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THE ROLE OF SEASONAL THERMAL ENERGY STORAGE IN SWISS NET-ZERO ENERGY SYSTEM SCENARIOS

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Summary

Seasonal mismatches between energy supply and demand are a central challenge for a net-zero Swiss energy system. This study evaluates the techno-economic contribution of pit thermal energy storage (PTES) and regenerated borehole thermal energy storage (BTES) to the Swiss energy system. Detailed dynamic storage models were translated into simplified archetypes for the linear Swiss EnergyScope model (SES-ETH). Nine scenarios for 2050 combine three energy-trade conditions with three technology-development pathways; 100 Monte Carlo calculations per scenario address uncertain model parameters. The value of seasonal thermal energy storage (STES) was assessed by comparing optimized systems with and without the option of BTES and PTES. Across the nine scenarios, the mean combined storage capacity ranges from approximately 6 to 10 TWh. Reported benefits include winter electricity import reductions of up to approximately 3.6 TWh per year and annual system cost savings of CHF 400-900 million CHF.

seasonal thermal energy storage, pit storage, borehole storage, sector coupling, Swiss EnergyScope, winter electricity, Monte Carlo analysis, energy system modeling

1. Introduction

The transition to a net-zero energy system requires balancing energy production and consumption across seasons. For Switzerland, the Energy Perspectives 2050+ scenario used as context for this study indicates a winter electricity deficit of approximately 9 TWh, to be covered by imports (Bundesamt für Energie, 2020). This value provides the motivation for the present study; it is not the reference electricity balance imposed on the scenarios analysed here. Electrification of heat supply makes the interaction between thermal demand and winter electricity availability particularly relevant.

Seasonal thermal energy storage (STES) can shift heat availability between summer and winter and modify the operation of coupled electricity and heating technologies. Pit thermal energy storage (PTES) supplies heat at temperatures useful to district heating networks. When integrated with a waste-to-energy or biomass combined heat and power plant, it can reduce winter heat extraction from the steam cycle and thereby increase electricity production during critical periods. Regenerated borehole thermal energy storage (BTES), in contrast, stores low-temperature heat that is upgraded by a heat pump. Its value depends on both the amount of heat stored and the temperature available at the heat-pump source (Worlitschek et al., 2026).

Representing these processes in a national linear optimization model requires a compromise between physical detail and computational tractability. This is especially important for BTES, whose effective capacity, power and temperature depend strongly on operation. The research addressed this challenge by linking dynamic storage simulations with Swiss EnergyScope (SES-ETH). The present paper focuses on the resulting national assessment analyzing the research question:

How much seasonal thermal energy storage is selected in a cost-optimal net-zero emission energy systems, and how does its availability affect winter electricity imports, fuel imports and annual system costs?

2. Modelling of BTES and PTES

Detailed PTES modelling

The PTES archetype represents a high-temperature heat source supplying a district heating network. During charging, the storage heat exchanger operates in parallel with the heat demand. During discharging, storage preheats part of the network return flow before the heat source raises it to the required supply temperature. An adapted MoSDH Modelica model, version 1.2, describes the storage water and surrounding ground by axisymmetric, two-dimensional finite-volume discretization, with 15 vertical water segments (Formhals and Winkler, 2022). Surface boundary conditions include convective heat exchange and solar heat gains. Charging and discharging boundary temperatures are 95 and 50 °C, respectively.

Simulations use heat demand profiles from an Energie Wasser Luzern (EWL) district heating network supplied by the Renergia waste-to-energy plant with a total heating demand of 75’880 MWh per year and a peak load of 32.5 MW. Two storage volumes were evaluated (Table 1). The direct-supply limits of 17 and 14 MW were selected through trial simulations to maximize winter storage discharge while maintaining heat-demand coverage. They are therefore operating assumptions for the local system, not independently established universal design limits (Worlitschek et al., 2026).

