size of the heated zone is set by three factors, in a clear order. Groundwater flow dominates: it changes the downstream reach of the 16 °C contour several-fold and stretches the zone from a compact patch at low flow into a long, narrow plume at high flow (Fig. 9). Injection temperature comes next, scaling the reach by about a factor of two without changing this shape; both effects are given in Tab. 4. Aquifer thickness matters least, carrying the heat only a little further downstream in a thicker aquifer, which moves more water at the same Darcy velocity (Tab. 5).

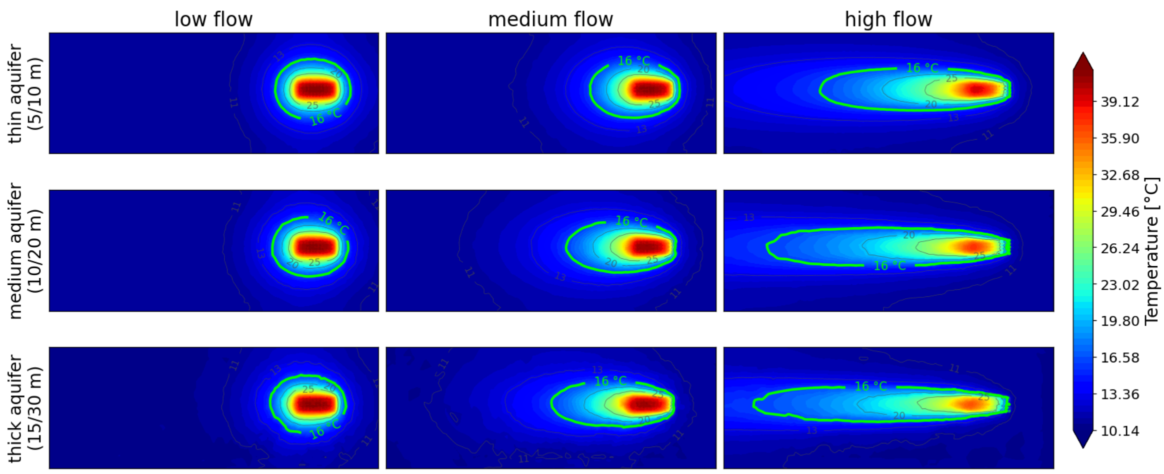


Fig. 9: Shallow-aquifer temperature after 50 years at 50 °C injection, by groundwater flow (columns: low, medium, high) and aquifer thickness (rows: thin, medium, thick). Each panel is a horizontal slice at $z = -22$ m, within the shallow aquifer for all three thicknesses. The green contour is the 16 °C edge of the heated zone; groundwater flows towards the left. All panels share one colour scale.

The maps describe the heated zone after 50 years; its development in time is followed at the 100 m and 200 m

Tab. 4: Downstream reach of the 16 °C contour from the field centre, in metres, for the medium aquifer thickness, by groundwater flow and injection temperature. Values marked > indicate the 16,°C contour reaches the downstream domain boundary, so they are lower bounds.

	Injection temperature (°C)				
Groundwater flow	30	40	50	60	70
low	55	70	80	85	95
medium	95	130	160	175	190
high	180	310	405	>490	>490

Tab. 5: Downstream reach of the 16 °C contour from the field centre, in metres, for medium groundwater flow, by aquifer thickness and injection temperature.

	Injection temperature (°C)				
Aquifer thickness	30	40	50	60	70
thin	75	100	115	125	135
medium	95	130	160	175	190
thick	105	150	185	210	230

observation points over the full simulation (Fig. 10). The warming builds up slowly, over decades, and reaches its final value only late in the period, so it would not be apparent from the first years of operation. It is also confined to the near field: at 100 m the temperature ends well above the natural 10.7 °C in every case, whereas at 200 m it remains close to 10.7 °C except at high flow, where it reaches about 20 °C. The groundwater flow again sets how far the heat is carried. The Swiss rule fixes the assessment at 100 m from the centre of the field, not from its edge. Since the field itself spans several tens of metres, this point lies only a short distance beyond the storage, where the warming is still near its maximum. Assessing so close to the store makes the 100 m criterion restrictive. As the warming has largely faded by 200 m, a large store like this one is exactly the case the planned exception is aimed at: relaxing the fixed 100 m distance in favour of the heated-zone extent would give it considerably more room for over-regeneration.

