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WinTES - Winterstrombedarf und Saisonale Thermische Speicher



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Luzern



THERMAL ENERGY STORAGE
www.hslu.ch/tes

ETH zürich

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Zusammenfassung

Das übergeordnete Ziel dieses Projekts ist das Potenzial der saisonalen Wärmespeicherung (STES) im künftigen Energiesystem der Schweiz zu bewerten.

Saisonale Wärmespeicher (STES) senken die Stromimporte im Winter, die Methan- und Dieselpimporte, den Bedarf an zusätzlicher Wintererzeugung durch Wärmekraftwerke sowie die Gesamtenergiesystemkosten. Je nach Szenario liegt die durchschnittliche thermische Speicherkapazität im Bereich von 6 bis 10 TWh, was zu einer erheblichen jährlichen Reduzierung der Stromimporte im Winter um bis zu 3.6 TWh führt. Zudem senkt der Einsatz von STES die Gesamtenergiesystemkosten um 400 bis 900 Millionen CHF pro Jahr. Daher müssen bereits **heute Pilotanlagen gefördert werden**, um die praktischen Erfahrungen aufzubauen und bei der landesweiten Umsetzung ab 2035 von diesen Erfahrungen profitieren zu können.

Eine GIS-basierte Analyse wurde durchgeführt, um potenzielle Standorte für die Umsetzung von STES in der Schweiz zu identifizieren. Dabei wurden geeignete Flächen unter Berücksichtigung energetischer, geografischer und infrastruktureller Randbedingungen bestimmt. Für die meisten analysierten Fälle konnten geeignete Speicherstandorte gefunden werden. Für die Erdbecken-Wärmespeicher (PTES) ist jedoch als Grundlage für die Bewilligungsfähigkeit hierfür in den meisten Fällen eine multifunktionale Abdeckung nötig.

Um diese Ergebnisse zu erzielen, wurden sowohl für die PTES als auch die Regeneration von Erdsonden (BTES) detaillierte Modelle typischer Ausführungsvarianten entwickelt.

Diese Ergebnisse wurden zur Implementierung von STES im Swiss Energy Scope-Modell (SES-ETH) verwendet, einem linearen Optimierungsmodell des Schweizer Energiesystems. Das SES-ETH wurde eingesetzt, um die Rolle von STES in verschiedenen Zukunftsszenarien zu untersuchen, darunter unterschiedliche Annahmen zu Klimazielen, internationaler Integration und technologischer Innovation. Unsicherheiten wurden mittels Monte-Carlo-Analyse berücksichtigt. Auf diese Weise zeigt das Modell, unter welchen Bedingungen STES kosteneffizient eingesetzt wird, in welchem Umfang dies geschieht und wie die gesamten jährlichen Kosten des Schweizer Energiesystems minimiert werden können.



Résumé

L'objectif général de ce projet était d'évaluer le potentiel du stockage saisonnier d'énergie thermique (STES) dans le futur système énergétique suisse.

Le stockage saisonnier d'énergie thermique (STES) permet généralement de réduire les importations d'électricité en hiver, les importations de méthane et de diesel, le besoin de production supplémentaire en hiver par les centrales thermiques, ainsi que les coûts totaux du système.

Selon le scénario, la capacité moyenne de stockage thermique se situe entre 6 et 10 TWh, ce qui entraîne une réduction annuelle significative de la consommation d'électricité en hiver. De plus, l'intégration des STES permet de réduire les coûts globaux du système de 400 to 900 millions de francs suisses par an. Ces résultats soulignent l'importance de promouvoir dès aujourd'hui des installations pilotes à pleine échelle afin d'acquérir l'expérience nécessaire pour un déploiement national à partir de 2035.

Une analyse basée sur un système d'information géographique (SIG) a été réalisée afin d'identifier les sites potentiels pour le déploiement du STES en Suisse. Cette analyse a permis de déterminer les surfaces appropriées en tenant compte de contraintes géographiques et infrastructurelles. Pour la plupart des cas analysés, des sites de stockage appropriés ont pu être trouvés. Dans la plupart des cas analysés, des sites de stockage appropriés ont pu être trouvés. Pour la majorité des sites, une couverture multifonctionnelle du PTES est nécessaire pour que l'autorisation puisse être accordée.

Pour obtenir ces résultats, des modèles détaillés ont été développés pour les stockages thermiques en fosse (PTES) et les stockages thermiques par sondes géothermiques (*Borehole Thermal Energy Storage*, BTES). Les simulations ont permis de déterminer des indicateurs clés tels que la capacité effective de stockage, le rendement et la puissance disponible. Des relations de performance simplifiées ont ensuite été dérivées pour l'intégration du STES dans le modèle Swiss Energy Scope, un modèle d'optimisation linéaire du système énergétique suisse. Le modèle élargi a été utilisé pour analyser le rôle du STES dans différents scénarios futurs, en tenant compte des objectifs climatiques, de l'intégration internationale, de l'innovation technologique et des incertitudes par analyse Monte-Carlo.



Summary

The overall aim of this project was to assess the potential of **Seasonal Thermal Energy Storage (STES)** in Switzerland's future energy system.

Seasonal Thermal Energy Storage generally reduces winter electricity imports, methane and diesel imports, the need for additional winter generation from thermal power plants, and total system costs. Depending on the scenario, the average thermal energy storage capacity is in the range of 6 to 10 TWh, leading to a significant annual reduction in winter electricity imports of up to 3.6 TWh. In addition, the inclusion of STES reduces total system costs by 400 to 900 million CHF per year. Therefore, **full scale pilot plants have to be fostered now** to fully benefit from these experiences in the wave of nationwide implementation from 2035 onwards.

A GIS-based analysis was conducted to estimate the potential locations for STES deployment in Switzerland by identifying suitable areas under geographic and infrastructural constraints. Suitable storage sites were identified in most of the analysed cases. However, multifunctional PTES coverage is usually a necessary prerequisite for approval.

To achieve these results, detailed models of archetypal implementation variants were developed for both PTES and borehole thermal energy storage (BTES). For PTES, different storage sizes and heating demands were analysed to determine key performance indicators such as effective storage capacity and efficiency. For BTES, a wider range of operating cases was investigated, since storage capacity and power strongly depend on charging and discharging strategies. Based on these detailed simulations, simplified performance relationships were derived for the implementation on the overall system model level.

These results were used to implement STES in the Swiss Energy Scope model (SES-ETH), a linear optimization model of the Swiss energy system. The enhanced model was applied to evaluate the role of STES across a range of future scenarios, including different assumptions on climate targets, international integration, and technological innovation, while accounting for uncertainty through Monte Carlo analysis. In this way, the model shows under which conditions STES is deployed cost-effectively and at what scale, while minimizing the total annual cost of the overall Swiss energy system.



Take-Home-Message

- **STES can provide significant benefits for the Swiss energy transition** by shifting heat supply from summer to winter, reducing pressure on the electricity system during the winter months, and increasing the flexibility of district heating and heat-pump-based energy systems. **Seasonal thermal storage reduces the total system costs** by 400 to 900 million CHF per year.
- **In a cost-optimal decarbonized Swiss energy system, model results indicate installed thermal energy storage capacities up to 10 TWh.** Pit thermal energy storage reaches between 3 to 6 TWh, decreasing from conservative to innovative scenarios, while borehole thermal energy storage ranges from 2 to 6 TWh, increasing from conservative to innovative scenarios.
- **Thermal energy storage reduces Switzerland's dependence on external energy sources**, such as gas and winter electricity imports. Compared with a system without thermal storage, winter electricity imports are reduced by up to 3.6 TWh/year, with a stronger impact in more ideal scenarios. Imported fuels are reduced by up to 3.2 TWh/year through the deployment of thermal storage options.
- **Full-scale pilot plants for thermal energy storage should be promoted and implemented now** to build the operational experience needed for broad nationwide implementation from 2035 onwards.



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List of abbreviations

AEE	AEE Suisse
BFE	Bundesamt für Energie
BEV	Battery Electric Vehicle
BLW	Bundesamt für Landwirtschaft
BTES	Borehole Thermal Energy Storage
CHP	Combined Heat and Power
COP	Coefficient of Performance
DHN	District Heating Network
DHW	Domestic Hot Water
EPFL	École Polytechnique Fédérale de Lausanne
ETH	Eidgenössische Technische Hochschule
EU	Europäische Union
EWL	Energie Wasser Luzern
GeoPATH	GIS-basiertes Analyse-Tool zur Potenzialabschätzung
GIS	Geographic Information System
HEX	Heat Exchanger
HP	Heat Pump
HSLU	Hochschule Luzern
HW	Hot Water
IEA	International Energy Agency
KPI / KPIs	Key Performance Indicator(s)
NZZ	Neue Zürcher Zeitung
PTES	Pit Thermal Energy Storage
PV	Photovoltaik
QM	Quality management
SAF	Sustainable Aviation Fuels



SES-ETH	Swiss EnergyScope ETH
SH	Space Heat
SIG	Système d'information géographique
SNF	Schweizerischer Nationalfonds
SOTES	Sociopolitical Acceptance of STES
SPF	Seasonal Performance Factor
STES	Seasonal Thermal Energy Storage
sTES	seasonal Thermal Energy Storage
TES	Thermal Energy Storage
TRL	Technology Readiness Level
UVEK	Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation
WIP	Waste Incineration Plant
WWTP	Wastewater Treatment Plant



1 Introduction

1.1 Motivation & Background

By 2050, the energy system must be transformed from a net emitter of greenhouse gases into a CO₂ sink. The challenges on the way there are manifold. One major challenge is to overcome the imbalance between production and consumption of electricity, heat and other forms of energy. According to the basic scenario of the federal government's Energy Perspectives 2050+, there is a deficit of around 9 TWh of electrical energy in winter, which must be covered by imports. Switzerland's security of supply would therefore be heavily dependent on electricity imports (1).

Various types of storage can enable temporal balancing between generation and consumption. By coupling the electricity and heating sectors (primarily by means of heat pumps), thermal energy storages (TES) can play a central role. The position paper of Forum Energiespeicher Schweiz "*Winterstrombedarf und saisonale Wärmespeicher – mit Sommerwärme Strom im Winter sparen*" states that large seasonal thermal energy storage (STES) systems can help to significantly reduce impending uncovered winter electricity demand. Studies conducted as part of the SWEET-DeCarbCH project show that STES can potentially reduce winter electricity demand by around 4 TWh. Thermal energy storage systems therefore make an important contribution to increasing security of supply. The results published in the position paper were generated using the Swiss EnergyScope ETH (SES-ETH) energy system model. This optimizes the provision of electricity, heat and mobility services in terms of system costs (annualized investment and operating costs) for a defined CO₂ target in a future year (e.g. 2050).

This project aims to improve the representation of the TES for the SES-ETH model. Therefore, detailed TES systems embedded in representative scenarios of local energy systems were modelled, to evaluate both different implementation scenarios and component sizes. Subsequently, polynomial functions of system variables (e.g., storage volume, storage height for large-scale sensible heat storage) will be fitted to describe the influence of these variables (inputs) on key system performance indicators (KPIs such as operating costs, self-sufficiency, etc.) as outputs. The results then represented TES technologies in a simplified way, to be integrated into the linear model structure of the SES-ETH.

In addition, GIS (geographic information system) data will be used to identify the potential for large-scale TES systems in Switzerland. Based on a nationwide analysis that considers various energy sources, placement possibilities and energy demand, the energy potential limited by geographical constraints are analysed.



1.2 Project Goals

The overarching goal of the project is to conduct an in-depth analysis of the potential for seasonal thermal storage systems within the Swiss energy system and to disseminate resulting recommendations, necessary actions, and specific implementation variants.

Goals:

- The potential analysis will be conducted both top-down, based on the representation of the Swiss energy system in the ETH Swiss EnergyScope (SES-ETH), and bottom-up, using GIS-based potential analysis models that generate a potential map for integrating large TES systems in Switzerland. These maps will analyse the distribution of archetypal, representative scenarios and focus on the neighbourhood and municipal levels.
- The implementation variants will provide detailed archetypal, representative scenarios for seasonal thermal storage systems within local energy systems.
- The recommendations will identify which technological TES options should be installed, in which context, where, and when in Switzerland.
- Dissemination will focus on publishing an updated and expanded second version of the **AEE Suisse Position Paper on Winter Electricity Demand and Seasonal Storage**, following the significant impact of the 2022 first version on politics and energy providers. Additionally, project results will be strategically communicated to the public, policymakers, and relevant stakeholders. Dissemination formats and methodologies will build on insights from the ongoing **SNF Sinergia Project SOTES** (Sociopolitical Acceptance of STES). Distribution will include collaboration with the **Swiss Association for Thermal Networks**, **Espace Suisse**, and the **Swiss Museum of Transport**.

Research Questions:

1. **What is the quantifiable potential of seasonal thermal storage systems to positively impact the resilience of the Swiss energy system in a net-zero scenario?**
This quantifiable potential includes reducing winter electricity demand through large heat pumps producing heat in the summer for winter use, combining year-round heat sources like waste incineration plants with thermal storage, and reducing energy imports for low-temperature industrial processes. Additional potential includes optimizing biomass usage for high-temperature applications and enhancing year-round energy security in Switzerland.
2. **Where, and at what time, should large seasonal thermal storage systems be installed in Switzerland to maximize this potential?**
3. **Which archetypal implementation variants** (e.g., detailed scenarios involving waste incineration plants and pit thermal storage integrated into 3rd generation thermal networks) **best represent the most replicable scenarios for seasonal thermal storage systems in the Swiss energy system?**



2 Detailed Modelling of Archetypical Implementation Variants

2.1 PTES

The following use case is considered: A PTES is connected to a high temperature heat source supplying a district heating network. As it is typical for biomass- and waste-to-energy power plants, the network is supplied by extracting steam from Rankine cycles after passing through high-pressure turbine stages. In such cases, supplying heat to the network somewhat reduces electricity generated by the power plant, making it desirable to reduce thermal load. The seasonal load-shifting achievable by PTES can thereby increase the power plant's electricity output during winter demand peaks. The assumed integration of the PTES within the district heating network is depicted in Figure 1. During charging, the PTES heat exchanger is parallel to the load (red arrow). During discharging, the backflow of the network – or some fraction of it – is preheated as it passes through the heat exchanger (orange arrow), before it is further heated to supply temperature by the heat source.

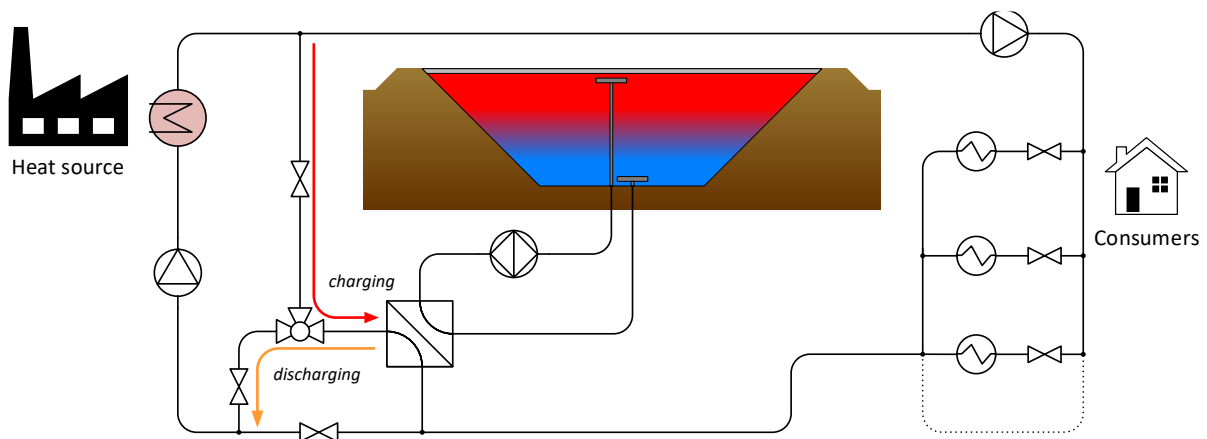


Figure 1: Considered PTES integration

To simulate the PTES, an adapted version of the pit storage model in the MoSDH Modelica library (v1.2) was employed (2). This model uses finite volume discretization for an axisymmetric 2D representation of the storage volume and the surrounding ground. The water volume is discretized vertically into 15 segments. The boundary condition prescribing ambient air temperature on the ground and lid surfaces was replaced; A thermal resistance representing convective heat transfer (partially windspeed-dependent) was added between the surfaces and the ambient temperature boundary condition, and additional surface heat flux was also prescribed to represent solar heat gain.

Most parts of the thermal network were not modelled but rather replaced by two working fluid boundary conditions at fixed temperatures of 95°C and 50°C to account for hot and cold fluid entering the heat exchanger during charging and discharging respectively. The heat exchanger was assumed to operate with identical mass flow rates on both sides, controlled to reach a specified charging / discharging power. This power was then set to compensate for the mismatch between heat demand and the maximum heat source power. Since this approach assumed that a variable fraction of the network's backflow is preheated by discharging, an additional limit was imposed on the flow rate to prevent it from exceeding the flow rate of the entire network. (This was only relevant when the pit is almost depleted and pre-heating only achieves limited temperature lift.)



The simulation was based on heat demand measured in a district heating network operated by EWL and supplied by the Renergia waste-to-energy plant. The annual heat demand corresponds to 75 880 MWh and a power of up to 32.5 MW, which is currently supplied by the waste incineration plant directly. Two cases were simulated with different PTES volumes. Naturally, a larger pit size means less of the demand must be supplied directly from the heat source, and it therefore allows limiting its power to a lower value. The power limits were picked by trial simulations in a way that ensured the pit is discharged as much as possible during winter, but without ever encountering a situation when demand cannot be met by the combined power of the heat source and the pit.

Results

The simplified SES-ETH model represents all storage technologies using only a handful of metrics including capacity, power and efficiency. The results for the two scenarios are summarized in Table 1. The difference between the minimum and maximum of enthalpy contained in the water volume was used as the effective capacity. This takes into account the imperfect stratification which prevents reaching a uniform temperature at the fully charged and discharged state, and the slight power-dependent variations in inlet temperature during charging and discharging due to the finite heat exchanger surface. The reported PTES power corresponds to the 95th percentile of the discharging power. Additionally, the number of storage cycles is computed by dividing the total energy discharged from the PTES by its effective capacity.