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

Effective capacity is the difference between maximum and minimum water enthalpy, including the effects of imperfect stratification and heat-exchanger operation. Annual equivalent cycles equal discharged energy divided by effective capacity. The larger pit has higher efficiency and covers 17.0% of annual heat demand, compared with 10.5% for the smaller pit (Table 1). PTES costs are derived from volume-dependent cost correlations (Lüchinger et al., 2025) and converted to capacity-specific costs using the archetype performance; the system-level analysis reports approximately 0.9 CHF/kWh (Worlitschek et al., 2026).

Detailed BTES modelling

A simple capacity-and-power representation, as used in SES-ETH, is not well suited to BTES because its effective storage capacity and discharge power depend strongly and nonlinearly on operating conditions. To address this limitation, several BTES operating cases were simulated, each resulting in a different effective storage capacity and/or peak power. These cases were subsequently represented as quasi-independent storage options in SES-ETH, allowing the optimizer to select the most favorable configuration. 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 use a field of 100 parallel single-U-tube boreholes arranged on a 10 × 10 grid. Each borehole is 150 m deep, with 7.5 m spacing and a diameter of 160 mm. Ground thermal conductivity and volumetric heat capacity are 1.5 W/(mK) and 1’620 kJ/(m^3K). This borehole field is represented by a model from the Modelica Buildings library (v10.0.0) (Wetter et al., 2014) that relies on Eskilson’s thermal response function approach (Eskilson, 1987). Further details on the mod-elling approach can be found in Picard and Helsen (2014).

The field supplies a heat pump driven by a synthetic heating-degree-hour demand profile, using measured

Würenlingen air temperature and a 14 °C heating limit. Operating cases include free regeneration through an air-brine heat exchanger, forced charging with constant heat supply, and forced charging with a sinusoidal supply profile. Constant supply approximates sources such as data-center waste heat; the sinusoidal case represents a strong seasonal supply-demand mismatch. Supply and demand scaling were varied to investigate capacity utilization and elevated storage temperatures. Ten years were simulated, and the final year was evaluated. The detailed heat-pump model uses a quality grade of 0.55 (Worlitschek et al., 2026).

BTES capacity was derived from integrated net charging power, and nominal discharge power from its 95th percentile. Greater utilization increases effective capacity but also increases temperature oscillation, potentially reducing heat-pump performance. Raising the mean field temperature improves the heat-pump source temperature at the expense of additional charging and ground losses (Table 1Table 2). Apparent storage efficiencies slightly above unity in some cases reflect net heat uptake from the surrounding ground (Table 2).

Table 2: Summary of metrics resulting from each BTES case

#	Case*	Power [W/m]	Capacity [kWh/m]	Efficiency [-]	Seasonal Performance factor (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*

*Naming convention for the cases:

	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)

The BTES simulations show an approximately linear relationship between the effective storage volume (effective capacity per meter of borehole), and annual fluid-temperature amplitude (Figure 1). Four linear-model archetypes that distinguish capacity utilization from mean temperature elevation were then implemented in SES-ETH (Table 3). Borehole investment is parameterized at 80 CHF/m.

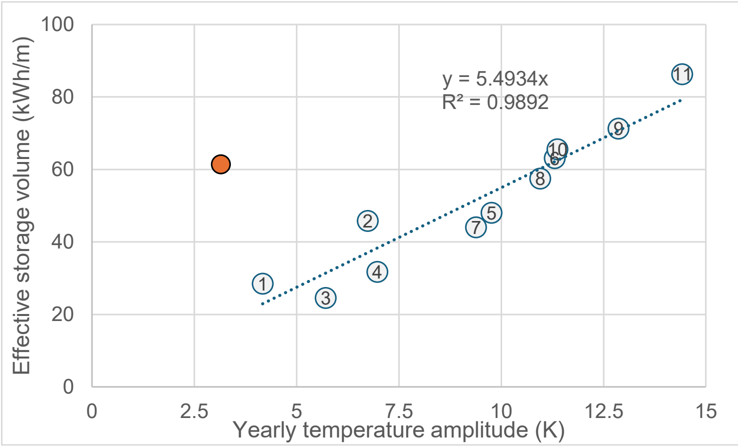

Figure 1:Effective storage volume as function of the yearly temperature amplitude.