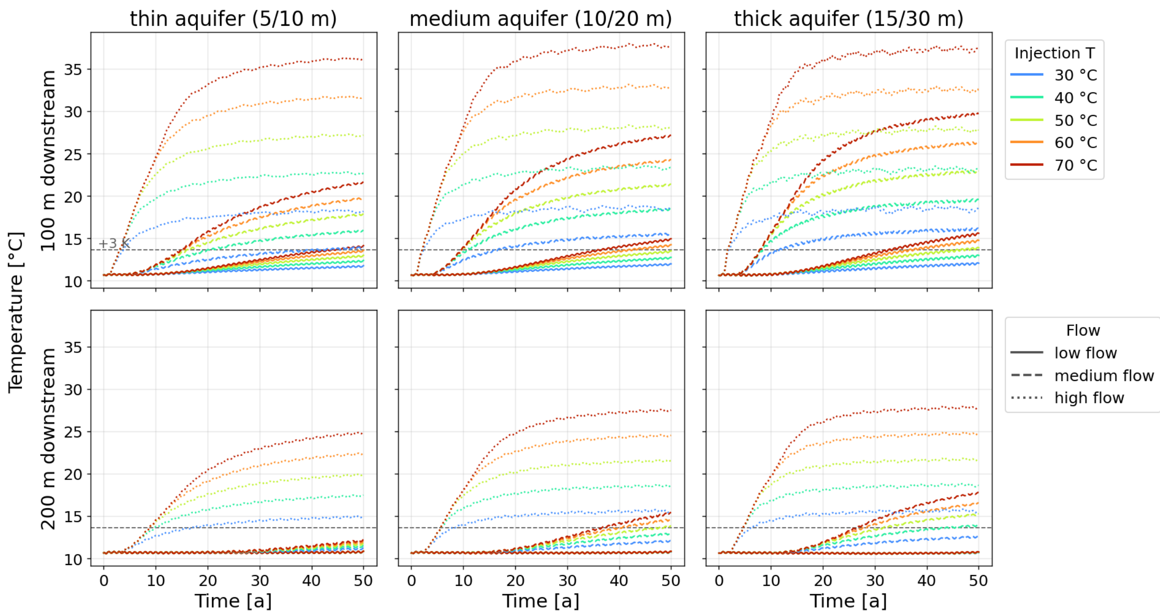


Fig. 10: Temperature over 50 years at the 100 m (left column) and 200 m (right column) downstream observation points, for the three aquifer thicknesses (rows). Line colour is the injection temperature; line style is the groundwater flow (solid: low, dashed: medium, dotted: high). The grey horizontal line marks the +3 K level above the undisturbed 10.7 °C. On the shared scale the 200 m warming stays far below the 100 m level, and at low flow it barely leaves the baseline.

3.3 Operating envelope

For each combination of groundwater flow and aquifer thickness, we determine the highest injection temperature that keeps the downstream warming within a chosen limit. Fig. 11 maps the mean temperature rise at 100 m over the final year against injection temperature and flow, one panel per thickness. Because the colour is the 100 m rise itself, the Swiss +3 K limit at 100 m is simply a contour of this field, drawn as the dashed red line; compliant combinations lie below and to the left of it. The dotted line marks the +3 K limit assessed at 200 m instead. The 200 m rise follows a different spatial pattern, so this line does not coincide with any contour of the 100 m field but cuts across it; it lies well above the dashed line, so moving the assessment out to 200 m enlarges the compliant region considerably.

