ASSESSING THE POTENTIAL OF LARGE-SCALE SEASONAL THERMAL ENERGY STORAGE IN SWITZERLAND USING INTEGRATED GIS-BASED ENERGY MODELLING AND OPTIMIZATION

Summary

Seasonal thermal energy storage (STES) can mitigate the seasonal mismatch between renewable energy supply and heat demand, particularly when integrated with district heating networks. This work presents a methodology that couples national-scale energy system analysis with GIS-based spatial screening and district-level optimization to assess the technically feasible and cost-optimal deployment of large-scale STES in Switzerland. The framework bridges top-down scenario boundary conditions with bottom-up implementation constraints by identifying district heating candidates, classifying them into archetypes based on accessible heat sources and storage placement potential, and optimizing representative districts. The analysis presents technology mixes, optimal storage sizing, and a national extrapolation of deployable STES potential.

Keywords: seasonal thermal energy storage, district heating, GIS, energy system optimisation, decarbonisation

Field of application for the findings: Energy system planning, district heating design, large-scale renewable integration

Addressed audience: Researchers, utilities, planners, technology developers, and policy makers

1. Introduction

Heating and domestic hot water account for a dominant share of final energy demand and greenhouse gas emissions in Switzerland (50% overall, 66% in January), similar to the broader European context. National decarbonization pathways consistently identify large-scale electrification via heat pumps, combined with a strong expansion of renewable electricity generation, as a cost-effective strategy to reach long-term climate goals. However, this approach will require a substantial reinforcement of electrical infrastructure to accommodate the significant increase in power demand from replacing gas boilers with electric systems. In this respect, alternative solutions capable of delivering and/or storing heat directly cal help easy this transition. Moreover, the pronounced seasonal mismatch between renewable energy availability and space heating demand remains a key challenge for the energy system.

Swiss national energy system analyses indicate that seasonal energy storage is required to achieve high shares of renewable energy while maintaining system cost efficiency and security of supply. Scenario analyses based on the Swiss EnergyScope framework show that several TWh of seasonal thermal energy storage are needed by 2050 to shift surplus summer renewable energy towards winter heat demand [1]. This applies to solar thermal and large-scale heat pumps in district heating systems, as well as to storing PV overproduction via electric boilers in industry. Large-scale seasonal thermal energy storage (STES), integrated with district heating networks, therefore emerges as a critical system component.

While national-scale models provide valuable insight into the magnitude of required storage capacities, they typically represent Switzerland as a single aggregated region and do not resolve spatial constraints, local feasibility, or technology-specific deployment limits. Conversely, local or district-level studies can assess technical feasibility in detail, but often lack consistency with national boundary conditions such as electricity price seasonality, emissions constraints, energy imports and exports, and long-term system evolution. Bridging this gap between top-down system needs and bottom-up spatial feasibility is essential for assessing the realistic potential for implementing STES and its impact at national scale.

2. Methodology

To bridge national energy system requirements with local deployment feasibility, this work combines top-down energy system modelling with GIS-based spatial analysis and bottom-up district-level optimisation. The methodological framework integrates three complementary components, as illustrated in Fig. 1.

First, national-scale energy system modelling is used to define consistent boundary conditions relevant for seasonal thermal energy storage, including long-term decarbonisation targets, electricity price seasonality, and the overall magnitude of required seasonal storage. These boundary conditions are informed by national energy system scenario analyses developed within the Swiss Energy Perspectives 2050+, which quantify the role of seasonal energy storage in achieving a fully decarbonised Swiss energy system [3].

Second, a GIS-based screening approach is applied to identify candidate district heating areas across Switzerland. Building-level heat demand data are aggregated spatially and analysed using a dedicated district scanning algorithm based on heat-density thresholds and spatial contiguity criteria. This approach follows established methodologies for mapping the heat density and evaluating the potential of district heating [2], while extending them to explicitly include the feasibility of large-scale thermal energy storage.

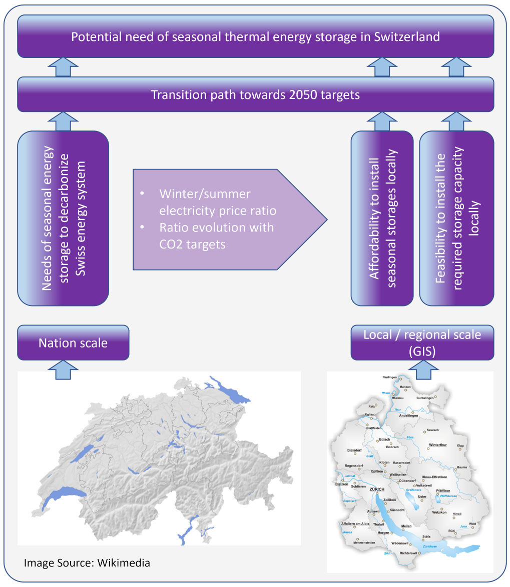

Fig. 1: Integrated top-down and bottom-up modelling framework linking national energy system scenarios, GIS-based district screening, and district-level optimisation.

Third, identified districts are classified into archetypes according to accessible heat sources and feasible thermal energy storage options. For each archetype, a representative district is selected for detailed techno-economic optimisation using a mixed-integer linear programming energy system model. Results are subsequently extrapolated from representative districts to assess the deployable potential of large-scale seasonal thermal energy storage at the national level.

3. GIS-Based District Identification and Optimisation

Building-level heat demand is aggregated into 1 ha hexagonal cells to enable scalable spatial screening while preserving the underlying urban structure. A dedicated GIS-based district scanner identifies contiguous clusters with sufficiently high (700 MWh/y or more) heat-demand density for district heating feasibility. Candidate districts are expanded by including neighboring cells above a lower demand threshold (400 MWh/y or more), resulting in coherent and contiguous district heating areas suitable for further assessment.