Table 1: Summary of metrics for the two PTES cases

pit size	direct supply power limit	effective PTES capacity	PTES efficiency	PTES power	Number of cycles
150 000 m ³	17 MW	5 402 MWh	81.5%	14.83 MW	1.48
280 000 m ³	14 MW	9 720 MWh	84.1%	17.14 MW	1.33

As expected, the larger pit capacity leads to (almost) proportionally larger capacity but also slightly less full storage cycles. The efficiency of the larger pit is also slightly higher due to more favorable surface-to-volume ratio. It must be noted that Figures above refer to the 6th year of operation. The efficiency in the first year is 6 - 7% lower, increasing gradually through the first 3-4 years as the ground surrounding the pit warms up.

Figures 2 and 3 present the annual progression of heat supply and demand along with PTES charging and discharging power, highlighting the seasonal load-shifting achieved. Comparing the discharged energy to the annual demand, the smaller PTES covers 10.5% while the larger one covers 17.0%. Given the magnitude of heat supply and demand, it would be conceivable (at least in principle) to further increase PTES size since there is still a large amount of unutilized heat available during summer.

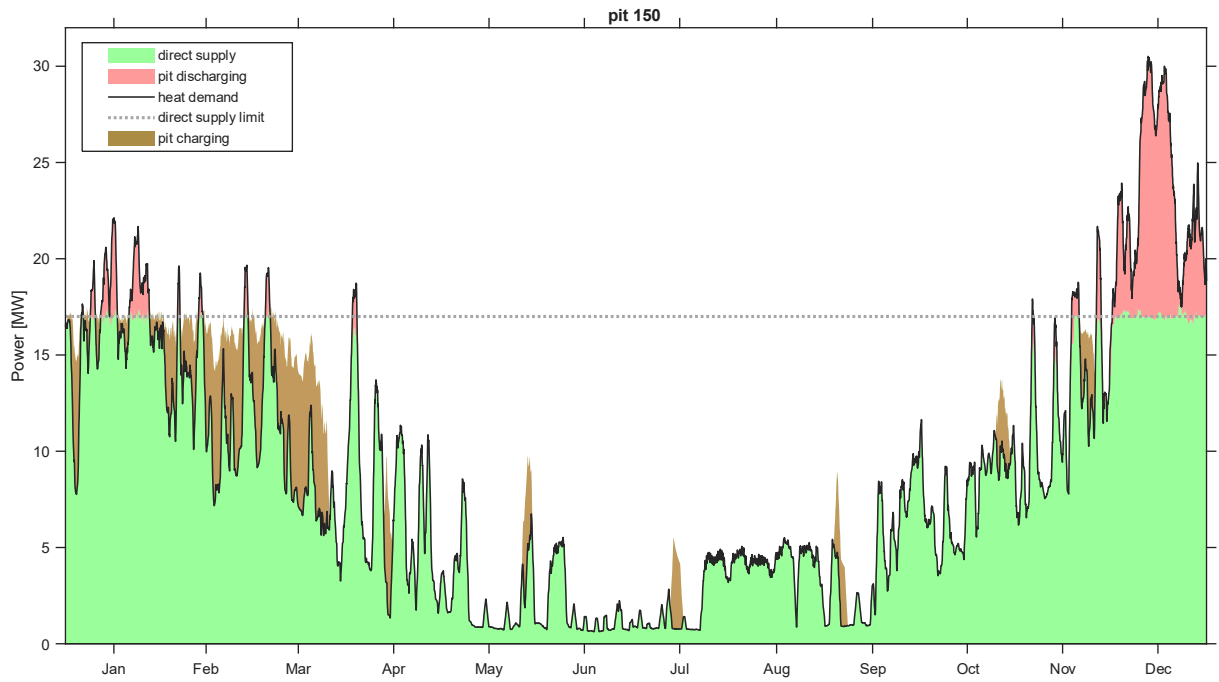


Figure 2: Annual power balance with the smaller PTES

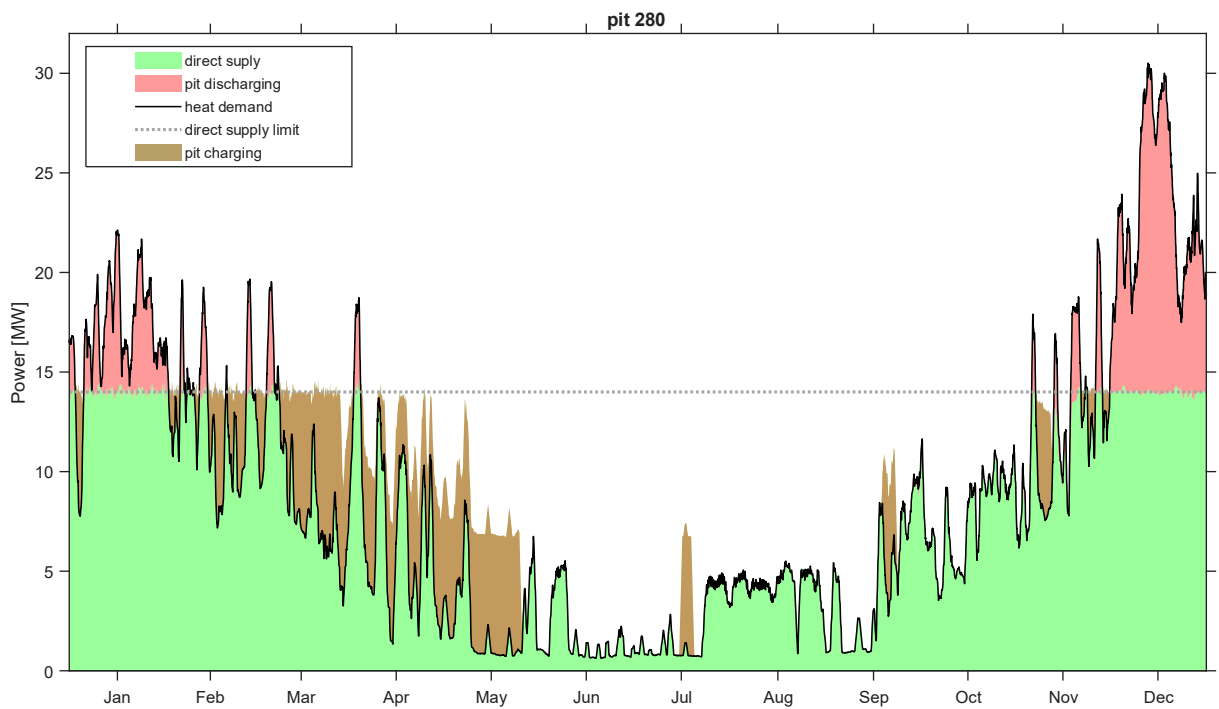


Figure 3: Annual power balance with the larger PTES



2.2 BTES

The storage representation of the simplified SES-ETH model based on capacity and power is particularly unsuitable for BTES, as the capacity and power of a borehole mostly results from the way it is operated. Since diffusion is the dominant mode of heat transfer, a non-negligible temperature gradient is always present in the storage medium. This means that one cannot simply designate a nominal temperature difference, as different regions within the storage medium are subject to very different seasonal temperature fluctuation. The magnitude of internal temperature gradients depends mostly on the power used to charge / discharge the BTES. However, making capacity dependent on the operation of the storage would introduce nonlinearities to the simplified model that cannot be handled by the optimizer. This problem was tackled by creating various operating cases for the BTES, each expected to result in different effective storage capacity and/or peak power. These cases can then be introduced to the simplified model as quasi-independent storage options, ideally leading to the optimizer selecting or prioritizing the most desirable operating case.

All BTES cases consider the same borehole field, the specifications are described in Table 2. This borehole field is represented by a model from the Modelica Buildings library (v10.0.0) (3) that relies on Eskilsson's thermal response function approach (4). To ensure accuracy on short timescales, heat transfer within the grout is resolved using the finite volume method with 6 vertical and 4 axial discretization segments. However, detailed modelling of the temperature evolution within the thermally active ground volume can be omitted by using the appropriate thermal response function. Further details on the modelling approach can be found in (5).

Table 2: Specifications of the considered BTES

Number of boreholes	100 (10 x 10 rectangular grid)
Borehole depth	150 m
Borehole spacing (center to center)	7.5 m
Borehole diameter	160 mm
Pipe configuration	Single U-tube, boreholes in parallel
Pipe diameter	40 mm
Shank spacing (pipe center to pipe center)	100 mm
Grout filling volumetric heat capacity	1'920 kJ/m ³ K
Grout filling thermal conductivity	2.5 W/mK
Ground volumetric heat capacity	1'620 kJ/m ³ K
Ground thermal conductivity	1.5 W/mK
Geothermal gradient	0.025 K/m

In all considered cases, the BTES is discharged by a heat pump supplying a heating network. A synthetic heat demand profile is used to prescribe condenser power, with the scaling of this profile varied between cases. The demand profile was constructed using the heating degree hours approach based on ambient air temperature (24-hour moving mean, measured in Würenlingen), and a heating limit of 14°C. The heat pump was represented by a single equation relating the condenser- and evaporator powers based on the evaporator inlet temperature, with a constant quality-grade of 0.55.

Individual cases were simulated with different heat supply and/or demand, resulting in different effective BTES capacity, power and temperature evolution. 10 years of operation were simulated for each case, and the results of the last year were evaluated. The temperature at the warmer side of the BTES field (inlet during charging, outlet during discharging) is later used to pre-compute the COP for each case in the linear SES-ETH model.



Free regeneration

In this scenario, an air-brine heat exchanger acts as the heat source. The ambient air temperature is specified as a dynamic boundary condition, along with the thermal conductance of the HEX (as opposed to specifying the available power). The considered hydraulic arrangement is depicted in Figure 4.

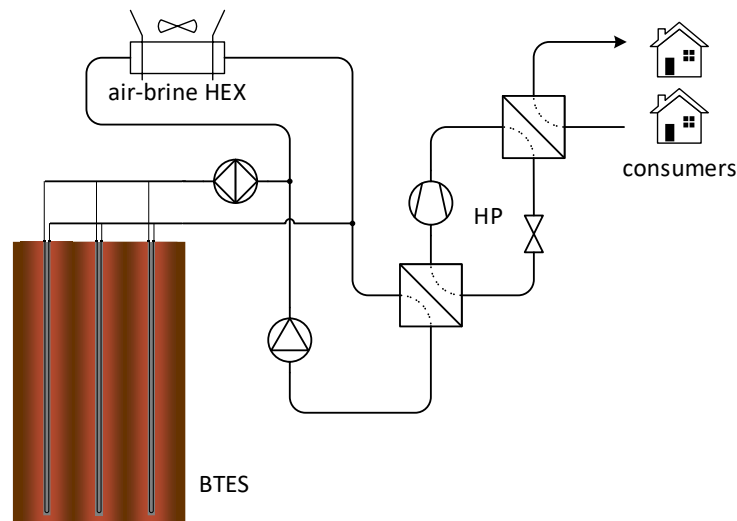


Figure 4: Considered system-integration of the BTES

During the heating season, boreholes are discharged with the HEX inactive as long as the BTES outlet temperature stays above the ambient air temperature (-3 K hysteresis). When heat can be extracted from ambient air at a higher temperature than available from the BTES, it is used to both to supply heat directly to the evaporator and regenerate the boreholes. The evaporator operates with a constant temperature difference of 3 K and the flow rate is therefore directly related to the evaporator power. During regeneration, the flow rate through the BTES is controlled to maintain the same 3 K temperature difference, meaning the working fluid's temperature evolves based on both ambient air temperature and BTES charging power (the higher the ambient air temperature relative to the BTES grout, the higher the charging power / flow rate).

Two cases were simulated with a factor of 2 difference in the heat demand profile's scaling. The case with higher demand was expected to lead to more energy being discharged from the BTES, but at a lower temperature. Additionally, a case with no regeneration and the BTES as the only heat source was simulated for reference, comparing 100 free-standing boreholes to one field of 100 boreholes.

Forced charging

In contrast to the previous scenario where the heat source's temperature was specified rather than its power, this scenario replaces the air-water HEX with a heat source delivering a specified power independent of temperature. This scenario simplifies the control logic, as the required BTES power is the difference between the power of the evaporator and the heat source. Two types of heat source profiles are investigated; The first one is a constant waste heat supply approximating, for example, the waste heat rejected by a data center. The second type is a sinusoidal heat supply profile with no offset that has its minimum in the middle of January. This represents a particularly relevant scenario for this project with a very strong mismatch between heat supply and demand.

The availability of an active heat source enables an increase of storage capacity and/or temperature: Since BTES power is determined by the chosen scaling of heat supply and demand, proportionally



increasing both leads to more energy being charged and discharged, at the cost of a higher charging- and lower discharging temperature. On the other hand, if a higher heat supply is specified than the total energy absorbed by the evaporator, the excess is accumulated in the ground until it is balanced by storage losses, thereby elevating the entire storage temperature range. Four cases were simulated with each supply profile (constant and sinusoidal) to explore both above effects.

Results

The relevant intermediate results obtained from simulations are the effective BTES capacity, power, efficiency and seasonal temperature evolution. The capacity was obtained by integrating the net BTES power, resulting in a seasonal oscillation representing the sum of energy accumulation- and loss. The peak-to-peak value of the rising (charging) segment was interpreted as the effective capacity. The 95th percentile of the BTES discharging power was chosen to represent the 'nominal' power in each case. The seasonal temperature evolution (smoothed with 30-day moving mean) is plotted in Figures 5 - 7 for comparison. Table 3 contains overall metrics for each case, with the SPF of the simulated heat pump indicative of heat source temperature. This SPF is for reference only and is not used in the simplified model.

Cases are identified by the following parameters:

	1	2	3	4
BTES	forced	scal100	Q107	Const

- 1 Type of regeneration /charging
- 2 Scaling of demand profile, a value of 1 corresponds to 12 MWh. (e.g. scal100 = 1200MWh)
- 3 Annual mean power of the heat source in kW (if applicable)
- 4 Shape of heat source profile (if applicable)



Table 3: Summary of metrics resulting from each BTES case

#	Case	Power [W/m]	Capacity [kWh/m]	Efficiency [-]	SPF [-]
0	BTES noReg scal100*	19.9	-	-	4.25
1	BTES free scal100	20.5	44.7	104%	4.54
2	BTES free scal50	10.6	29.8	92%	4.98
3	BTES forced scal100 Q107 const	17.2	30.0	102%	4.72
4	BTES forced scal125 Q161 const	20.3	47.2	68%	5.21
5	BTES forced scal200 Q215 const	33.3	59.8	102%	4.48
6	BTES forced scal250 Q322 const	40.1	93.3	68%	5.35
7	BTES forced scal100 Q107 sin	24.6	54.5	101%	4.52
8	BTES forced scal109 Q161 sin	27.7	85.2	67%	5.32
9	BTES forced scal150 Q161 sin	36.2	81.5	98%	4.39
10	BTES forced scal163 Q241 sin	41.3	116.8	68%	5.52

* Single unregenerated borehole with a demand scaling of 1, comparable to the BTES field with *scal100*

Comparing the two cases of free regeneration, downscaling the demand leads to an expected drop in capacity and power, and in return higher temperature and SPF. The storage efficiency changes accordingly, as an indication of the mean temperature of the thermally active ground volume relative to the undisturbed ground temperature. (The efficiency exceeding 100% in case 1 implies overall thermal gains rather than losses.) This is also valid for forced charging; in cases 3, 5, 7 and 9 an efficiency close to 100% means an oscillation around the undisturbed ground temperature, while the 67-68% efficiency in cases 4, 6, 8 and 10 implies an elevated temperature range. Note that the choice of heat supply and demand in forced charging cases pre-determines the efficiency in steady state.

Comparing different supply profiles, an identical scaling of annual heat supply and demand in cases 3 and 7 leads to less energy stored in the BTES if the heat supply is constant, since a larger share of the demand can be covered directly. (This is the reason why the demand profile's scaling was chosen differently for further constant and sinusoidal cases.) Comparing cases 3 to 5, and 7 to 9, it can be confirmed that a more intense use of the BTES – with the same mean temperature but larger oscillation amplitude – has negative impact on heat pump performance. There is therefore a trade-off between the cost of additional boreholes and savings on electricity. Similarly, increasing the overall temperature range trades additional heat supply in summer due to increased storage losses for reduced electricity consumption in winter due to higher COP.