Table 3: Definition of regenerated borehole variants.

Case	T_{high}-T_{low} (K)	T_{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

3. National energy-system model and boundary conditions

SES-ETH is a linear optimization model based on the EnergyScope framework (Moret, 2017; Marcucci et al., 2021) (Figure 2). It minimizes annualized investment, operation and maintenance, and resource costs while satisfying electricity, heat and mobility demands and a net-zero constraint. The emissions boundary includes difficult-to-abate contributions from agriculture, industry and aviation, following the CROSS-scenario framework (Marcucci et al., 2022). The model is a 2050 snapshot, not an optimization of the transition pathway. Hourly resolution is used within a typical-day representation. Daily, seasonal and multi-year storage have cyclic balances over a day, year and ten-year scenario cycle, respectively (Marcucci et al., 2021).

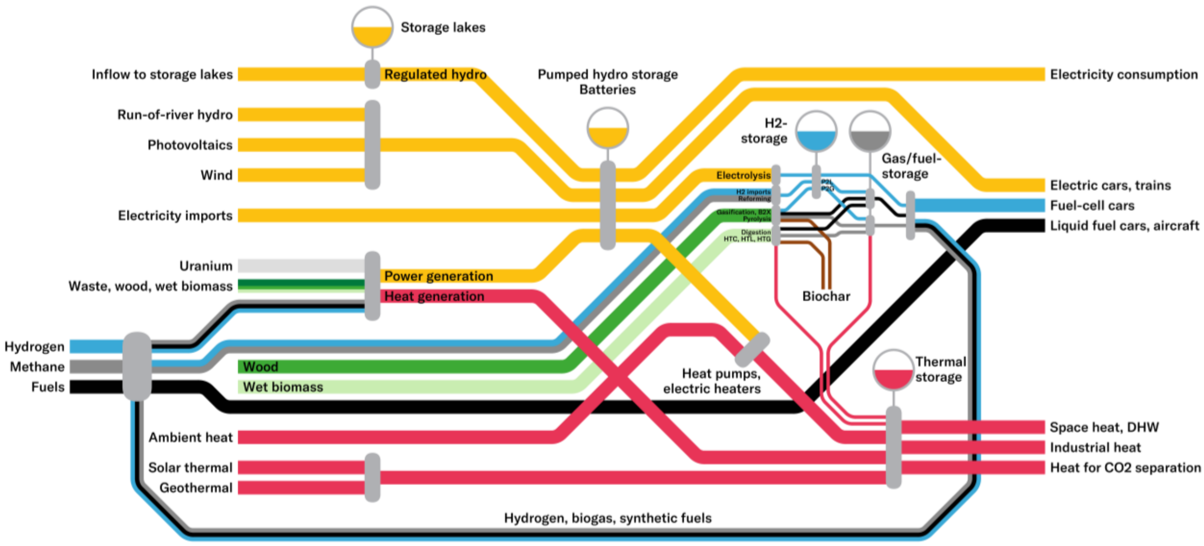

Figure 2: Schematic representation of the energy system as modelled in SES-ETH

Within the SES-ETH, scenario analysis is carried out through a 3 × 3 matrix reflecting two major uncertainty dimensions: Switzerland's future relationship to European energy trade and alternative technology development pathways. The framework spans cases from strong import disruption to unrestricted energy trade (isolation, robust, ideal (Figure 3)), and from innovative to conservative assumptions regarding technology adoption (conservative, realistic, innovative (Figure 4)). For each of the nine scenario combinations, 100 Monte Carlo runs are performed to capture uncertainty in key parameters such as technology costs. To isolate the value of seasonal thermal storage, an additional variant is calculated in which both pit storage and borehole storage are disabled, allowing a direct comparison between systems with and without STES.