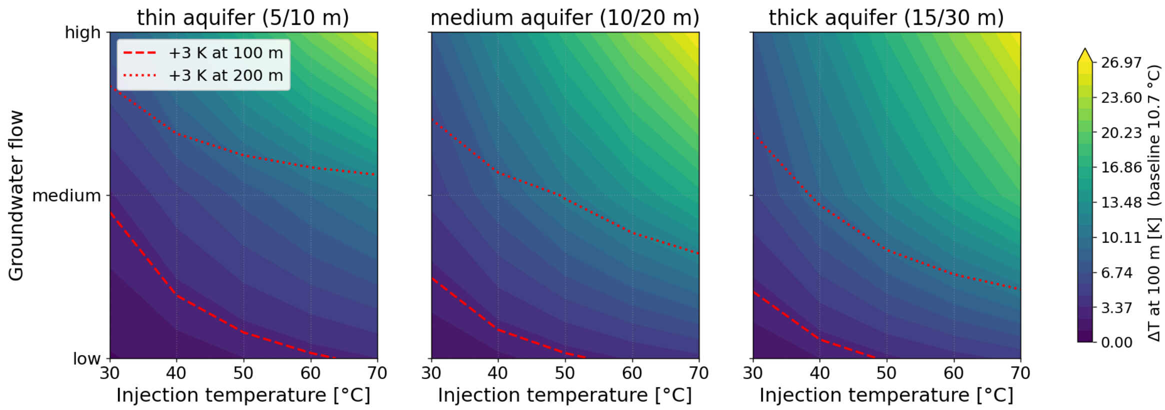


Fig. 11: Operating envelope: mean temperature rise over the final year above the undisturbed 10.7 °C, as a function of injection temperature and groundwater flow, for the three aquifer thicknesses. Colours and the dashed red line are the rise at the 100 m observation point, the dashed line marking the +3 K limit; compliant combinations lie below and to the left. The dotted red line is where the 200 m rise reaches +3 K — assessed at that distance, the compliant region is much larger.

Whether over-regeneration is possible at all is set by the groundwater flow. Only at low flow does the field tolerate charging well above the natural temperature, and even then the ceiling is modest: the 100 m rise stays within 3 K up to about 64 °C in the thin aquifer, 54 °C in the medium, and 49 °C in the thick, the thicker aquifer being more restrictive because it carries more heat to the 100 m point. At medium and high flow there is no room left: even the lowest injection tested, 30 °C, already exceeds the limit, by 3–5 K at medium flow and about 8 K at high flow. Over-regeneration is therefore an option only where the groundwater moves slowly.

The verdict depends strongly on where the limit is assessed. Measured at 200 m instead of 100 m (dotted line in Fig. 11), the compliant region grows sharply: at low flow the 200 m rise never reaches 3 K, and at medium flow it stays within the limit up to about 49 °C in the medium aquifer and 38 °C in the thick one, where the 100 m rule allows nothing. Only high flow breaches 3 K at 200 m throughout. Assessed at that distance, most of the medium-flow range would already permit over-regeneration.

These results describe a generic setting rather than one site, which is both their strength and their limit. The groundwater flow is prescribed as a controlled Darcy velocity across the plausible range, and the field is driven with a realistic seasonal injection cycle rather than a constant worst case, so the strong dependence on flow is a property of the physics and not of a particular calibration. Applying the envelope to a real site therefore requires that site's flow to be characterised, for instance by a thermal response test. The geology is representative of the Swiss Plateau, the layers are homogeneous, and each borehole carries a single U-tube; and while we map the extent of the 16 °C zone, we do not evaluate the 10 % habitat criterion of the Swiss exception, which needs the reference volume defined by the authority for the specific site.

4. Conclusion and future work

This work combines an operational energy-system analysis with a three-dimensional subsurface and groundwater model to assess deliberate over-regeneration of a borehole thermal energy storage at the OST Rapperswil campus demonstrator.

On the operational side, three regeneration concepts were compared. Relying on the cooling demand alone leaves the field in long-term thermal decline and requires deep boreholes, whereas adding an ambient-air heat exchanger achieves full regeneration and roughly halves the required borehole length. Driving the field further with active heat-pump regeneration charges the ground above its natural temperature: this lowers the electricity used for heating by about 50%, at the cost of about 30% higher total annual electricity consumption, and shifts the share of the electricity demand out of winter and into the summer. The winter-peak reduction and the better use of summer electricity are the operational motivation for over-regeneration.

On the subsurface side, this compact, over-regenerated field was modelled across a range of groundwater flow rates and aquifer thicknesses and regeneration temperature limits. The groundwater flow rate dominates the thermal impact: the Swiss limit of +3 K at 100 m is respected only when the flow is low, where the field can be charged up to roughly 49–64 °C depending on aquifer thickness, while at medium and high flow the limit is exceeded even at the lowest injection temperature tested. The permissible over-regeneration envelope is therefore narrow wherever groundwater flows through the field.

Taken together, the two analyses reveal a clear trade-off: over-regeneration is operationally attractive for reducing winter electricity, but at a groundwater-influenced site it is tightly bounded by groundwater-protection limits. A practical consequence is to operate conservatively at first - starting at low injection temperatures with monitoring and raising them only if the measured subsurface response allows - rather than committing to high-temperature charging from the outset. Future work will focus on a dedicated measurement campaign, including a thermal response test and distributed fibre-optic temperature sensing in a downstream borehole, to characterise the site-specific groundwater flow and thus tighten the operating envelope, together with a small set of low-temperature simulations to pin down the maximum compliant injection temperature at the measured flow.

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