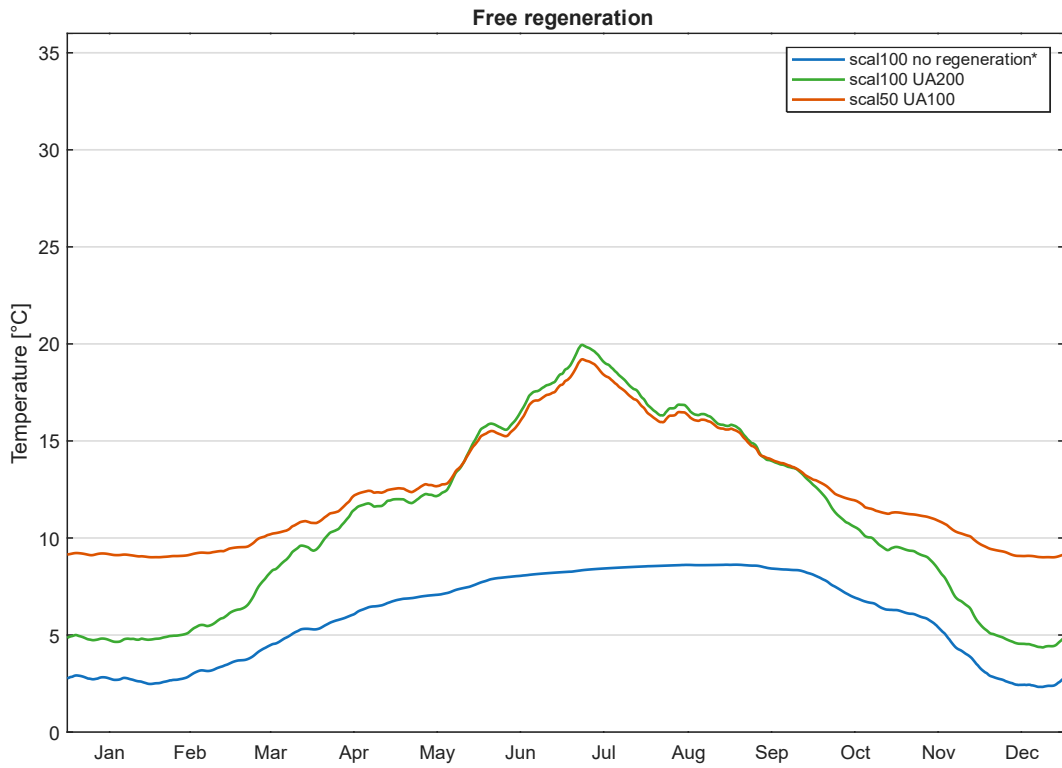


Figure 5: Fluid temperature evolution of free regeneration cases
*single free-standing borehole with no regeneration, for reference

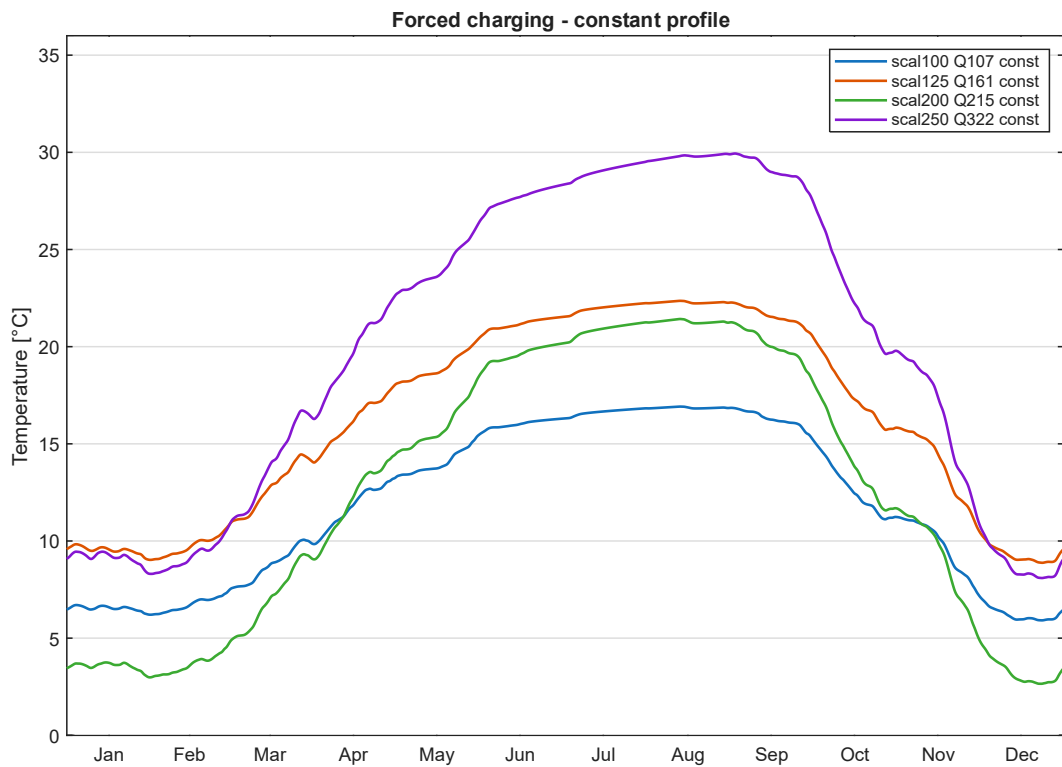


Figure 6: Fluid temperature evolution of forced charging cases with constant heat source profile

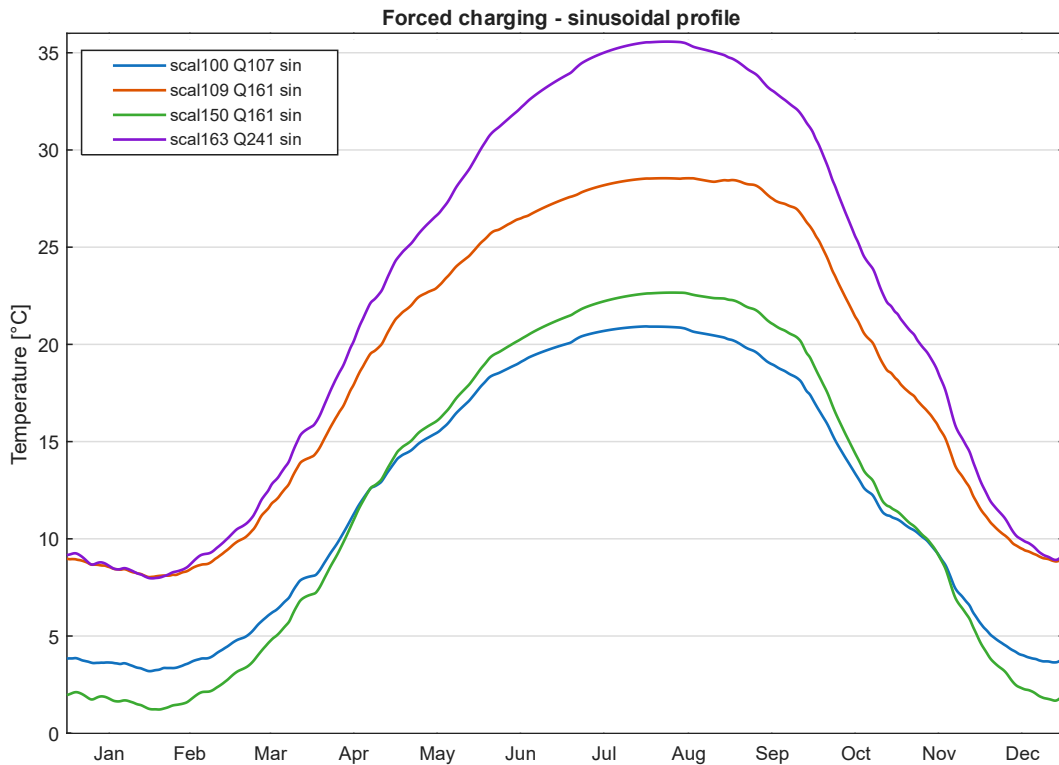


Figure 7: Fluid temperature evolution of forced charging cases with sinusoidal heat source profile

2.3 Cost

In the SES-ETH model, technology costs are parameterized through investment costs defined per unit of energy capacity and per unit of power. The derivation of these cost inputs differs between storage concepts.

For PTES, energy capacity and charging/discharging power can be treated independently, as the storage volume and the heat-exchanger design are decoupled. Investment costs are therefore defined per cubic meter of storage volume and translated into costs per unit of energy capacity using archetypal simulation results. These simulations account for the effectively usable storage capacity of the reference volume, determined by the application-specific useable temperature difference.

In contrast, for BTES, both energy capacity and power are primarily governed by the total length of the ground heat-exchanger pipes and additionally depend on the chosen operational strategy. Since multiple operational strategies are considered, several BTES archetypes are defined. Investment costs are therefore calculated per meter of borehole length and subsequently converted into costs per unit of energy capacity and power separately for each archetype based on their specific operational behaviour.

PTES

The investment-cost data for PTES systems show a clear correlation with storage volume, with specific costs decreasing as volume increases. Reported volume-specific investment costs range from approximately 35 to 320 USD/m³, with a median of about 115 USD/m³ (6). For the two cases with storage volumes of 100'000 m³ and 280'000 m³, the cost function reported by Lüchinger et al. (6) yields specific investment costs of 63.62 USD/m³ and 41.11 USD/m³, respectively. Applying the exchange rate of 0.77 CHF/USD by February 2026 (7), this corresponds to 48.99 CHF/m³ and 31.65 CHF/m³.



Dividing by the discharged energy density per unit volume, $54.02 \text{ kWh}_{\text{discharged}}/\text{m}^3$ and $34.71 \text{ kWh}_{\text{discharged}}/\text{m}^3$, results in specific costs of 0.907 CHF/kWh and 0.912 CHF/kWh, respectively.

BTES

Borehole installation costs depend on local ground properties, drilling depth, and site-specific conditions. Publicly available sources report typical costs in the range of 50 to 100 CHF/m for borehole installation in Switzerland. A factsheet published by Geothermie Schweiz reports costs of 60 to 90 CHF/m for single boreholes under conventional conditions (8). This cost range is consistent with values reported by various online sources such as online cost calculators and websites of Swiss drilling companies. A comparison with borehole drilling costs in neighbouring countries, based on the GeoBOOST deliverable report (9), indicates similar orders of magnitude, with reported costs of 70 to 130 EUR/m in Austria, France, and Germany.

Most available references primarily focus on single-borehole installations. For large BTES systems consisting of borehole fields, lower unit costs per meter can be expected due to economies of scale. Conversely, several of the cited sources are based on older data, implying that present-day costs are likely higher due to inflation. It is assumed that these opposing effects largely compensate each other. Consequently, borehole installation costs are assumed to remain within the same order of magnitude presented. This aligns well with cost correlations reported by LÜchinger et al. (10), which point to drilling costs of approximately 85 to 108 USD/m for BTES systems of comparable size to the reference system considered here (15'000 m), which corresponds to roughly 65 to 83 CHF/m using exchange rate of 0.77 CHF/USD. Based on this assessment, an average borehole cost of 80 CHF/m is adopted for the BTES cost parameterization in the SES-ETH model.



3 Potential Map for Seasonal Storage Technologies

To assess the potential and impact of large-scale heat pump integration with thermal energy storage and district heating networks in Switzerland, the GIS-based analysis tool GeoPATH was developed. GeoPATH provides a systematic framework for identifying and evaluating the maximum potential deployment of a given technology based on spatial and energetic constraints. Unlike site specific case studies, GeoPATH is designed to assess opportunities across the entire country. It combines high-resolution geographical datasets (e.g., land use, topography, slope) with energy-related indicators (e.g., heating demand, supply infrastructure) to construct a consistent and scalable evaluation methodology. The goal is to identify the geographical maximum potential of TES implementation under varying assumptions and constraints. The tool allows users to define technical and spatial constraints, identify feasible areas, and analyze how different assumptions influence the deployment of a given technology.

Within this project, the GeoPATH tool was used to identify thermal energy storage sites close to heat demand and heat source (optional). The workflow is described in detail in section 3.2.

3.1 Data Aggregation

GeoPATH utilizes a wide range of spatial datasets, primarily derived from swisstopo and is complemented by heating demand data from PATHFINDER WP2 (11). The following data layers are considered:

- Land use (agricultural areas (12), leisure areas (13), transportation infrastructure (13))
- Topography (slope data, elevation models, (14))
- Buildings (data with associated heat demand and heat source, (11), (15))

3.2 GeoPATH workflow

The analysis workflow in GeoPATH is structured into three main steps:

Step 1: Identification of building clusters with high heat demand and fossil heating

- Buildings with heat demand are grouped into clusters. (potential DHN)
- Configurable parameters include:
 - Minimum number of buildings per cluster
 - Minimum heat demand per cluster
 - Maximum distance between buildings (cluster span)

Step 2: Storage site identification

- Potential sites for thermal energy storages are identified based on:
 - Zoning category (e.g., agricultural or recreational land)
 - Maximum slope gradient (reasons high inclination angles would bring additional challenges for construction and, therefore, have not been constructed like this before). Typical values include less than 5°
 - Land surface area requirements, which depend on the desired coverage rate and storage density



Step 3: Linking clusters and sites

- The required area of the storage site is selected depending on the energy demand of the cluster.
- A maximum allowable distance is defined (e.g., 20 meters per kilowatt of installed capacity) to ensure technical feasibility.

For Step 3, an algorithm was developed, which was published at CISBAT 2025 (16).

3.3 GeoPATH input definition

Step 1: Formation of heat demand clusters

In a first steps, areas of potential district heating networks are identified. Therefore, building groups with heating density of 70 kWh/m² (17) and a maximum distance between two buildings of 200 m were clustered. The minimum number of buildings to build a cluster forming a new district heating network was set to 50 buildings. This results in a total heat demand of 16 TWh/y divided into different clusters within Switzerland (Figure 8).

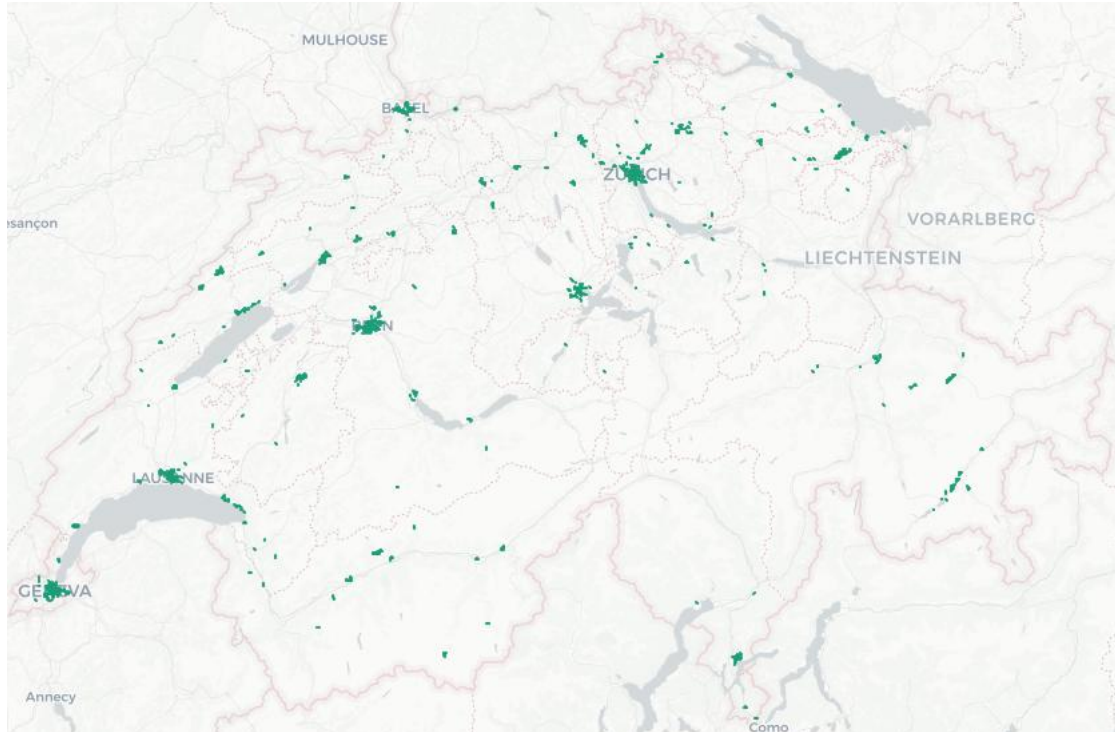


Figure 8: Locations of clustered district heating networks according to the selection criteria in Section 2.2.2, adding up to a total of 16TWh of heat demand.



Step 2: Waste heat source identification

Secondly waste heat sources were identified. Within WinTES the following heat sources were identified:

- No restriction
- Wastewater treatment plants (WWTP)
- Waste incineration plant (WIP)

Step 3: Storage site identification

For the storage sites two different technologies were analyzed: pit thermal energy storage (PTES) and borehole thermal energy storage (BTES). It was assumed that both PTES and BTES can only be constructed on surfaces without existing buildings and a maximum slope of 5%.

Additionally, the suitable land can be chosen as one or multiple of the following zones:

- Agricultural area “Landwirtschaftliche Nutzungsflächen Schweiz (Bundesamt für Landwirtschaft BLW, Kantone)”
 - Cropland (Ackerflächen)
 - Permanent meadows and pastures (Dauerwiesen & Dauerweiden)
 - Others were neglected after consolidation with cantonal agriculture experts. Either it is not feasible due to long lifetime of the surface plants and deep roots (Forest, Reben, Obstanlagen) or it is highly unfeasible due to natural protection (Sömmerungsflächen) or other reasons.
- Golf course area
- Sport ground area
- Zone for public use (Zonen für öffentliche Nutzung)
- Restricted building area (eingeschränkte Bauzonen)

To enable an actual placement of a PTES systems on most of the above-mentioned areas, a multi-use of the PTES lid is a prerequisite. This condition is not state of the art today, however within the Innosuisse Flagship project SwissSTES (<https://www.swissstes.ch/>), the multi-use of the PTES lid is investigated. Furthermore, within the same Innosuisse project the social acceptance of the PTES system depending on the multi-use is investigated. Preliminary results show that each of the possible multi-use within the survey (Sport ground, parking space, Biodiversity area) increases the social acceptance of PTES.

Step 4: Linking Clusters, Source and Sites

It is assumed that TES covers only a fraction of the DHN heat demand. Accordingly, the required storage capacity for a given DHN can be determined.

For PTES, this share is predefined as 15%, and the areal energy storage density is calculated as follows: (Figure 9):

$$ArealEnergyStorageDensity_{PTES} = \frac{Q}{A} = \frac{(V \cdot c_p \cdot \Delta T) \cdot 2}{A} = \frac{(c_p \cdot \Delta T) \cdot 2}{\frac{A}{V}} = \frac{60000 m^3 \cdot 1.163 \frac{kJ}{m^3 K} \cdot 80 K \cdot 2}{13670 m^2} = 817 \frac{kJ}{m^2} \approx 800 \frac{kJ}{m^2} *$$

*Assumptions: Storage medium water, Delta T of 80 K, Volume and Surface area from Dronninglund (18), factor 2 is considered since PTES capacity is discharged multiple times over one year.



For BTES, storage coverage and the areal energy storage density are obtained from the simulation results (Figure 9). The areal energy storage density is defined by the ratio of discharged heat divided by the surface area required:

$$ArealEnergyStorageDensity_{BTES} \left[\frac{kWh}{m^2} \right] = \frac{Q_{discharge}}{A}$$

The required surface area is then calculated from of the areal energy storage density, the TES coverage and the heat demand of the computed district heating network within the GeoPATH tool.

Additionally, the distance between DHN and TES had to be limited, since piping cost, pumping energy and thermal losses increase with increased distances. An economically viable range for piping lengths is defined by a minimum linear heat density of 2 MWh/(m·a) (17).