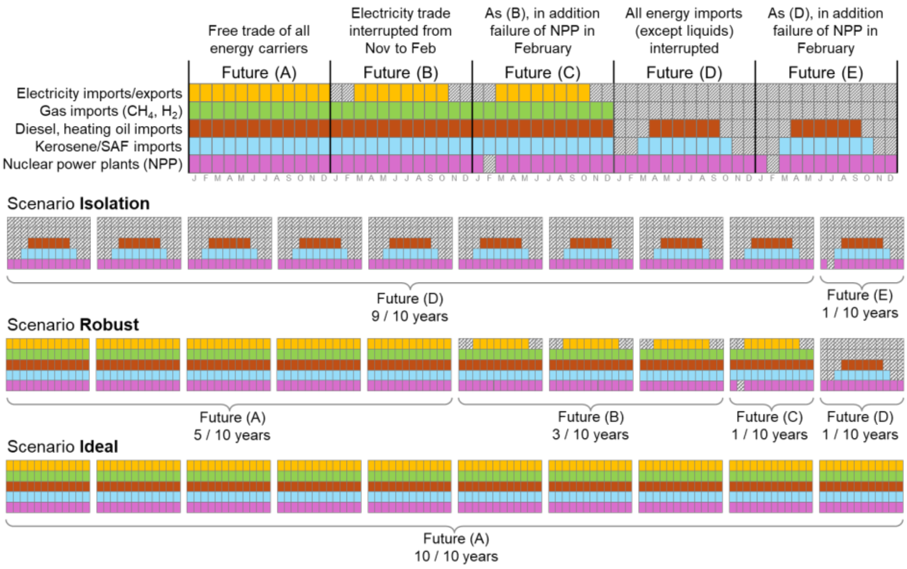

Figure 3: Definition of three scenarios that are composed of the five different futures.

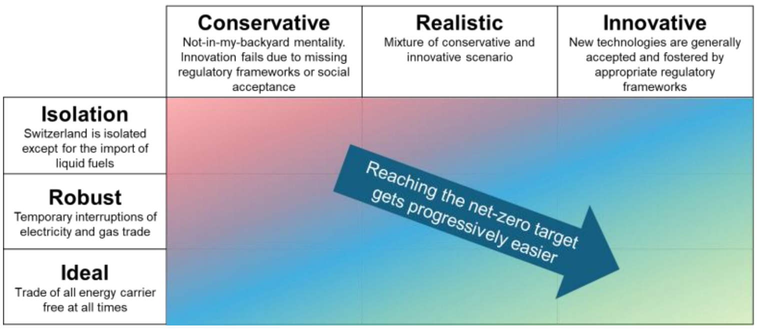

Figure 4: 3 x 3 Scenario matrix, formed with the two dimensions «relationship to Europe» and «attitude towards innovation».

4. Results

Cost optimal seasonal storage deployment

The scenario assumptions influence the cost-optimal electricity generation mix. More conservative technology pathways generally exhibit lower combined electricity generation from wind and photovoltaics (PV), while nuclear generation plays a greater role (Figure 5). This is particularly pronounced in the Isolated scenario, where electricity imports are unavailable throughout the year. Under conservative assumptions, nuclear electricity generation in this scenario reaches a scale comparable to the existing Swiss nuclear generation level used for comparison in the report.

STES is selected across all the scenarios. The reported scenario-average combined capacity is approximately 6-10 TWh (Figure 5). PTES capacity (labelled thermal energy storage in Figure 5) is approximately 3-6 TWh and decreases from conservative to innovative pathways, whereas regenerated BTE (labelled anergy storage in Figure 5) capacity is approximately 2-6 TWh and increases in the same direction (Figure 5).

Within the wider storage portfolio, the Robust scenario generally exhibits the largest methane and diesel storage capacities, particularly under conservative technology assumptions (Figure 5). Unlike PTES and BTES, these chemical storage options are represented as multi-year storage. They support security of supply during periods of interrupted energy trade. In particular, diesel can be imported and accumulated over several years, then used to generate electricity and heat during winter periods affected by electricity-trade disruptions.

The electricity trade balance also varies substantially across scenarios. Unrestricted energy trading in the ideal scenario results in the highest net winter electricity imports, reported at approximately 11–23 TWh per year, compared with 3–11 TWh per year in the robust scenario (Figure 5). Within both trading regimes, moving from conservative to innovative technology assumptions reduces winter electricity imports.

