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

Summary

Switzerland's transition to a net-zero energy system faces a major challenge: a seasonal mismatch between energy supply and demand, leading to a projected winter electricity deficit of about 9 TWh by 2050.

This study evaluates the techno-economic potential of large-scale seasonal thermal energy storage (STES) to reduce this deficit. The influence of STES on the overall Swiss energy system is analyzed with the SES-ETH framework, a linear optimization model that minimizes total annual system costs subject to technology performance, resource availability, and net-zero constraints.

The scenario analysis shows that STES can reduce winter electricity imports by up to 1–3 TWh per year. It also lowers annual system costs by several hundred million CHF, particularly under constrained electricity import conditions. Overall, STES is not only a heat-sector flexibility option, but also a strategic infrastructure element for improving winter energy security and system resilience.

Keywords: Seasonal Thermal Energy Storage, Energy System, Winter Electricity Gap, Pit Storage, Borehole Storage, Sector coupling, Monte Carlo

Field of application for the findings: Politics, District heating networks

Addressed audience: Researcher, Politician

1. Introduction

By 2050, Switzerland's energy system must transform from a net greenhouse-gas emitter to a net-zero or net-negative system. A key challenge in this transition is the seasonal imbalance between energy supply and demand. According to the Federal Energy Perspectives 2050+, Switzerland may face a winter electricity deficit of around 9 TWh (Bundesamt für Energie BFE, 2020). Seasonal thermal energy storage (STES) is increasingly discussed as a sector-coupling option to mitigate winter deficits in highly electrified energy systems. To mitigate this imbalance, this study assesses the techno-economic potential of large-scale thermal energy storage technologies. The analysis builds on detailed modelling of pit thermal energy storage (PTES) and borehole thermal energy storage (BTES) and investigates their contribution to reducing electricity imports, lowering overall energy system costs, and strengthening winter adequacy in a highly electrified future energy system.

2. Methodology

The analysis is based on SES-ETH (Figure 1), a linear optimization model of the Swiss energy system that minimizes total annual system costs subject to technology performance, resource availability, and net-zero constraints. The model represents electricity, heat, and mobility demand. All simulations refer to the target year 2050.

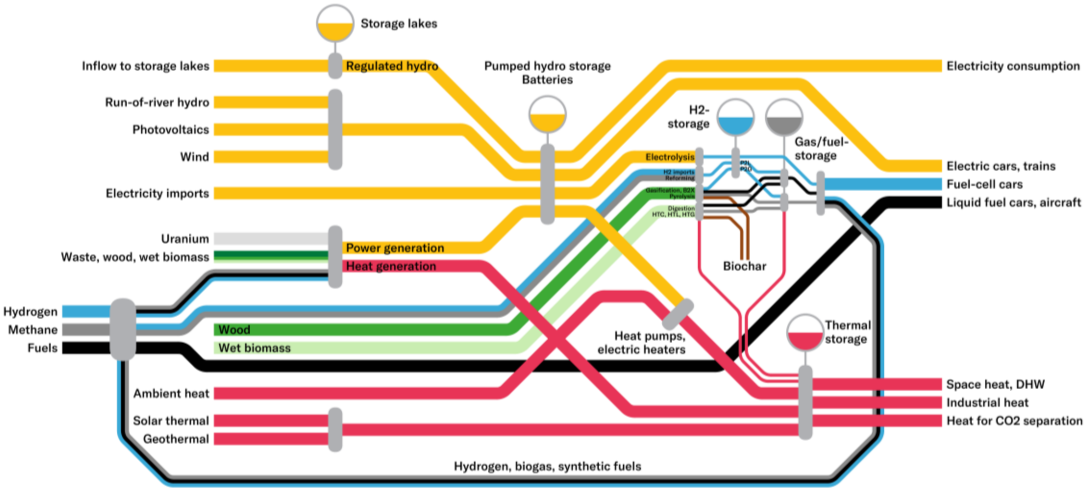

Figure 1: Schematic representation of the energy system as modelled in SES-ETH

Dynamic models of pit thermal energy storage (PTES) and borehole thermal energy storage (BTES) technologies are developed to derive key performance parameters such as storage capacity, charging/discharging power, and efficiency. These parameters are translated into simplified archetypes for use in the linear SES-ETH framework, where the storage technologies can be coupled to the heating and cooling demand of district energy networks. For BTES, four archetypes are defined that vary in temperature amplitude and in the balance between charged and discharged energy, resulting in different temperature profiles and heat losses. For PTES, two archetypes are developed, each characterized by specific power limits, efficiencies, and annual cycle numbers as inputs to the SES-ETH model.

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 unrestricted energy trade to strong import disruption (isolation, robust, ideal), and from innovative to conservative assumptions regarding technology adoption (conservative, realistic, innovative). 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.