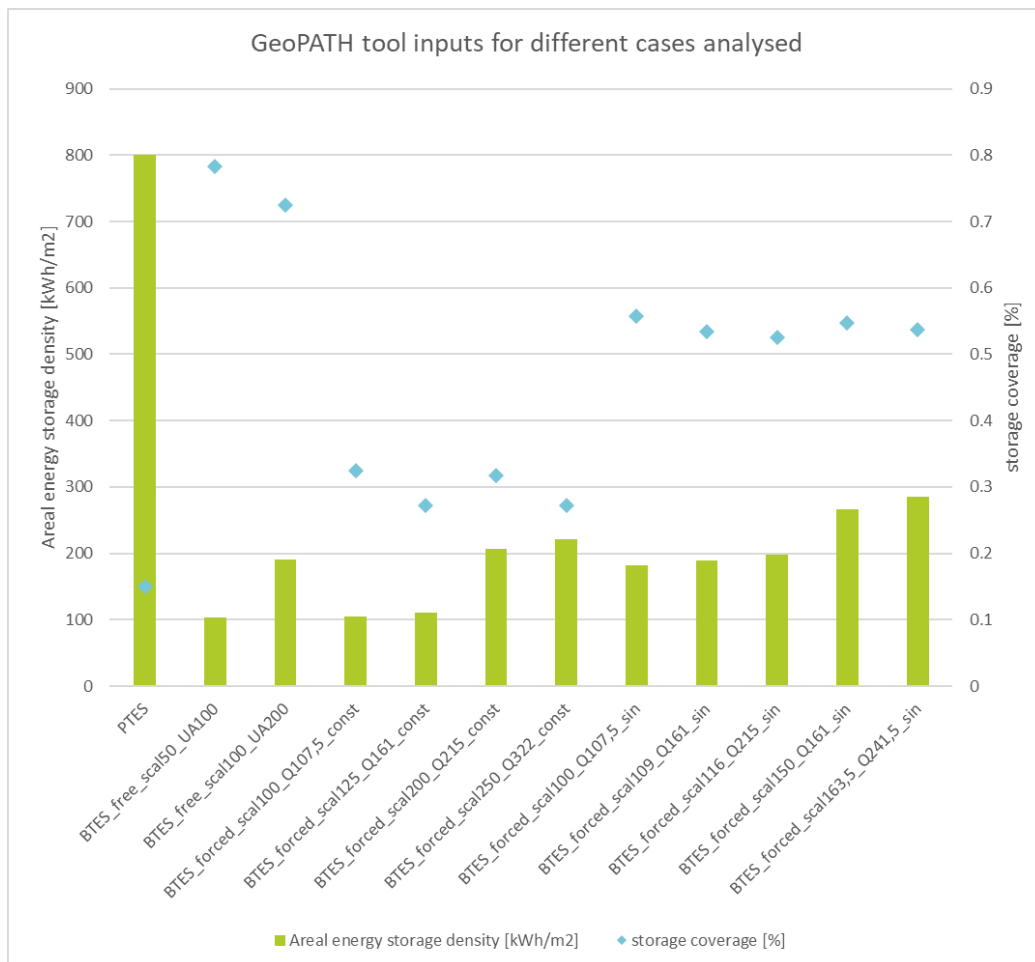


Figure 9: GeoPATH tool inputs for different cases analysed



3.4 GeoPATH results: Seasonal Storage Potential Map for Switzerland

3.4.1 PTES GeoPATH results, depending on heat source

The potential energy storage capacity for PTES in Switzerland depending on the heat source was analysed.

For the WIP+PTES case, the possible location is bound to the WIP, 29 in Switzerland, and their heat production data from 2022, summing up to 4.1 TWh/y (Figure 10). Under the give boundary conditions, for 20 out of the 29 WIP a suitable location for one or multiple PTES were found, covering 0.35 TWh/y, resulting in a storage coverage of 9% (Figure 10).

For the WWTP + PTES case, more source location in terms of numbers could be found due to 700 sites in Switzerland, leading to an identified heat demand where WWTP and potential DHN are of 9.3 TWh/y. This also leads to a total storage capacity of about 1.2 TWh/y (Figure 10), resulting in a storage coverage of 13%, meaning that in most cases a location for a PTES was found.

The combination of WWTP or WIP with PTES, results in a total heat demand of 9.7 TWh/y, not much more than the heat demand of the WWTP with PTES case, indicating that often the same heat demand could be covered by WWTP or WIP (Figure 10). The total storage potential is 1.3 TWh/y, resulting in a storage coverage of 14%, higher than WWTP and WIP individual. This is indicating that heat demand that can be covered by either by WWTP or WIP, the one with the option of a PTES was chosen, as indicated in the developed algorithm (Annex) (Figure 10).

Lastly, the potential without any specific sources was analysed, to find possible storage locations close to high density heat demand areas, where 287 different storages were placed in Switzerland (Figure 12, Figure 13). The total storage capacity resulted is 2.4 TWh/y, representing nearly a storage coverage of 15% (Figure 9), indicating that a suitable storage location was found for all heat demand clusters.

In summary, for all cases the median storage capacity varies between 2.96 GWh to 3.31 GWh (Figure 10), which are in a similar range as the Hoje Taastrup PTES system with a storage capacity of 3.3 GWh (19). The technical feasibility however of the largest storage implemented by the GeoPATH tool, reaching up to 255 GWh (and a surface area of 0.33 km²), remains unknown (Figure 13).

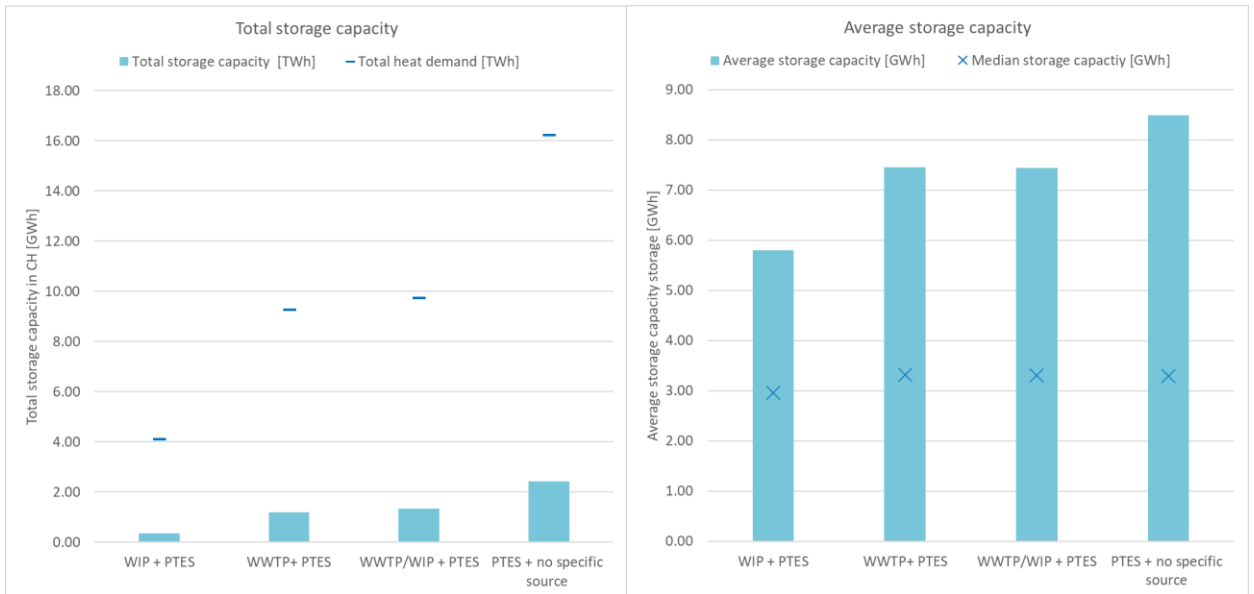


Figure 10: GeoPATH results on PTES potential

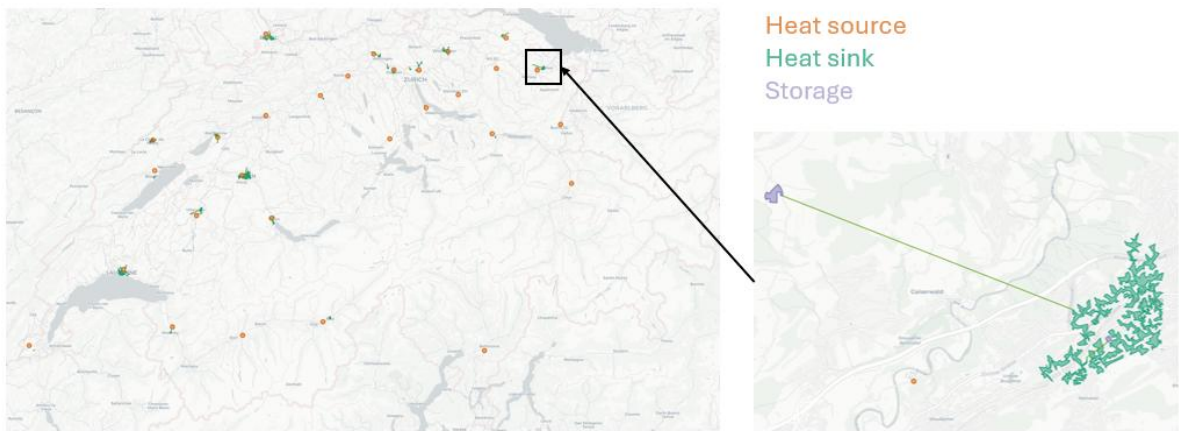


Figure 11: Place PTES system case: WIP + PTES + heat demand

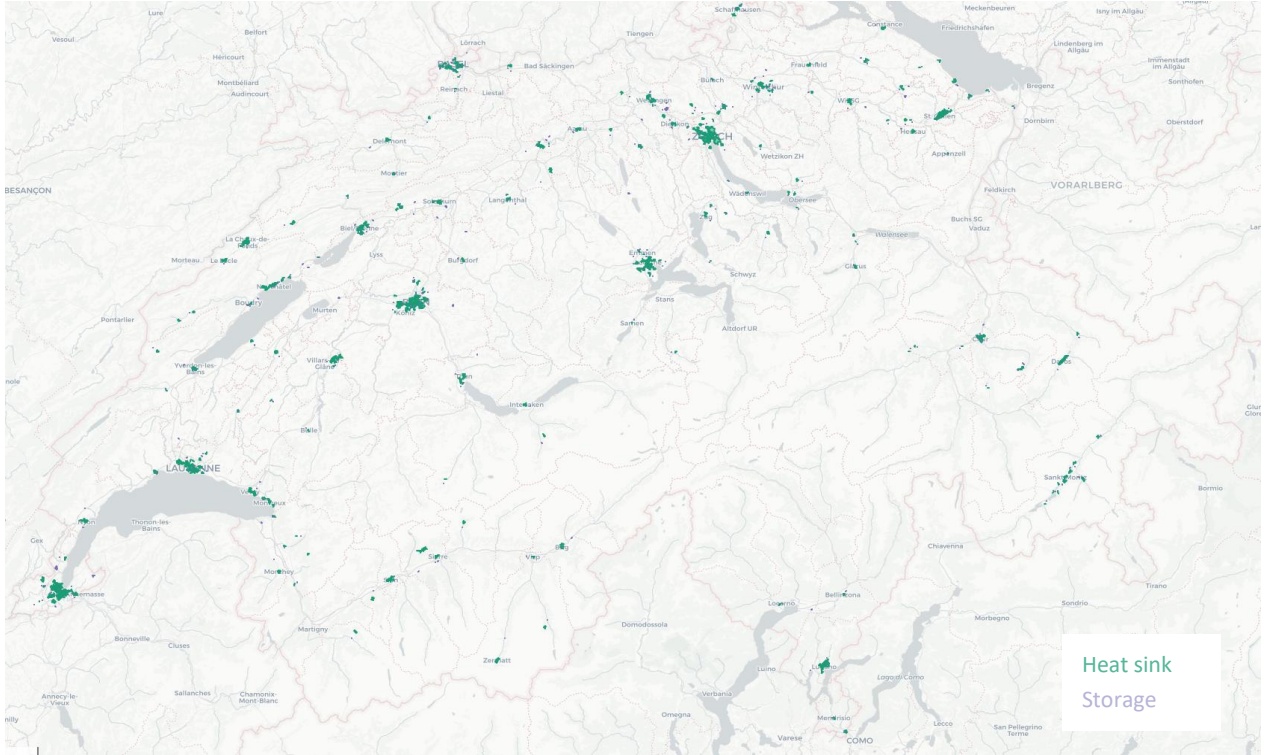


Figure 12: Placed PTES system case: Heat demand + PTES, no heat sources

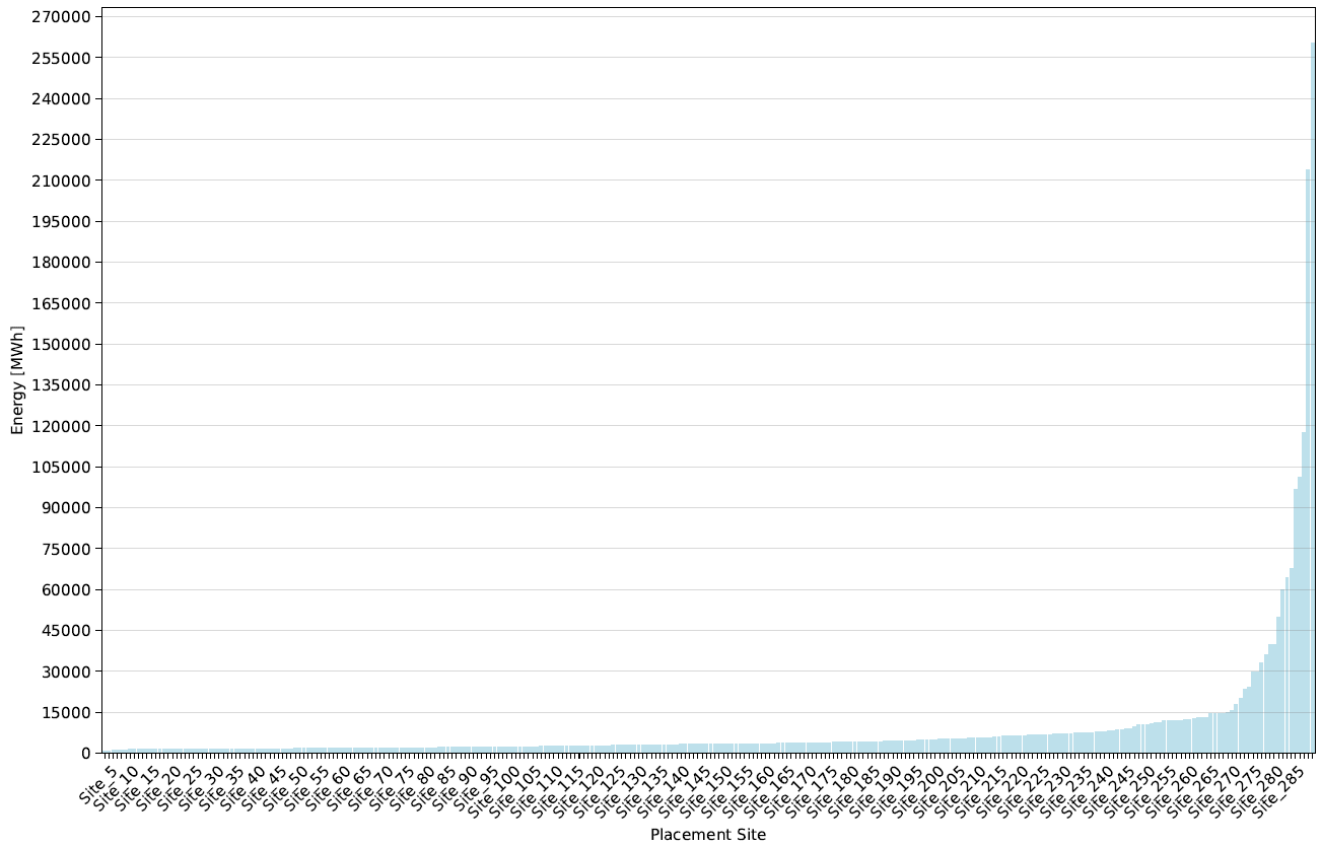


Figure 13: Details about the energy storage capacity of the placed PTES systems case: Heat demand + PTES, no heat sources

3.4.2 PTES GeoPATH results, depending on land use

To understand which placement conditions show the most potential for the deployment of PTES, the different placement options (Cropland, Permanent meadows and pastures, Golf course area, Sport ground area, Zone for public use, Restricted building area) were iterated and the total storage capacity compared.

When considering only the possible sites, however neglecting whether there is heat demand in proximity, the largest potential lies in permanent meadows and pastures followed by cropland (Figure 14, Figure 15). The least potential is found for sport ground area and golf course area (Figure 17, Figure 16).

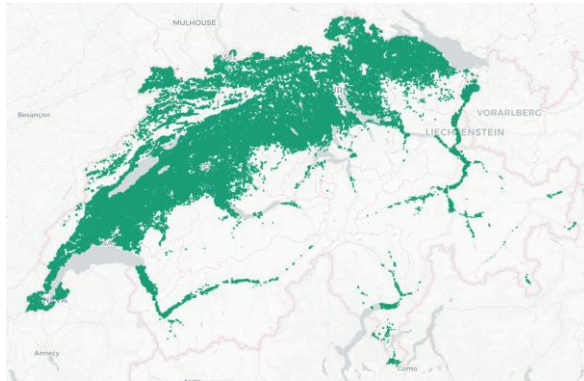


Figure 14: Possible placement for PTES on croplands

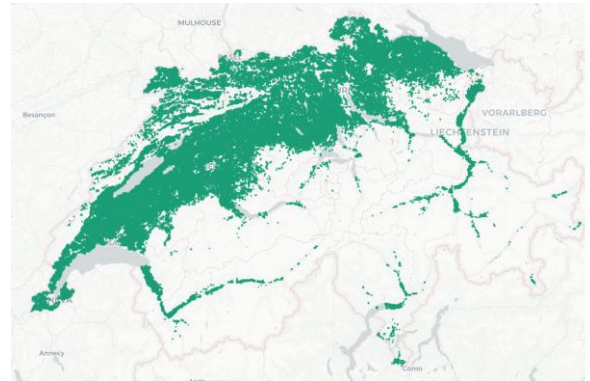


Figure 15: Possible placement for PTES on permanent meadows and pastures.

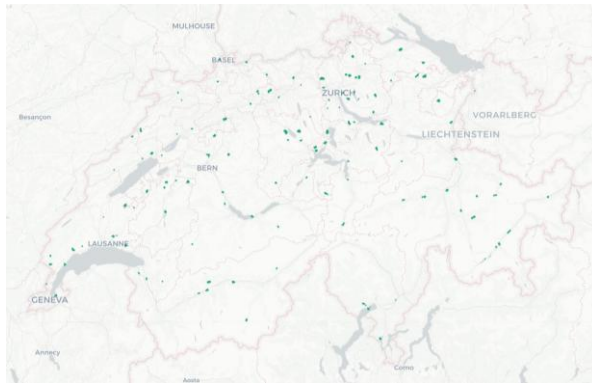


Figure 16: Possible placement for PTES on golf course areas

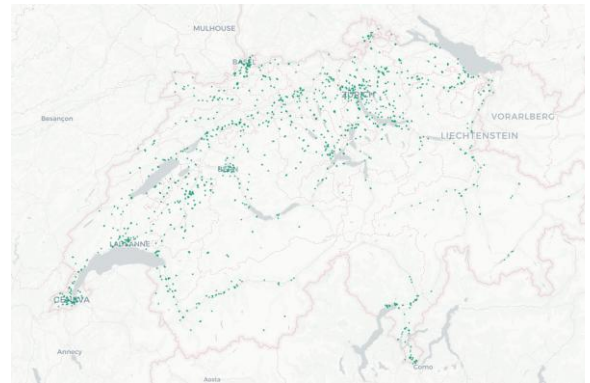


Figure 17: Possible placement for PTES on sport ground areas.