Annual final electricity demand ranges from approximately 76 to 110 TWh across the analysed scenarios (Figure 5). For a given technology pathway, demand is lower under isolation and increases towards unrestricted energy trading. For a given trading regime, however, conservative technology assumptions generally lead to higher final electricity demand than innovative assumptions. The effects of trade openness and technological innovation on electricity demand must therefore be distinguished rather than interpreted as a single trend.

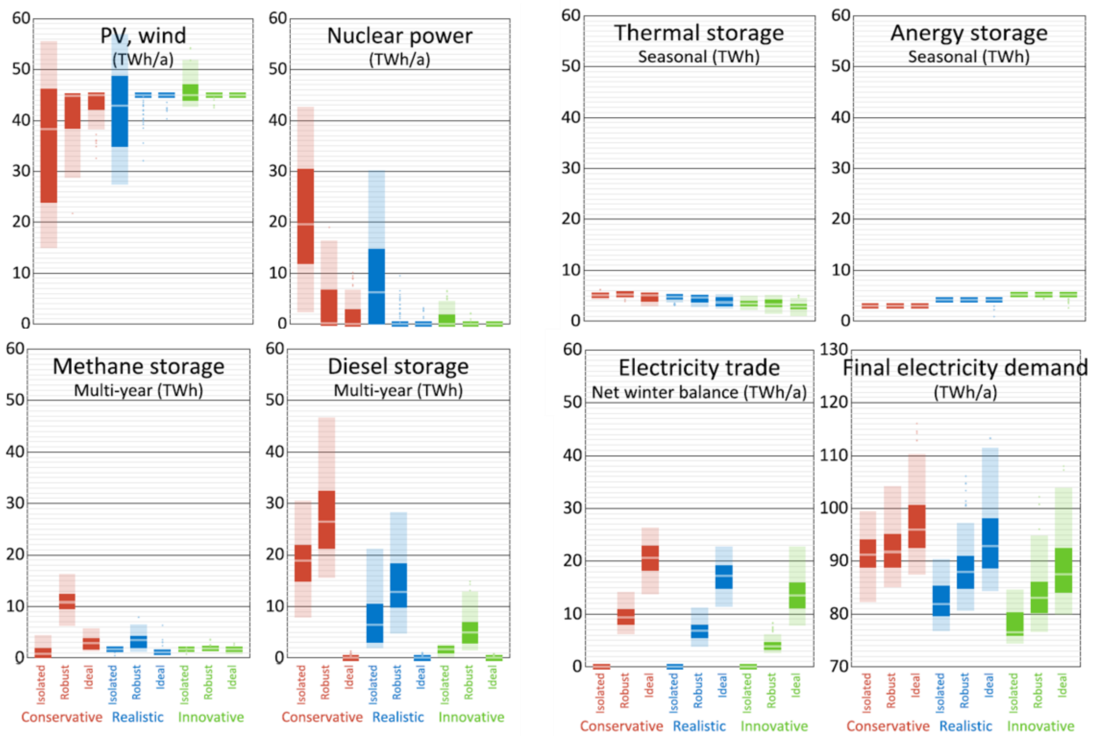

Figure 5: Cost optimal storage requirement and other relevant indicators.

Comparison to system without storage

Figure 6 compares optimized systems with and without both STES options. Removing STES generally increases winter electricity imports, methane and diesel imports, and winter generation from thermal plants. Effects are strongly scenario dependent. Winter-import reductions are negligible in isolation, where electricity imports are unavailable by construction. The largest reductions occur in the ideal scenarios, reaching approximately 3.6 TWh/year in the conservative case and about 1.6 TWh/year in the innovative case (Figure 6).

Imported-fuel reductions of up to approximately 3.2 TWh/year are reported. The graphical distributions also include small or negative changes in some cases; fuel savings are therefore not uniform across all scenarios and parameter combinations (Figure 6). In the isolated case, the benefit is expressed more through changes in domestic generation and fuel requirements than through an electricity-import reduction. An unchanged import balance in isolation consequently does not imply that STES has no system value.