3. Results

The model results show that seasonal thermal storage can provide measurable system value in Swiss net-zero scenarios. In general, the availability of PTES and BTES decreases winter electricity imports, methane and diesel imports, additional winter generation from thermal power plants, and total annual system costs. The magnitude of this benefit depends strongly on the scenario context. In some cases, winter electricity imports are only weakly affected, whereas in others they are reduced by approximately 1-3 TWh/a (Figure 2).

Across the scenario set, the presence of seasonal thermal storage generally lowers total system costs by a few hundred million CHF per year (Figure 2). The value of STES is particularly pronounced under constrained import conditions, where security of supply becomes more critical and flexibility options within the domestic energy system gain importance (Figure 2).

These findings suggest that STES should be understood not only as a heat-sector flexibility option, but also as strategic infrastructure for increasing resilience across both the heating and electricity sectors.

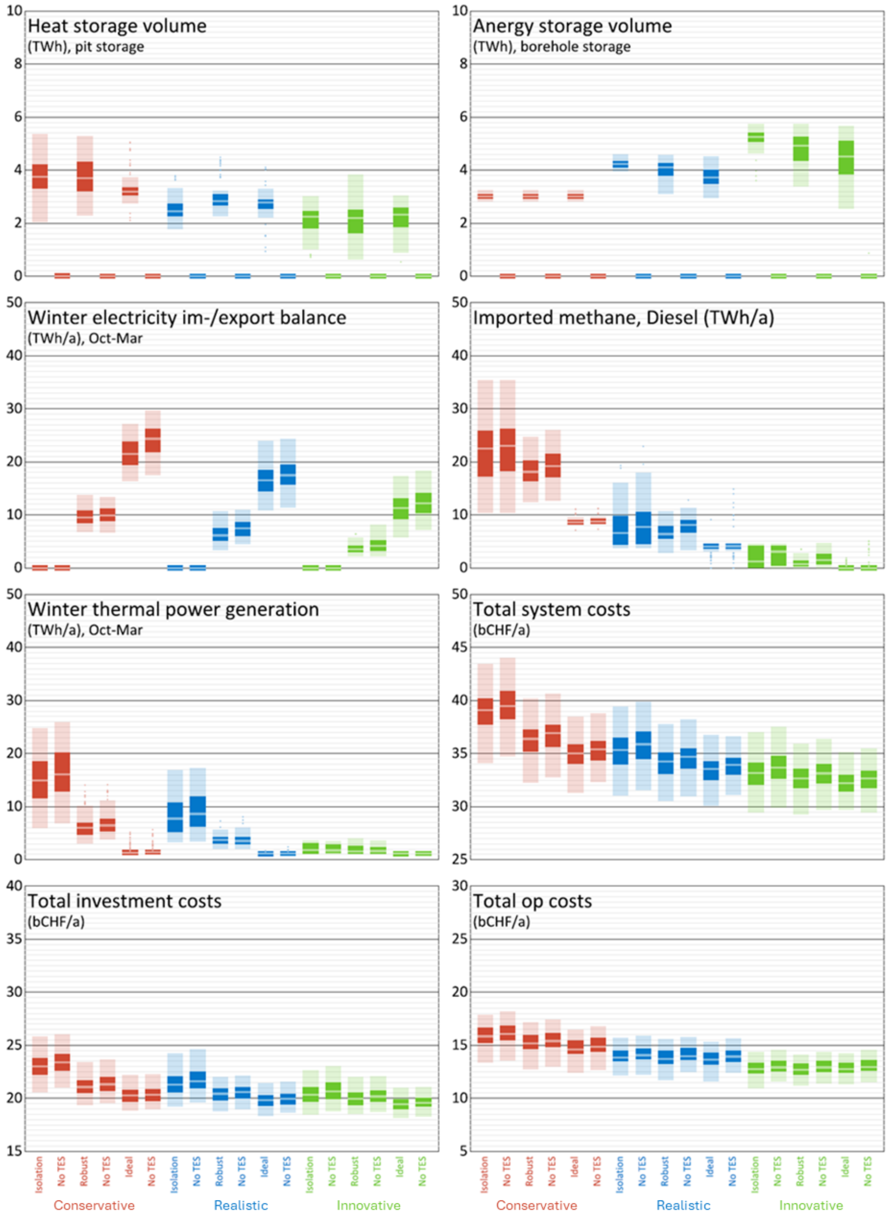

Figure 2: The value of thermal energy storage

4. Reference

Bundesamt für Energie BFE, 2020. Energieperspektiven 2050+. Zusammenfassung der wichtigsten Ergebnisse. Bundesamt für Energie BFE, Bern.