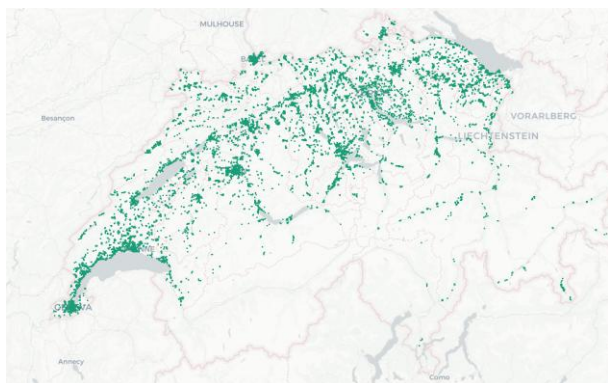


Figure 18: Possible placement for PTES on restricted building area

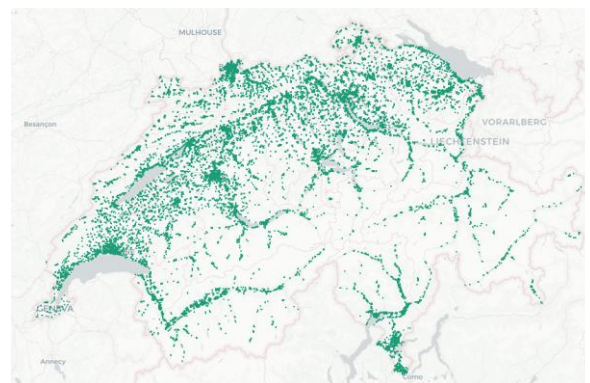


Figure 19: Possible placement for PTES on zone for public use



If in each case given the boundary condition a PTES could be placed, the resulting PTES capacity is 2.4 TWh/y (Figure 20 green line).

Considering all placement options combined, for 99.8% of the maximum possible storage capacity a potential location was found (Figure 20). The single placement conditions with most identified storage capacity is the zone for public use with 71%, followed by cropland with 61%, permanent meadows and pastures with 55%, sport ground with 53%, restricted building area with 47% and lastly with golf courses with 10% (Figure 20).

The average storage capacity varies between 5.3 GWh/y to 6.8 GWh/y, with a median between 3.3 GWh/y and 4.8 GWh/y (Figure 21). The average distance is shortest for zones for public use followed by sport ground area and restricted buildings area, due to their urban locations (Figure 22).

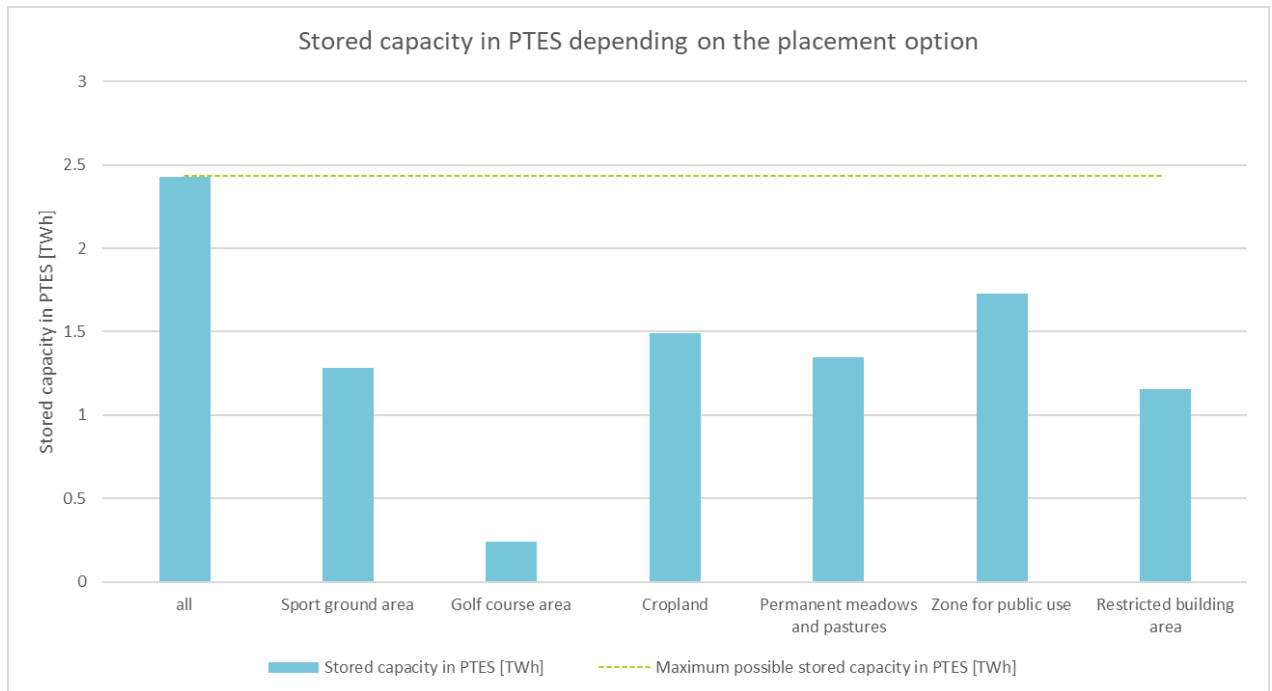


Figure 20: Stored capacity in PTES depending on the placement option

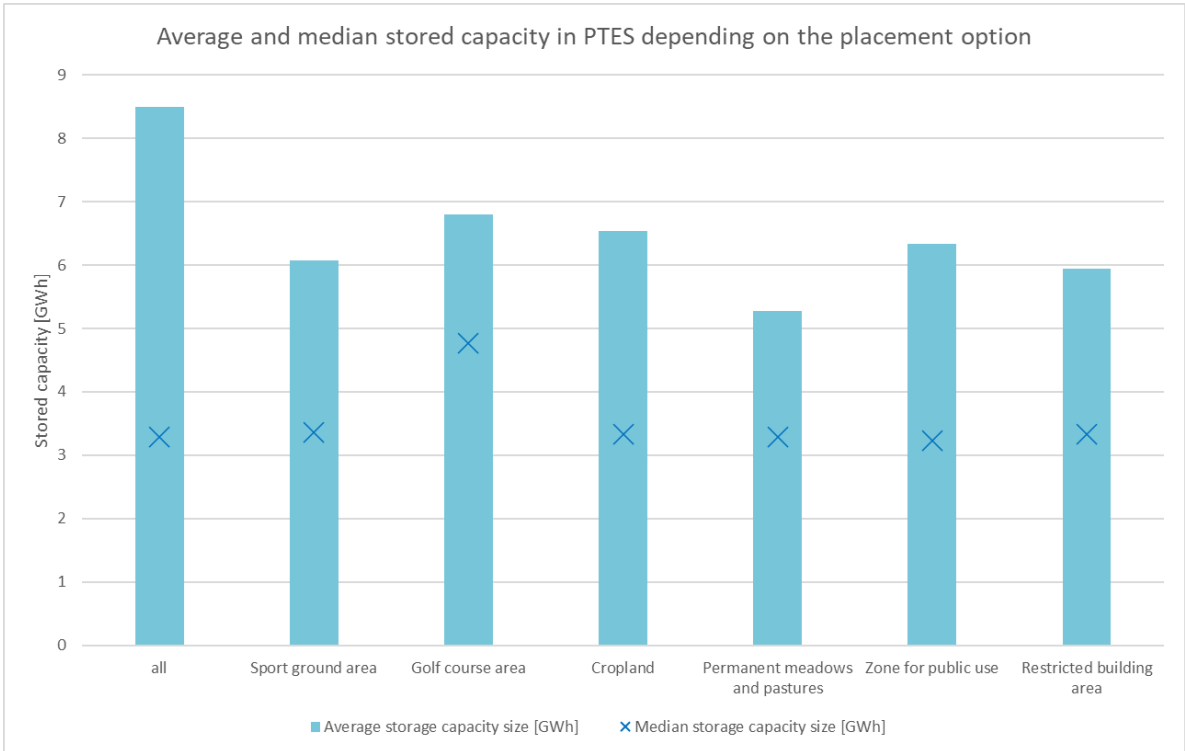


Figure 21: Average and median stored capacity in PTES depending on the placement option

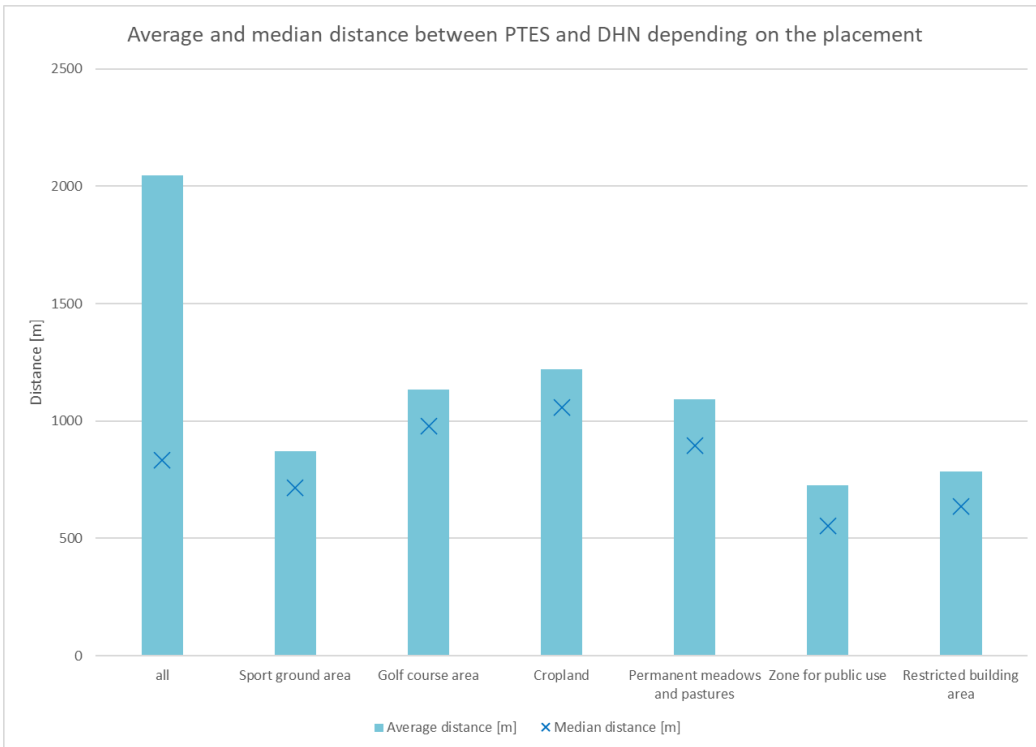


Figure 22: Average and median distance between PTES and DHN depending on the placement



3.4.3 BTES GeoPATH results, depending on BTES configuration

First results showed that large fields (surface area of up to 1.62 km²) were connected by long distance (up to 70 km) to a possible district heating network, as an example the storages for Bern were placed in the cantons Lucerne and Fribourg (Figure 23). Therefore a maximum distance of 3 km was included to limit the shortest distance between storage location and heat demand was included for the BTES use cases.

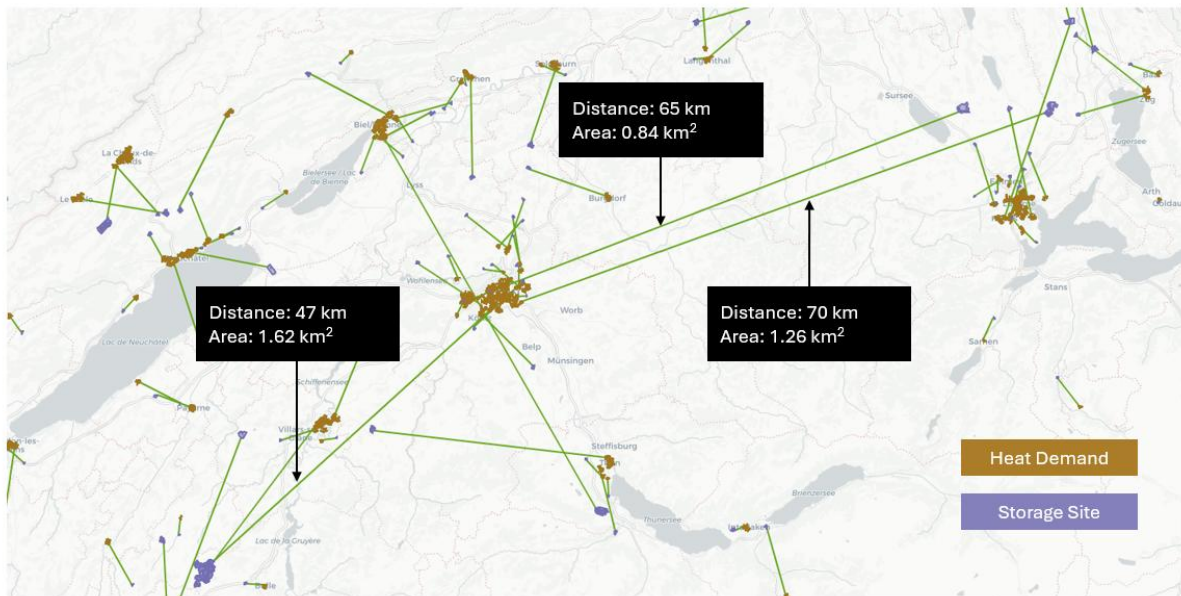


Figure 23: Identified storage sites connected to the heat demand of Bern without a limitation of a maximum distance.

For the BTES, the storage coverage as well as the areal energy storage density do differ for the different case studies (Table 3, Figure 9). For the heat source, no restrictions in term of geographical location were given.

The total identified storage capacity for the different case studies, was between 1.6 TWh and 3.9 TWh, representing a range of 10% to 23% of the total heating (Figure 24).

The average storage capacity varies between 7 GWh to 15 GWh (Figure 24), larger than the average PTES storage capacity. This is mostly since for the BTES, higher storage coverage was assumed and given as an input (Figure 9).

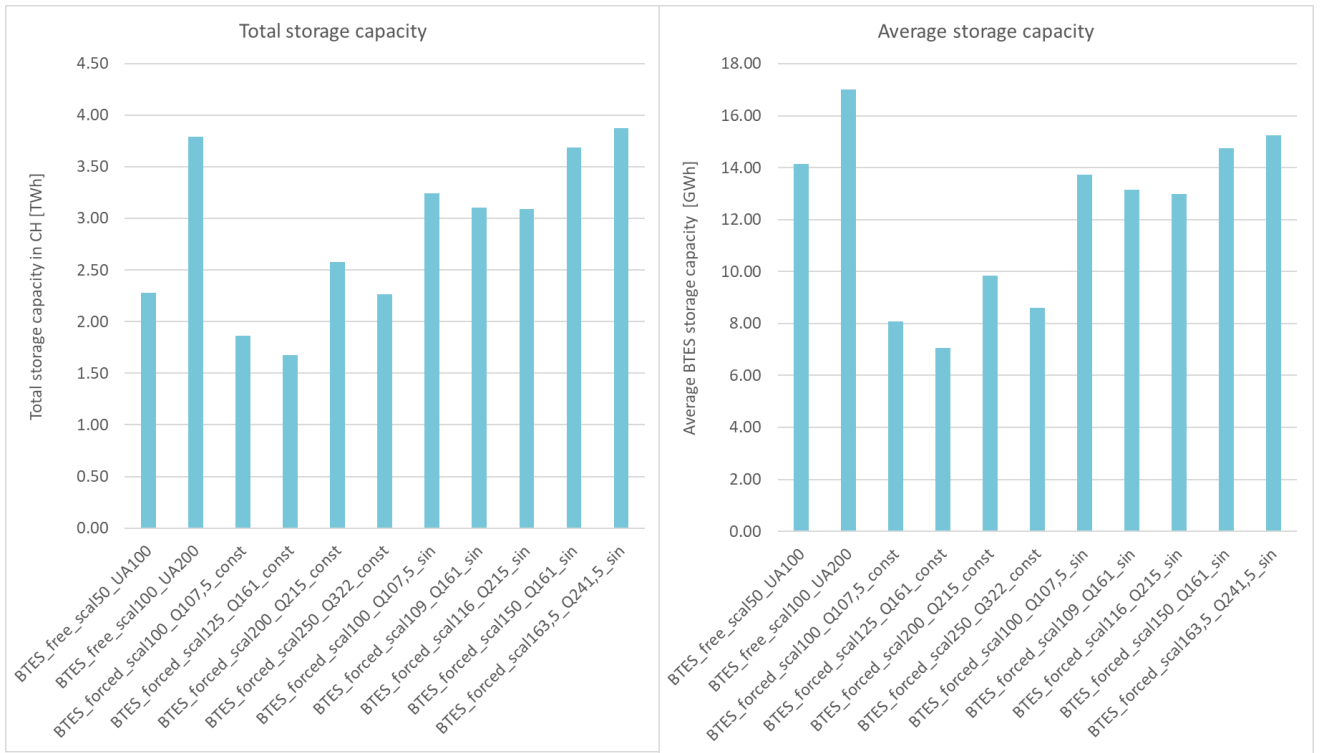


Figure 24: Results from GeoPATH for BTES cases



4 Analysis of the Value of Seasonal Thermal Storage in Net-Zero Scenarios

Based on the detailed modelling of pit storage and borehole fields in Section 2, the Swiss Energyscope model was updated and used to quantify the value of these thermal energy storage options within net-zero scenarios. The first section below explains the translation from the detailed model to the simple model that covers the whole Switzerland. The second section explains the scenarios that were defined in order to cover a broad range of possible future developments. Finally, the last two sections highlights the results of the modelling with specific focus on the value of thermal storage.