The implementation of STES reduces winter electricity generation from thermal plants by 0–1.8 TWh/year, with the largest reductions occurring in the Isolation scenario (Figure 6).

Excluding seasonal thermal storage increases total annual system costs by approximately CHF 400–900 million per year (Figure 6).

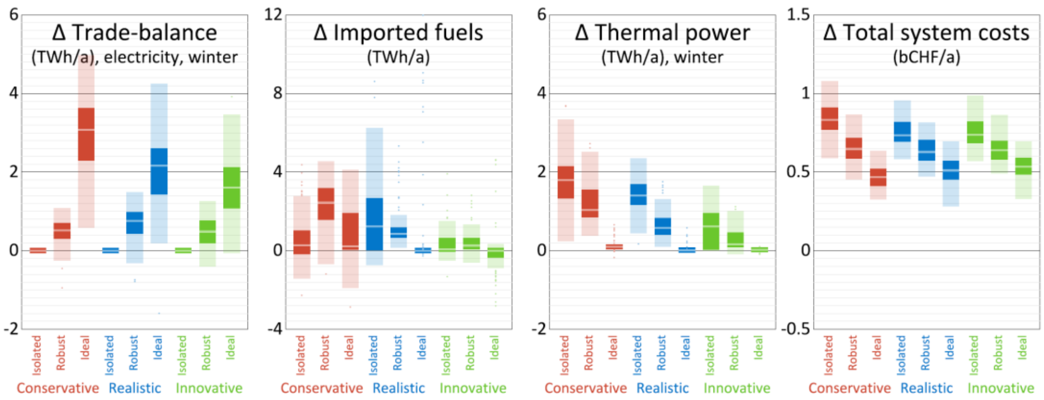

Figure 6: System result comparison with and without thermal energy and anergy storage options

5. Discussion

The scenario comparison therefore supports interpreting STES as a cross-sector flexibility option. It does not, however, quantify probabilistic reliability, loss-of-load risk or performance under all possible disruptions. Resilience in this assessment refers to the ability of cost-optimal systems to satisfy specified demand and disruption conditions, rather than a directly measured reliability index.

The estimated value of STES is conditional on district heating expansion, storage costs, heat-pump temperatures, the availability of alternative technologies and the treatment of imported fuels and emissions. The Monte Carlo analysis explores selected parameter uncertainties, while the scenario matrix addresses broader trade and technology conditions. It does not remove structural uncertainty arising from spatial aggregation, typical-day representation or predefined archetypes. In particular, the reported cost savings are not independently validated construction budgets, and technology-level attribution remains limited by the system-wide response to each counterfactual.

The results support early pilot deployment and further integration of physical, spatial and national-system modelling. The project recommends building full-scale operational experience to support broader implementation from approximately 2035 onwards. This timing is an implementation recommendation, not a result derived from the 2050 snapshot optimization. Pilot projects would also provide evidence on initial ground warm-up, sustained cycling performance, multifunctional covers and realized costs, helping to test the assumptions underlying the national storage potential.

6. Conclusion

Linking dynamic PTES and BTES simulations with SES-ETH shows that seasonal thermal storage can contribute materially to a cost-optimal net-zero Swiss energy system. The scenario analysis reports combined average capacities of approximately 6-10 TWh, winter electricity import reductions reaching approximately 3.6 TWh/year, and annual system cost savings of 400-900 million CHF. PTES is more prominent under conservative technology assumptions, while regenerated BTES gains importance under innovative pathways.

Electricity-import reductions and cost savings respond differently to trade conditions: the former are greatest where imports remain available, whereas the latter are larger under constrained trade. STES should therefore be evaluated through both heating- and electricity-sector effects rather than a single import indicator. Its practical contribution depends on suitable locations, network integration, validated performance and cost assumptions. Full-scale demonstration and consistent spatial-system assessment are important next steps toward realizing the identified potential.

Acknowledgement

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