4.1 Adaptation of Swiss Energyscope model

4.1.1 Model set-up

In the present report we use the Swiss Energyscope model (add ref), which was developed at ETH Zurich based on the original model by Stefano Moret from EPFL (add ref). SES-ETH is a linear optimization model of the energy system. It determines the investment and operation strategies that minimize the total annual cost of the energy system, given the end-use energy demand, the efficiency and costs of the conversion technologies, and the availability and costs of the energy resources. SES-ETH represents the main energy demands: electricity, heat and mobility (Figure 25). It is a snapshot model, i.e., it models the energy system in a target year but it does not make any statements on the trajectory to reach this future state. The original SES included monthly periods that could capture the seasonal aspects of generation, demand, and storage. We have further developed the model to include an hourly resolution that allows us to represent the intra-day variations of the energy demand and resource availability. Note that all inputs and results in this report refer to the target year 2050.

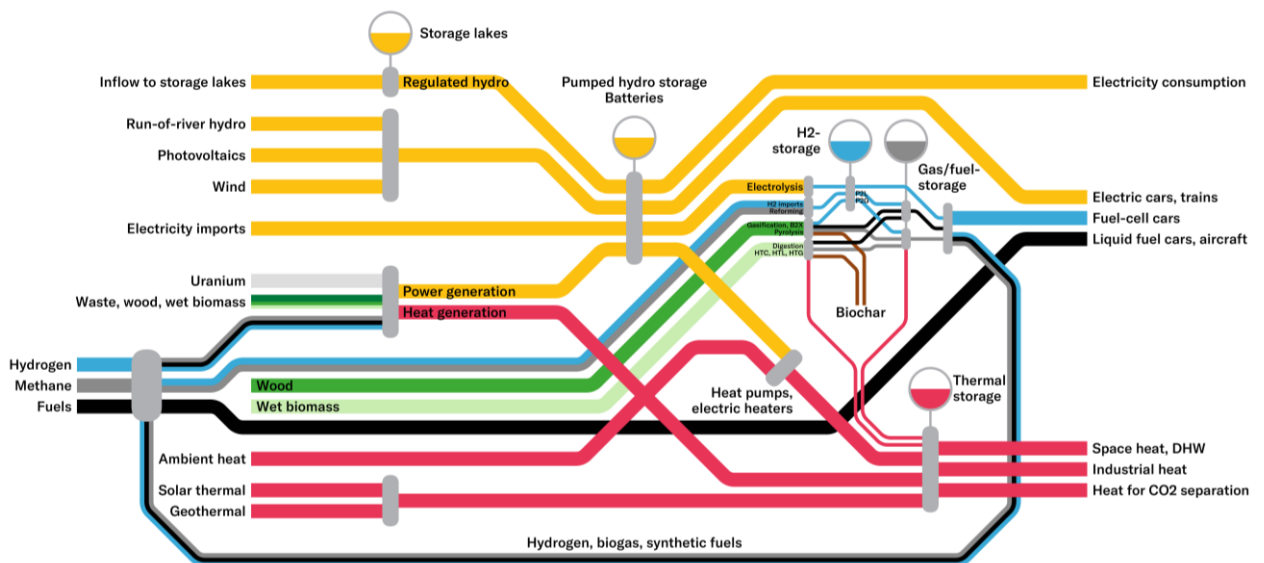


Figure 25: Schematic representation of the energy system as modelled in SES-ETH.



4.1.2 Archetypes

The model has no spatial resolution, there is only one wind turbine that represents all wind turbines, one photovoltaic installation, etc. For electricity this simplification is justifiable by making the usual assumption of a copper plate, i.e. an ideal electrical network. Also for methane, hydrogen, wood and other energy carriers a transport over long distances is feasible. However, this assumption is invalid for other energy forms such as heat or the motion force in transport. Therefore, the respective demand streams are broken down into archetypes that are not connected.

An example is a gas boiler and a heat pump. Assume that one dwelling is equipped with a gas boiler, another with a heat pump. It may be beneficial to operate the heat pump mostly in summer and the gas boiler in winter. However, the two dwellings cannot exchange heat, therefore the complete demand has to be sliced in two portions that have to be satisfied independently by the two technologies. Another example is a Diesel car and a battery electric vehicle. The model could choose to run the BEV only in summer and the Diesel in winter, however, a car owner has either one or the other car, again the demands are split and have to be satisfied separately. Within individual archetypes, a mixture of technologies is indeed possible, e.g. a pellet boiler with a solar thermal collector. Table 4 lists all archetypes for space heat and domestic hot water currently defined. More can be added easily. The archetypes that are relevant for the present project are marked in orange.

Table 4: Archetypes for space heat and DHW.

Single and multi-family houses		District heating networks	
DEC0	<ul style="list-style-type: none"> - Ground-source heat pump - Electric heater - Solar thermal - Short-term TES 	DHN0	<ul style="list-style-type: none"> - High temperature grid - Data center as low temperature heat source - Large heat pump - Electric heater - Solar thermal - Short-term TES - Seasonal TES (optional)
DEC1	<ul style="list-style-type: none"> - Ground-source heat pump <u>with regeneration</u> - Electric heater - Solar thermal - Short-term TES 	DHN1	<ul style="list-style-type: none"> - Low temperature cooling & heating grid - Water body as low temperature heat source - Large heat pump - Electric heater - Solar thermal - Short-term TES - Seasonal TES (optional)
DEC2	<ul style="list-style-type: none"> - Ground-source heat pump <u>with regeneration</u> - Electric heater - Solar thermal - Short-term TES 	DHN2	<ul style="list-style-type: none"> - Mid-sized gas CHP plant - Auxiliary gas boiler - Solar thermal - Short-term TES - Seasonal TES (optional)
DEC3	<ul style="list-style-type: none"> - Ground-source heat pump <u>with regeneration</u> - Electric heater - Solar thermal - Short-term TES 	DHN3	<ul style="list-style-type: none"> - Wood CHP plant - Solar thermal - Short-term TES - Seasonal TES (optional)
DEC4	<ul style="list-style-type: none"> - Ground-source heat pump <u>with regeneration</u> - Electric heater - Solar thermal 	DHN4	<ul style="list-style-type: none"> - Small rural biogas plant - Solar thermal - Short-term TES - Seasonal TES (optional)



	- Short-term TES		
DEC5	- Air-source heat pump - Electric heater - Solar thermal - Short-term TES	DHN5	- High temperature grid - Water body as low temperature heat source - Large heat pump - Electric heater - Solar thermal - Short-term TES - Seasonal TES (optional)
DEC6	- Water-source heat pump - Electric heater - Short-term TES - Long-term ice storage	DHN6	- Deep geothermal source - Solar thermal - Short-term TES - Seasonal TES (optional)
DEC7	- Gas boiler - Solar thermal - Short-term TES	DHN7	- Small gas CHP plant - Solar thermal - Short-term TES - Seasonal TES (optional)
DEC8	- Oil boiler - Solar thermal - Short-term TES	DHN8	- Pyrolysis plant - Solar thermal - Short-term TES - Seasonal TES (optional)
DEC9	- Wood boiler - Solar thermal - Short-term TES	DHN9	- Waste-to-energy plant - Wood CHP plant - Gas CHP plant - Auxiliary gas boiler - Short-term TES - Seasonal TES (optional)
DEC10	- Electric heater - Short-term TES	DHN10	- Low temperature cooling & heating grid - Data center as low temperature heat source - Large heat pump - Electric heater - Solar thermal - Short-term TES - Seasonal TES (optional)



4.1.3 Explicit model of borehole field

Previously, a ground-source heat pump with a borehole field (DEC0) was considered as one element with one investment cost. The regenerated version (DEC1) had the same cost structure. The cost of the storage was assumed to be for free since it is implicitly included in the cost for the heat pump system itself. Within the project, a more explicit modelling of the two elements, heat pump and borehole field was realized. The latter is based on the detailed analysis done within the project and reported in section 0. Here a field with 10 x 10 boreholes of 150 m length that are spaced 7.5 m apart was considered. The borehole field was integrated into the model for a multi-family house and operated in different ways, varying the overall annual energy input and output, the mean temperature of the borehole field (see Figure 5 to Figure 7) and the charging pattern for the regeneration.

A total of 11 variants was created (see Table 2). These were evaluated in terms of the effective storage volume and the losses to the environment. This was based on time series of charging and discharging power and on the temperature at which fluid exits the borehole field. The latter is not identical to a mean borehole field temperature but is taken as a proxy for it.

Figure 26 shows the effective storage volume as function of the yearly temperature amplitude. It can be seen that the volume (measured in kWh/m borehole length) scales nearly linear with the amplitude of the borehole field temperature.

Figure 27 shows the losses to the ground as function of the difference in mean borehole field temperature and undisturbed ground temperature. Again it can be seen that a linear relationship exists. The costs of the borehole field were estimated as 80 CHF/m.

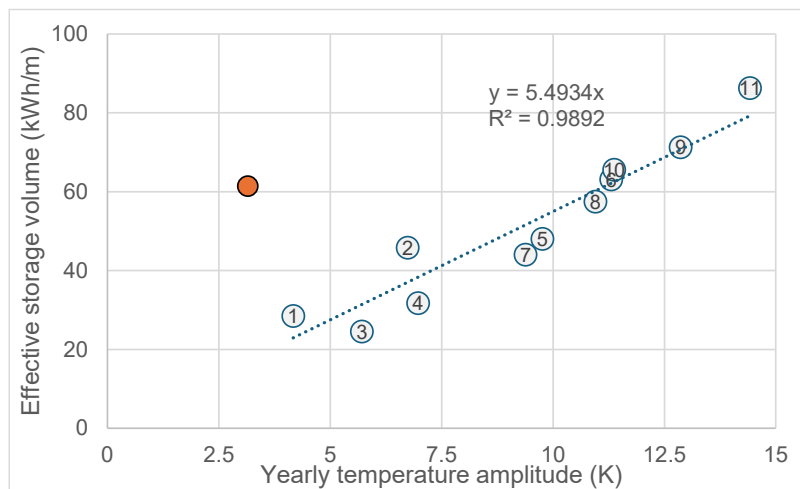


Figure 26: Effective storage volume as function of the yearly temperature amplitude.

Based on these insights a simple model could be built that can be included in Swiss Energyscope. We defined 4 cases that differ in terms of temperature amplitude (that affects the effective storage volume and hence the specific costs) and mean borehole field temperature (which affects the losses). Table 5 shows the parameters for the 4 variants.

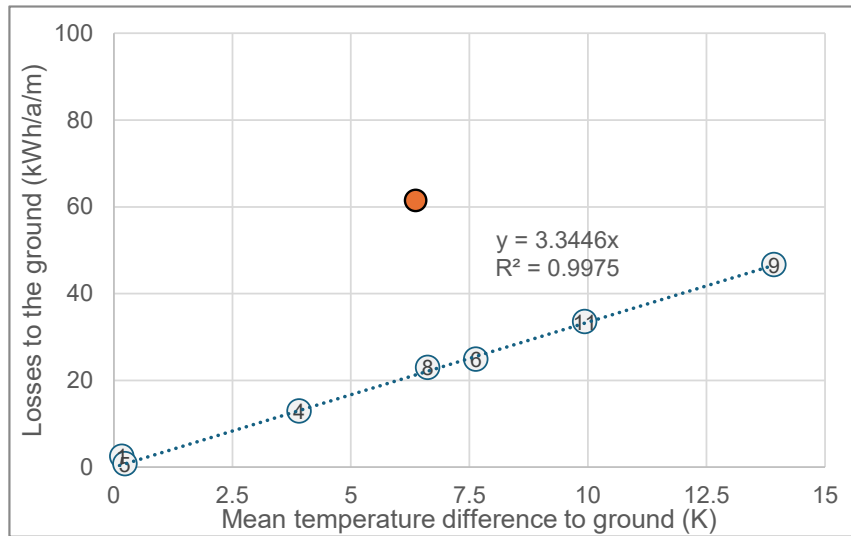


Figure 27: Losses to the ground as function of the mean temperature difference between the borehole field and the undisturbed ground.

Table 5: Definition of regenerated borehole variants.

Case	$T_{\text{high}}-T_{\text{low}}$ (K)	$T_{\text{mean}}-T_0$ (K)	Storage volume (kWh/m)	Annual losses (kWh/m/y)	Specific costs (CHF/kWh)
DEC1	6	0	33	0	2.4
DEC2	12	0	66	0	1.2
DEC3	6	3	33	10	2.4
DEC4	12	6	66	20	1.2

Using this information allows to pre-calculate the coefficient of performance of the heat pumps using the simple Carnot formula and an exergetic efficiency of 50% (see Figure 28). This varies with the temperature of the fluid that exits the borehole field and the sink temperature in the building. Here we define an innovative scenario where convective systems are used that operate at very low temperatures and a conservative scenario that is based on standard underfloor heating. The potential benefit of variants DEC3 and DEC4 is the higher ground temperature that further increases the COP. Note that the COP was capped at 13.

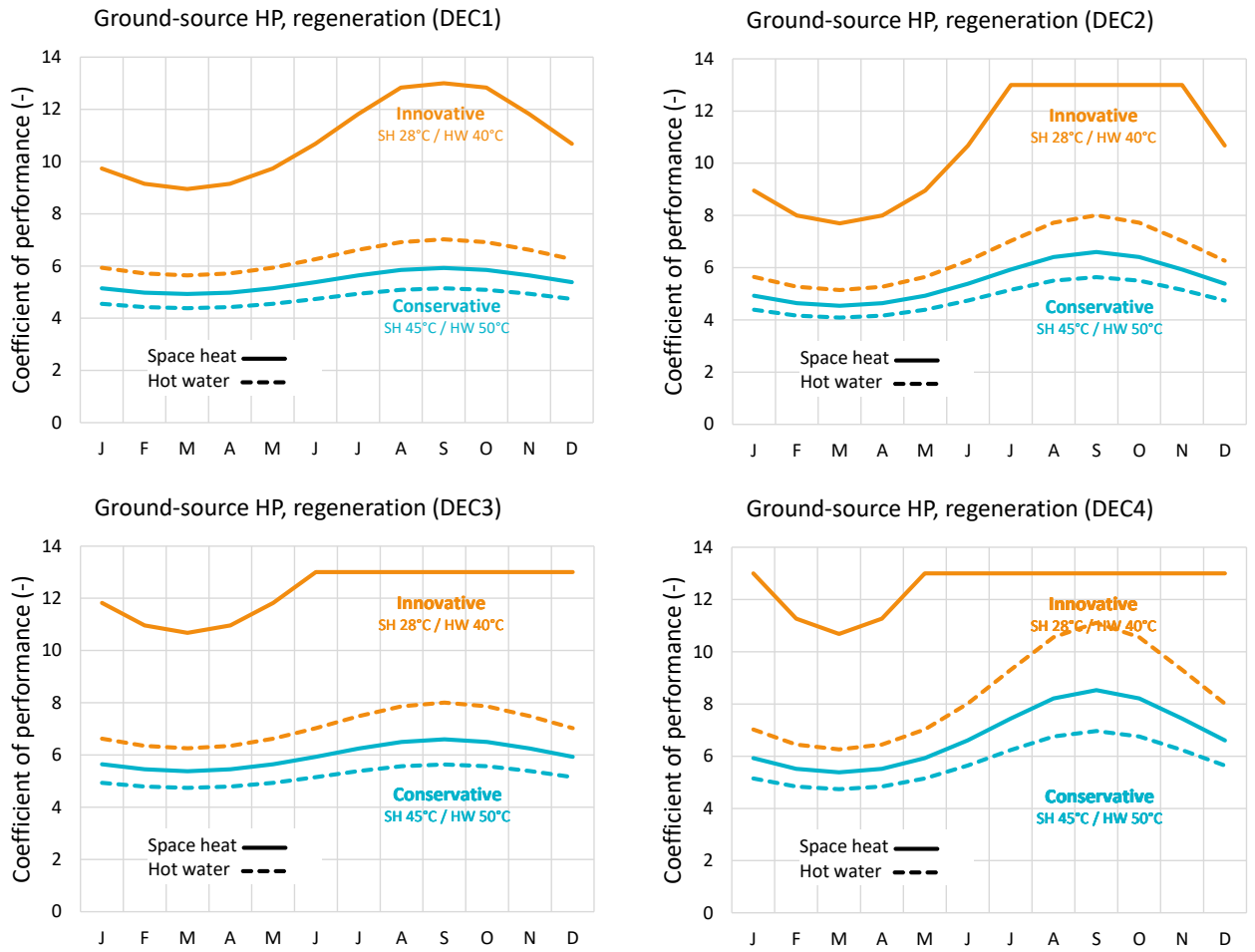


Figure 28: Pre-calculated coefficients of performance for the four types of regenerated borehole fields.



4.2 Definition of scenarios

4.2.1 Switzerland's attitude towards Europe

The dominant topic in the discussion about future energy supply is security of supply. This is often reduced to the supply of electricity, but in fact it encompasses all aspects, including liquid and gaseous energy sources. Switzerland is currently 100% dependent on other countries for the latter. In terms of electricity, the trade balance has been balanced on average over the years, with a tendency toward net imports in the winter months and net exports in the summer months. Looking at total final energy consumption, imports account for 70-80%.

In order to reflect the concerns of the population and political decision-makers, five different “futures” were constructed, which differ in terms of the possibility of exchanging energy with other countries (see also Figure 29):

- **Future (A)** assumes that all energy trading – in particular electricity imports and exports – is possible without restriction at all times. This is essentially the current situation. Concluding the electricity agreement with the European Union would provide additional security in this regard.
- **Future (B)** assumes that electricity trading will be interrupted during the winter months from November to February. This may seem unrealistic, but it reflects the fear that our neighbors will need their own electricity in winter and will not be willing to sell it to us.
- **Future (C)** is identical to Future (B), with the addition of the assumption that a (potentially newly built) nuclear power plant will fail in February.
- **Future (D)** assumes that all electricity and gas imports will be interrupted throughout the year. Such a situation is hardly conceivable without a serious crisis or armed conflict in Central Europe. It is assumed that at least liquid energy sources that are independent of vulnerable infrastructure such as gas pipelines and power lines can still be imported.
- **Future (E)** is identical to Future (D), with the addition of the assumption that a (potentially newly built) nuclear power plant will fail in February.

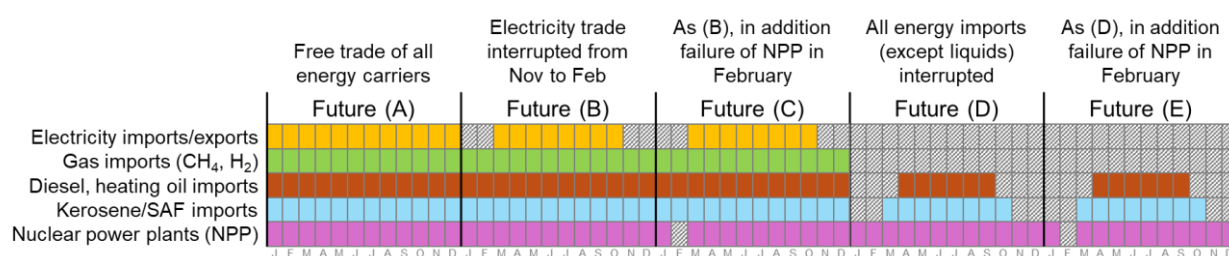


Figure 29: Definition of five different futures.

In a second step, three different scenarios are constructed from these futures. To do this, it is assumed that a typical decade in the future will consist of a combination of different futures: in some years, electricity trading will be free, in others it will be restricted, etc. The three scenarios are as follows:

- **Isolation** scenario: Here, Switzerland is permanently considered an “energy island” (with the exception of liquid energy sources, Future (D)). It is also assumed that one nuclear power plant will fail in one out of every 10 years (Future (E)).
- **Robust** scenario: Here, we assume that energy trading takes place without restriction in 5 out of 10 years (Future (A)), that winter electricity imports are interrupted in 3 years (Future (B)),



that a nuclear power plant fails in one year (Future (C)), and that, finally, almost all energy trading comes to a standstill in one out of 10 years (Future (D)).

- **Ideal** scenario: Here, every year corresponds to the Future (A): Energy trading is possible at any time without restriction.

These three scenarios form the first axis of our scenario matrix.

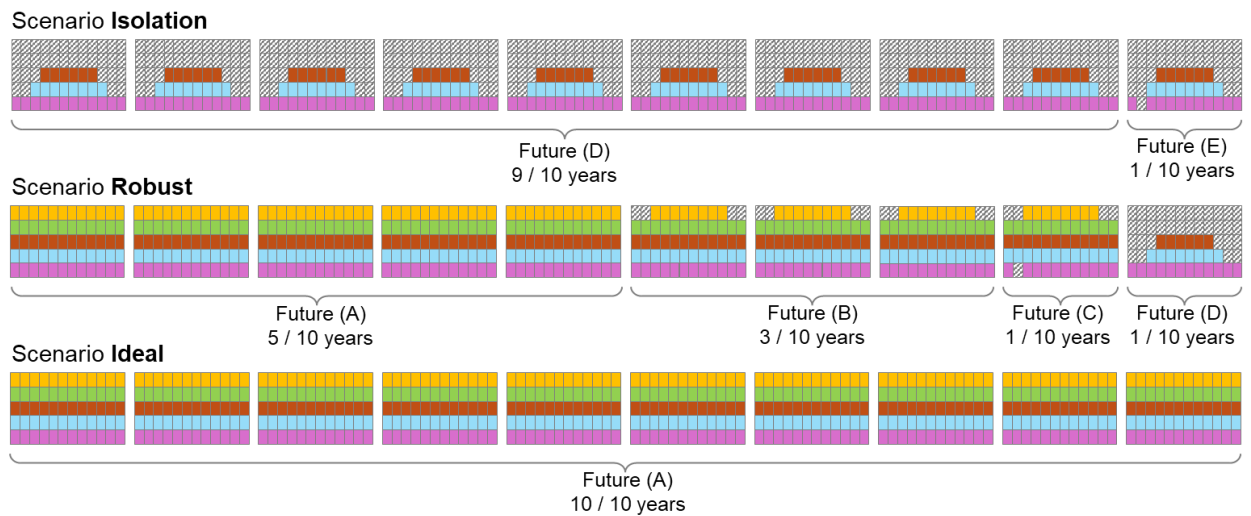


Figure 30: Definition of three scenarios that are composed of the five different futures.

4.2.2 Switzerland's attitude towards innovation

The second axis concerns our attitude toward innovation. At one end of the spectrum is a “not in my backyard” mentality. Wind energy projects are never realized, or only after decades of delays, geothermal energy fails due to objections, etc. Added to this are rigid regulations in the area of spatial planning, which make agri-photovoltaic systems or even large thermal storage facilities impossible.

At the other end of the spectrum, such innovations are made possible by a forward-looking attitude among the population and a sensible regulatory framework. Three scenarios are constructed along this axis, ranging from conservative to realistic to innovative. In most cases, these differ in terms of the availability of technologies (see Table X in the appendix). Finally, a 3 x 3 scenario matrix is formed from the two axes described above (see Figure 31).



4.3 Cost optimal storage requirement

A large number of scenarios are calculated based on the scenario matrix described above. Some important assumptions and boundary conditions are summarized here:

- The optimization goal is always to minimize total costs. These consist of annualized investment costs, operating and maintenance costs, and resource costs.
- The target year is 2050. Swiss Energyscope is a so-called snapshot model that “jumps” into the future and does not allow any conclusions to be drawn about the exact path to get there.
- Each solution corresponds to a net-zero scenario. This also takes into account emissions from agriculture, industry, and air traffic that are difficult to avoid. The definition of net-zero is based on the CROSS scenario suite.
- For each of the 3 x 3 scenarios, 100 calculations are performed in which uncertain parameters, such as the investment costs for photovoltaics, are systematically varied. This so-called Monte Carlo method allows more robust statements to be made about the cost-optimal storage requirements.
- According to EU directives, 70% of aviation fuels in the target year 2050 will consist of so-called sustainable aviation fuels (SAF). These are considered climate-neutral.
- The production of SAF inevitably generates a range of hydrocarbons, so it is assumed that climate-neutral diesel fuels and combustibles will also be available in addition to SAF.
- Switzerland is integrated into the European electricity system and the European trade in gaseous and liquid fuels. Switzerland is also connected to a European CO₂ transport and storage infrastructure.
- New nuclear power plants are included as an option in the model. The assumptions are overnight investment costs of CHF 8,000/kW, a construction period of 10 years, and an operating period of 60 years. An interest rate of 8% is assumed, which corresponds to private-sector financing.
- An additional electricity consumption of 6 TWh/y is assumed for data centers.
- In accordance with the currently valid specifications, domestic generation from climate-neutral sources (excluding hydropower) is set at 45 TWh/y. Part of this target can be achieved through nuclear power. Such a target in the model implicitly means that technologies such as PV, wind, and nuclear power are subsidized.
- The similarly postulated limit of 5 TWh/y of net electricity imports in winter is not enforced, but this is evaluated in the results.

The results of the modelling are shown in Figure 32. These show the cost-optimal storage requirements and other important key Figures.

- Final electricity consumption is in the range of 76-110 TWh/y. This depends heavily on the assumptions selected. It increases for increasingly conservative assumptions and when electricity trading is unrestricted.
- Net winter imports amount to 11-23 TWh/y when electricity trading is unrestricted (**Ideal** scenario). In the **Robust** scenario, net winter imports are 3-11 TWh/y, close to the legal target of 5 TWh/y.
- Nuclear power plants are not part of the cost-optimal solution in the **Ideal** and **Robust** scenarios. In the **Isolated** scenario, where electricity imports are not possible at any time, nuclear power plants produce electricity on a similar scale as today.
- Chemical storage in the form of diesel, aviation fuel, and methane dominates seasonal and multi-year storage. The former in particular is crucial for security of supply in years when electricity trading is partially or completely interrupted. Diesel is imported and stored over the years and used in crisis years to generate winter electricity and heat. Hydrogen storage is insignificant.



- Hydro reservoirs make a decisive contribution to winter electricity supply. Their importance declines somewhat in the **ideal** scenario, when imports are possible without restriction at any time.
- Heat storage systems come in two variants:
 - Pit storage systems store heat at a usable temperature (Figure 32 “thermal energy storage”). They allow large heat pumps to be operated continuously, thereby consuming more electricity in winter and less in summer. They also transfer excess heat from waste incineration plants to winter. The storage capacity ranges between 3-6 TWh depending on the scenario, decreasing from conservative to innovative.
 - Anergy storage systems are regenerated geothermal probe fields (Figure 32 “anergy storage”). These allow the flow temperature of the heat pumps to be increased, thereby saving electricity in winter. The storage capacity ranges between 2-6 TWh depending on the scenario, increasing from conservative to innovative.
- Waste storage systems are an interesting new option. They allow the fuel for the waste incineration plant to be stored for the winter. However, they require space and also necessitate oversizing of the combustion capacity.
- In the area of short-term storage, pumped storage power plants and batteries are particularly noteworthy, the latter as stationary installations or in battery-powered vehicles. These storage facilities provide important short-term flexibility, which allows for better integration of photovoltaics.
- Similarly, heat storage in buildings offers flexibility, allowing hot water to be produced around midday when electricity is cheapest in summer.



4.4 The value of seasonal thermal storage

This section focuses on the value of the two seasonal thermal storage variants, pit storage and regenerated borehole fields. **Error! Reference source not found.** shows the results of the analysis. Here the same 3 x 3 scenarios were used defined before, however, a variant was calculated where both the pit storage and the borehole storage are turned off. This allows to precisely identify the benefit of having a thermal storage of this kind. The following observations can be made:

- Not having seasonal thermal storage generally increases the need for winter electricity imports, the need for methane and diesel imports, the extra winter generation of thermal power plants and the total system costs.
- The differences vary strongly across the 3 x 3 scenarios. Winter electricity imports are not affected in some scenarios, in others we can see increases of 1-3.5 TWh/y. The same can be observed both for methane and Diesel imports and for winter electricity generation by thermal plants.
- The total system costs are generally increased by 400-900 Mio CHF/y when a seasonal thermal storage is not available.

The same analysis is repeated, now removing only the option of pit storage but keeping borehole regeneration in the mix (Figure 34). For the more conservative scenarios, PTES contributes more strongly to system cost reduction than BTES (Figure 34). This stronger cost-reduction effect explains the larger storage capacity share of PTES observed (Figure 32). In the more innovative scenarios, the opposite pattern emerges.

The last experiment is the removal of nuclear power from the mix. Not having nuclear power as an option has only a small effect on total system costs and winter electricity balance. It increases the need for fuel imports and decreases the thermal power generation in winter. It can be concluded that the option to have nuclear power plants is not relevant for reaching the net zero target. It is mostly relevant in a situation where Switzerland is permanently isolated from the European electricity and gas system, a scenario that can hardly be considered realistic for future developments in Europe.

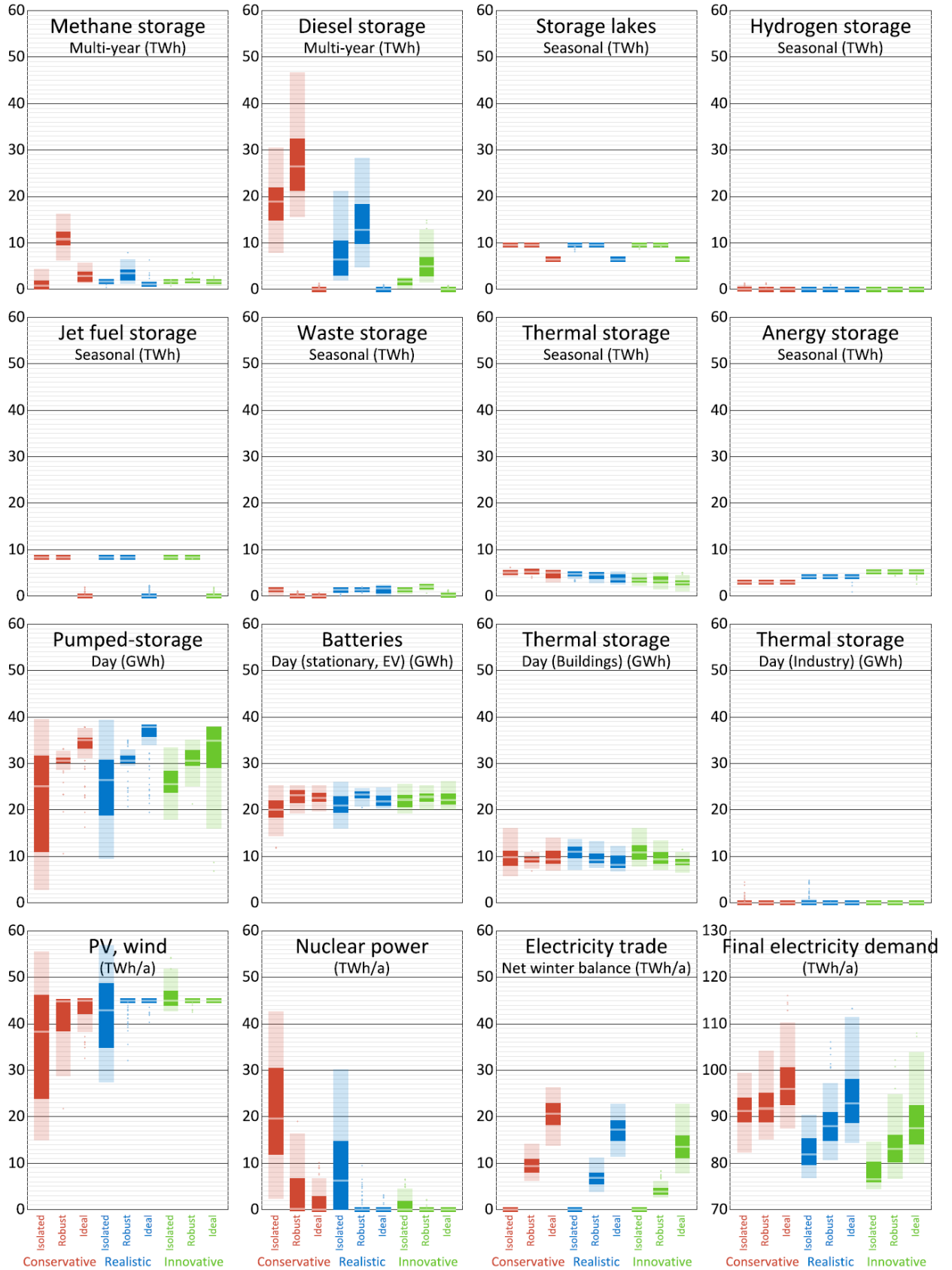




Figure 32: Cost optimal storage requirement and other relevant indicators.

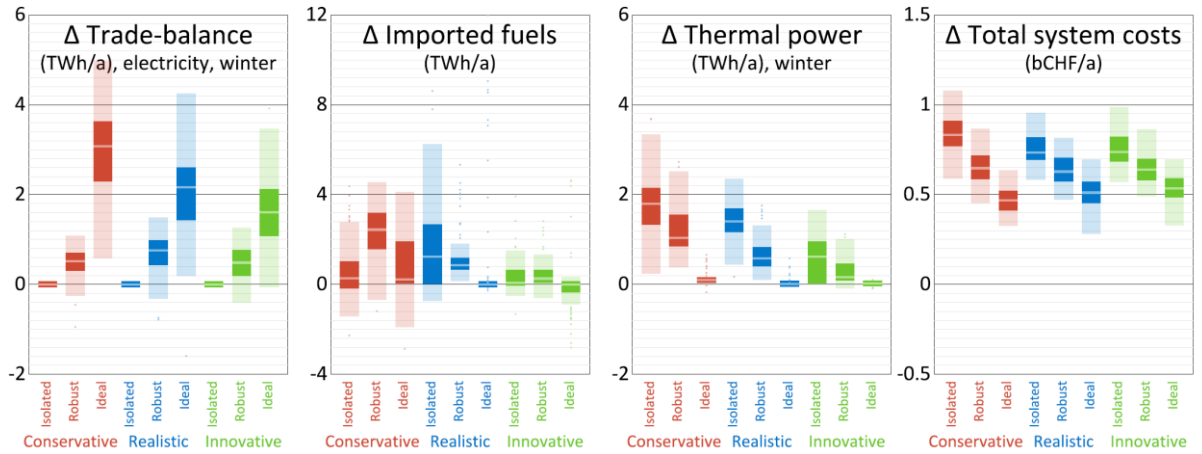


Figure 33: Changes to selected indicators when pit-storage and borehole regeneration is removed from the technology mix.

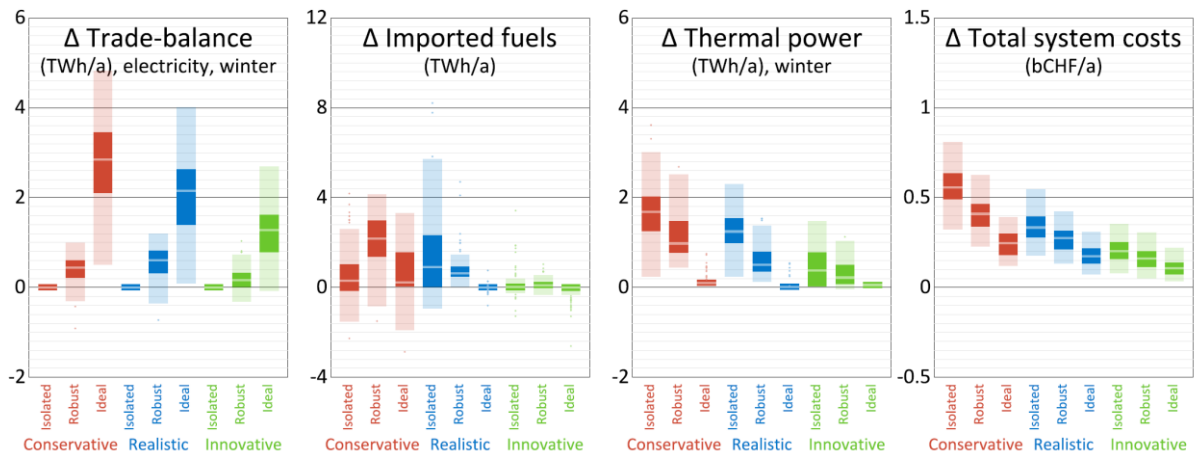


Figure 34: Changes to selected indicators when only pit-storage is removed from the technology mix.

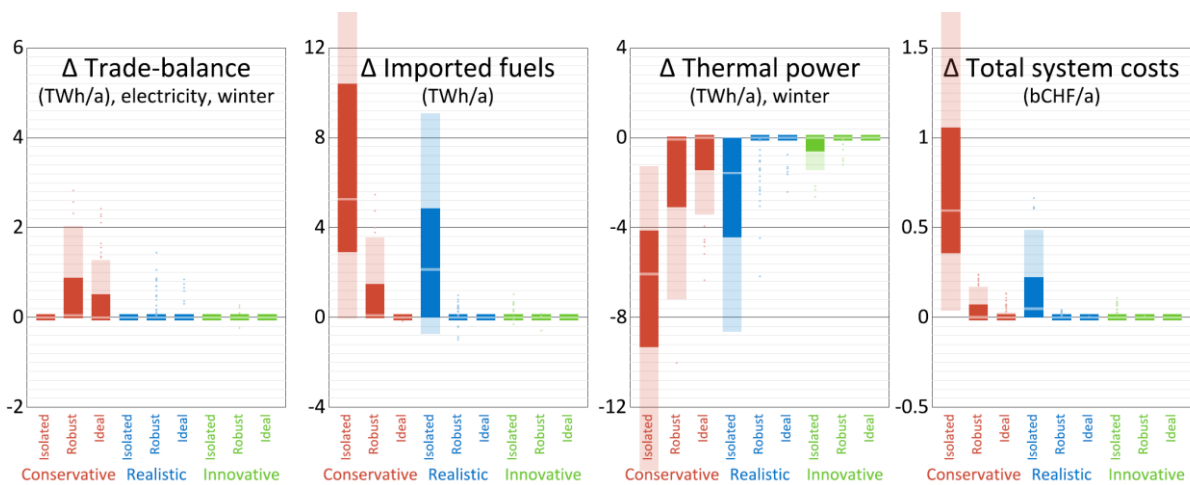


Figure 35: Changes to selected indicators when nuclear power is removed from the technology mix.

4.5 Timing for the Construction of Thermal Energy Storage

The timing of thermal energy storage (TES) deployment is critical for achieving a completed large-scale implementation by 2050. Since the development and realization of such projects require long lead times, action must start immediately. In particular, full-scale pilot plants need to be initiated now in order to generate practical experience, enable technological innovation, and increase the technology readiness level (TRL) of thermal energy storage systems by 2035. Only with sufficiently mature technologies by that time does the national deployment of large-scale thermal energy storage systems become feasible, allowing the resulting storage capacities of up to 10 TWh/y to be reached by 2050.

This need for early action is further reinforced by the complexity of these projects. The planning and approval of PTES facilities, including legal and regulatory procedures, typically take several years. From the initial idea to the start of implementation, projects usually require 3 to 4 years (20). Construction, filling, and commissioning then take an additional 1 year for smaller storage facilities and up to 2 years for storage systems with capacities above 60'000 m³ (20). However, some projects have a significantly longer lead time. For example, in Hechingen, work on the idea for a pit thermal energy storage system began in 2020, while commissioning is planned for autumn 2028, even though the storage volume is only 18'000 m³ (20). In addition, innovation in the field increasingly depends on the application of multi-use LID concepts, which require targeted support in both development and implementation.

Therefore, full-scale pilot plants have to be fostered now to fully benefit from these experiences in the wave of nationwide implementation from 2035 onwards.



5 Conclusion & Discussion

5.1 Conclusion

This project shows that seasonal thermal energy storage (STES) can play an important role in Switzerland's future net-zero energy system. The results show that STES can provide relevant benefits for the Swiss energy transition by shifting heat supply from summer to winter, reducing pressure on the electricity system during winter months, and increasing the flexibility of district heating and heat-pump-based energy systems.

Detailed modelling provided a sound foundation to represent PTES and BTES technologies in the linear SES-ETH model with drastically reduced complexity. Well-informed capacity and efficiency metrics have been derived for two pit storage sizes, based on a district heating application coupled with a waste-to-energy plant. A similar representation of BTES was deemed inadequate due to the strong influence of operating strategy. This challenge was addressed by exploring a range of operating scenarios, varying effective capacity utilization and heat input during regeneration. The results highlight and quantify relevant trade-offs between investment- and operating costs, and system performance, providing a basis for their optimization within the subsequent system-level analysis.

The GIS-based analysis added an important practical perspective by showing that the technical value of STES is closely linked to spatial feasibility. Suitable PTES locations were identified for most wastewater treatment plants and for a large share of waste incineration plants, indicating substantial storage potential 2.4 TWh/y near heat demand clusters. For BTES, the identified potential depends strongly on the assumed storage configuration and on distance constraints between storage site and heat demand but still reaches relevant capacities in the order of 1.6 to 3.9 TWh. The analysis makes clear that deployment will depend on site-specific conditions such as land availability, distance to heat demand, and local infrastructure. Additionally, for pit thermal energy storage, the spatial planning framework would need to allow the use of public spaces, agricultural land, or sports fields for storage placement. In this context, multi-use PTES covers could provide an important additional benefit.

The integration of STES into Swiss EnergyScope model showed that seasonal thermal storage is valuable at the national energy-system level. Across the analysed scenarios, the availability of STES generally reduces winter electricity imports, methane and diesel imports, additional winter generation from thermal plants, and total system costs. The model results indicate installed storage capacities in the range of 3 to 6 TWh for PTES and a 2 to 6 TWh for regenerated BTES fields. Thus, winter electricity imports are reduced by up to 3.6 TWh per year, while lowering annual total system costs by 400-900 million Swiss francs. This indicates that STES can make a meaningful contribution to improving security of supply and reducing the cost of decarbonization in Switzerland.

Overall, the project shows that seasonal thermal energy storage is a promising flexibility option for a net-zero Swiss energy system, especially in combination with district heating networks, large heat pumps, waste heat sources, and renewable heat supply. At the same time, the results also demonstrate that the achievable potential depends strongly on the local context, the storage concept, and the system assumptions. Therefore, a realistic assessment of STES requires the combination of detailed component modelling, spatial analysis, and integrated energy system modelling. Because STES projects involve long development and approval phases, full-scale pilot plants need to be initiated now if the necessary experience, technological maturity, and institutional readiness are to be in place for broader deployment from 2035 onwards.



Therefore, full scale pilot plants have to be fostered now to fully benefit from these experiences in the wave of nationwide implementation from 2035 onwards.

5.2 Cost analysis

The TES cost from the SES-ETH model were compared with the cost derived from the GeoPATH tool, where the volume-dependent cost function (6) were combined with the storage size resulting from the GeoPATH analysis. The total PTES cost resulting from the SES-ETH model are between 2'700 to 5'400 Mio CHF (for a total PTES storage capacity of 3-6 TWh). The resulting storage costs derived from GeoPATH are 690 Mio CHF (for 2.1 TWh of PTES storage capacity).

The costs are significantly lower coming from the GeoPATH tool since 4 out of 285 PTES, make up 15% of the storage capacity and have very low specific costs due to their size. However, as mentioned before, the technical feasibility of those storage volumes remains unknown (3.4.1).

5.3 Comparison with similar studies

Comparing these results with those of the study *Speicherbedarf Schweiz* shows that the present analysis yields substantially higher deployment of thermal energy storage.

In the study *Bedarf an Energiespeichern in der Schweiz* (21), tank thermal energy storage for short-term applications and pit thermal energy storage (PTES) were included. Depending on the scenario, installed PTES power reached up to 0.9 GW and storage capacity ranged from 330 to 442 GWh by 2050. This comparatively low deployment is largely explained by the assumed district heating network (DHN) demand of only 3.67 TWh by 2050, which limited the role of PTES in the system. Accordingly, installed PTES capacity corresponded to 9–12% of DHN heat demand. The study further assumed a specific PTES cost of 455 CHF/MWh of storage capacity (21).

By contrast, the WinTES project assumed a DHN heat demand of 19 TWh by 2050 within the SES-ETH model. With an average PTES storage capacity of 3-6 TWh, this implies storage capacity of 16–31% of DHN heat demand. Hence, even though the assumed PTES cost in WinTES was approximately twice as high at around 900 CHF/MWh, the model results indicate markedly higher TES deployment in many scenarios. This can mainly be attributed to the different system boundaries and modelling assumptions applied in the two studies.



6 Dissemination

6.1 Dissemination of Project Results

For the Dissemination of TES technologies, different measures initiated.

- Jörg Worlitschek and Gianfranco Guidati together published an article in the NZZ “Saisonale Energiespeicher: Mit der Wärme des Sommers wird es im Winter behaglich” with the aim to bring the topic of seasonal thermal energy storage to the broad population (Figure 36).
- Willy Villasmil and Malin Siegwart have recorded a Podcast together in the framework of the HSLU research-podcast. This should be published in Q1 2025. Keeping up with this level of dissemination supported by the research results.
- Contributing with our results to the “Speicherplan” of AEE Suisse that will be presented at the AEE Suisse congress on 7 May 2026.
- The results will be presented at the Swiss Symposium Thermal Energy Storage 2027 and will significantly contribute to further publications in the context of national energy strategy white papers.
- Oral Presentation and publication of the Results at the EuroSun2026 conference in Freiburg
- Joint publication of HSLU and ETH about the project results beginning of the heating season winter 2026/2027

NZZ

Saisonale Energiespeicher: Mit der Wärme des Sommers wird es im Winter behaglich

In Erdbecken oder wasserleitenden Gesteinsschichten lässt sich die Wärme des Sommers speichern. Das hilft, im Winter Strom zu sparen und senkt die CO₂-Emissionen.

Ralph Diermann (Text), Joana Kelén (Infografik)



Hören



Merken



Drucken



Teilen

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Langfristig nutzbare Wärmespeicher dienen auf clevere Weise dem Klimaschutz. Denn man kann im Winter Energie sparen, wenn man mit im Sommer gespeicherter Wärme heizen kann – das hilft, Emissionen zu vermeiden. Ausserdem entlasten die Speicher die Stromnetze. In Dänemark hat man mit solchen Anlagen schon viele positive

Figure 36: NZZ publication (22)



National and international Collaboration

As part of the WinTES project, synergies are actively achieved through the creation and coordination of links with national and international business and research partners as well as research projects.

Examples of such synergies are used with the following projects and partners:

- SWEET DeCarbCH: The project aims to decarbonize the heating and cooling system. Thermal storage is an important part of the project. The developments of the SES-ETH model were co-funded by DeCarbCH. Especially the new 3x3 scenario matrix is extensively used in both projects, as well as in SWEET-PATHFNDR and SWEET-Cosi. (<https://sweet-decarb.ch/>)
- SWEET PATHFNDR: The project aims to develop and analyze transition pathways for renewable energy integration in Switzerland. The Energy Balance Model, and the Gis-Framework have been firstly developed within the PATHFNDR project and are further developed and used for WinTES. (<https://sweet-pathfndr.ch/>)
- SWEET EDGE: The EDGE consortium aims to provide scientific findings to accelerate the use of renewable energies locally and decentral in Switzerland. The HSLU's Recommender Tool was created as part of SWEET EDGE and offers a community overview and recommendations for improved energy planning. This platform will also be used for the potential assessment within WinTES. (<https://www.sweet-edge.ch/de/home>)
- IEA TASK 45 “Acceleration the uptake of large thermal energy storages”: This collaboration allows the knowledge transfer and expertise from successful European research and industry partners. (<https://iea-es.org/task-45/>)
- SwissSTES: The SwissSTES project is founded by Innosuisse and aims to reduce Switzerland's dependency on fossil fuels by pioneering seasonal thermal energy storage (STES) to become a net-zero carbon society. An interdisciplinary consortium develops and assesses novel STES technologies and proposes a systemic STES action and implementation plan. Finding from SwissSTES and WinTES are exchanged closely to achieve excellence. (<https://www.swisstes.ch/>)
- The INTERSTORES project advances future renewable energy systems by developing and demonstrating efficient, reliable seasonal thermal energy storage (sTES) solutions. Through full-scale demonstrations of two tuneable sTES concepts (Reno-STES and Giga-STES), it proves their techno-economic and environmental benefits. The project also focuses on market uptake and replication across Europe.



7 Bibliography

1. **Bundesamt für Energie BFE, Prognos AG, INFRAS AG, TEP Energy GmbH, Ecoplan AG.** *Energieperspektiven 2050+, Technischer Bericht.* Zürich : Bundesamt für Energie BFE, 2021.
2. **Formhals, Julian and Winkler, Dietmar.** MoSDH - Modelica Solar District Heating library. *GitHub.* [Online] 2022. <https://github.com/MoSDH/MoSDH>.
3. *Modelica Buildings library.* **Wetter, Michael, et al.** 4, s.l. : Journal of Building Performance Simulation, 2014, Vol. 7.
4. **Eskilson, Per.** *Thermal analysis of heat extraction boreholes.* Lund : Department of Physics, Lund University, 1987.
5. *Advanced Hybrid Model for Borefield Heat Exchanger.* **Picard, Damien and Helsen, Lieve.** Lund : Proceedings of the 10th International ModelicaConference, 2014.
6. *Cost Analysis for Large Thermal Energy Storage Systems.* **Richard Lüchinger, Reto Hendry, Heimo Walter, Philipp Schuetz.** 021006-1, s.l. : ASME Journal of Engineering for Sustainable Buildings and Cities, 2025, Vol. 6. 10.1115/1.4069122.
7. **Schweizerische Nationalbank.** www.snb.ch. [Online] 2026. https://www.snb.ch/en/the-snb/mandates-goals/statistics/statistics-pub/current_interest_exchange_rates#t000.
8. **Geothermie.ch.** GEOTHERMIE-FACTSHEET-ERDWAERMESONDEN. *Geothermie-Schweiz.* [Online] 20 01 2016. https://geothermie-schweiz.ch/wp_live/wp-content/uploads/2016/01/GEOTHERMIE-FACTSHEET-ERDWAERMESONDEN.pdf.
9. **GeoBOOST, GoGeothermal.** Ground Source Heat Pumps in Europe. *gogeothermal.* [Online] 2024. <https://gogeothermal.eu/wp-content/uploads/2024/04/Geoboost-Deliverable-D2.1-Ground-Source-Heat-Pumps-in-Europe.pdf>.
10. *Cost Analysis for Large Thermal Energy Storage Systems.* **Lüchinger, Richard; Hendry, Reto; Walter, Heimo; Worlitschek, Jörg; Schuetz, Philipp.** s.l. : ASME Journal of Engineering for Sustainable Buildings and Cities, 2025, Vol. 6. 10.1115/1.4069122.
11. *Estimating the heating energy demand of residential buildings in Switzerland using only public data.* **Sarah Schneeberger, Curtis Meister, Philipp Schuetz.** 116371, s.l. : Energy and Buildings, 2025, Energy and Buildings, Vol. 347 B.
12. **Landwirtschaft, Bundesamt für.** geocat.ch. *geonetwork.* [Online] 30 09 2025. <https://www.geocat.ch/geonetwork/srv/ger/catalog.search#/metadata/ae183bc4-5c91-467e-89bc-85f390340efb>.
13. **Landestopografie, Bundesamt für.** *swissTLM3D – Das grossmassstäbliche Topografische Landschaftsmodell der Schweiz. swisstopo.* [Online] 08 03 2024. https://www.swisstopo.admin.ch/de/landschaftsmodell-swisstlm3d?utm_source=chatgpt.com.



14. —. digitale Höhenmodell (DHM25). *swisstopo*. [Online] 08 01 2024. [Cited: 01 08 2025.] <https://www.swisstopo.admin.ch/de/hoehenmodell-dhm25>.
15. —. Amtliches Verzeichnis der Gebäudeadressen. *swisstopo*. [Online] 08 01 2024. <https://www.swisstopo.admin.ch/de/amtliches-verzeichnis-der-gebaeudeadressen>.
16. *Mapping Switzerland's energy potential: a data-driven geo-analysis of energy technologies*. In: **Albon, Simon; Schmitt, Emma; Siegwart, Malin; Worlitschek, Jörg**. 3, s.l. : Journal of Physics: Conference Series, 2025, Vol. 3140. 10.1088/1742-6596/3140/3/032012.
17. **Arbeitsgemeinschaft QM Fernwärme, Nussbaumer Thomas, Thalmann Stefan, Jenni Andres, Ködel Joachim**. *Planungshandbuch Fernwärme (Version 1.3a, leicht überarbeitet vom 3. Mai 2021)*. P.108 Table 6.3. Zürich : Verenum AG, EnergieSchweiz, 2021.
18. *Advances in seasonal thermal energy storage for solar district heating applications: A critical review on large-scale hot-water tank and pit thermal energy storage systems*. **Abdulrahman Dahash, Fabian Ochs, Michele Bianchi Janetti, Wolfgang Streicher**. s.l. : Applied Energy, 2019, Applied Energy, vol. 239, Vol. 239, pp. 296-315.
19. **Planenergi**. Høje Taastrup. *PlanEnergi*. [Online] [Cited: 28 1 2025.] <https://planenergi.eu/de/projects/hoje-taastrup/>.
20. **Mangold, Dirk**. *Projektzeit PTES, SOLITES*. 04 2026.
21. **Schlecht, Ingmar, et al**. *Bedarf an Energiespeichern in der Schweiz* . s.l. : Bundesamt für Energie BFE , 2025.
22. **Worlitscheck, Jörg and Guidati, Gianfranco**. NZZ. *Saisonale Energiespeicher: Mit der Wärme des Sommers wird es im Winter behaglich*. [Online] 30 10 2024. [Cited: 05 12 2024.] <https://www.nzz.ch/wissenschaft/saisonale-energiespeicher-mit-der-waerme-des-sommers-wird-es-im-winter-behaglich-ld.1853219>.
23. **Commission, European**. ReFuelEU Aviation. *Mobility and Transport - European Commission*. [Online] 2024. https://transport.ec.europa.eu/transport-modes/air/environment/refueu-aviation_en.
24. **Cross, Sweet**. Swiss Energy Scope - ETH. *sweet-CROSS*. [Online] [Cited: 12 12 2025.] <https://sweet-cross.ch/models/SES-ETH>.
25. **Moret, Stefano**. Strategic energy planning under uncertainty. *EPFL Infoscience*. [Online] 2017. <https://infoscience.epfl.ch/handle/20.500.14299/141466>.
26. **Marcucci, Adriana, et al**. CROSS scenarios (V2022-09), CROSS Scenarios and Drivers Definition. *Sweet Cross*. [Online] 19 07 2023. [Cited: 12 12 2025.] https://sweet-cross.ch/api/media/file/CROSS_scenarios_V2022-09_2023_07_19.pdf.



8 Declaration AI-Tools

AI-based Tool	Use-case	Chapter
ChatGPT	Grammar correction, reviewing and revising text, Coding support for GeoPATH	Entire Document
Microsoft Copilot	Coding support for GeoPATH	Chapter 3
DeepL write	Grammar correction, reviewing and revising text	Entire Document
DeepL translate	Translation of Abstract to German and French	Abstract, Résumé, Zusammenfassung