For each identified district, spatial overlays are used to evaluate access to potential heat sources (e.g. waste heat, surface water, groundwater) as well as the feasibility of different large-scale thermal energy storage options, including surface-based and subsurface concepts. These feasibility layers are not interpreted as final design constraints, but provide a consistent screening basis for subsequent techno-economic optimization. Examples of resulting districts and their main heat source are shown in Fig. 2. To retain national coverage while limiting computational effort, districts are grouped into archetypes defined by characteristic combinations of accessible heat sources and storage feasibility. One representative district per archetype, selected to reflect typical heat demand and local conditions, is used for detailed optimization and subsequent extrapolation. A mixed-integer linear programming (MILP) energy system optimization model is applied to each representative district to minimize total annualized system cost subject to capacity, and optional emissions constraints. The technology portfolio includes central heat pumps, biomass boilers, photovoltaic generation, electrical battery storage, and multiple seasonal thermal energy storage options (pit, borehole, aquifer and tank TES). Thermal energy storage models account for investment costs, thermal losses, and geometry-dependent constraints, while maximum capacities are bounded by GIS-derived feasibility areas. Hourly weather and heat demand time series are used to represent seasonal dynamics. The analysis accounts for technology costs, feasibility constraints, and scenario variations to ensure robust quantification of system performance across seasonal conditions.

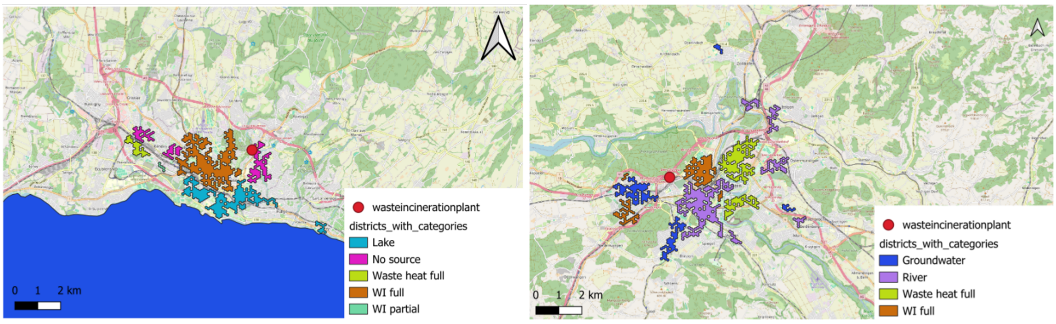

Fig. 2: Examples of district heating candidates and resulting archetypes identified through the GIS-based screening across selected urban areas. Districts are classified based on heat-demand density and local availability of heat sources and seasonal thermal energy storage options. WI refers to waste incineration and full refers to the possibility to cover the full district solely with its heat source.

4. Results

An overview of the aggregated heat demand represented by the different district archetypes considered in this work is provided in Tab. 1, illustrating the relative relevance of source and storage placement conditions across the national building stock. The proposed methodology is transferable to other regions and offers a robust basis for strategic energy planning, supporting informed decisions on district heating development, storage deployment, and the integration of renewable energy sources in future low-carbon heating systems.

Tab. 1: Aggregated annual heat demand and storage capacity by district archetype.

Archetype	**WI full**	**WI partial**	**Waste heat full**	**Waste heat partial**	**River**	**River large**	**Ground water**	**Lake**	**No source**
Heat demand [TWh/y]	3.936	0.359	1.211	0.522	2.831	8.650	1.045	1.538	0.482
Total heat demand [TWh/y]					**20.574**				
TES type	PTES	BTES	PTES	PTES	PTES	PTES	PTES	BTES	PTES
Storage capacity [TWh]	1.377	0.054	0.424	0.134	1.401	4.334	0.516	0.136	0.240
Total storage capacity [TWh]					**8.620**				

The results indicate that STES is a central component of cost-optimal district heating configurations across a wide range of spatial contexts, with technology choice strongly driven by local storage placement conditions and accessible heat sources. Surface-based storage concepts are favored where land availability allows for large seasonal capacities, while subsurface storage options enable integration in dense urban environments. Beyond local system optimization, the archetype-based extrapolation provides insight into the spatial distribution and aggregate scale of deployable STES capacities at the national level.

In concluding, this work presents an integrated framework that combines national energy system perspectives with GIS-based spatial screening and district-level energy system optimization to assess the realistic deployment potential of large-scale seasonal thermal energy storage (STES) at national scale. By explicitly linking top-down boundary conditions with bottom-up feasibility constraints, the approach addresses a key gap between system-level scenario analyses and implementation-oriented planning.

References

[1] Matthias Berger, Helene Sperle, Samuel Kummer, Andreas Häberle, Daniel Carbonell, Gianfranco Guidati, Adriana Marcucci, Sabine Perch-Nielsen, Milena Krieger, David Stickelberger, and Nathalie Spiller. *SolTherm2050 - Chancen durch Solarwärme und thermische Energiespeicher für das Energiesystem Schweiz 2050.* Swiss Federal Office of Energy (SFOE), Research Programme Solar Heat and Heat Storage, CH-3003 Bern, 2021.

[2] Thomas Nussbaumer, Stefan Thalmann, Andres Jenni, and Joachim Ködel. Handbook on planning of district heating networks. *Bern: Swiss Federal Office of Energy*, 2020.

[3] Prognos AG and TEP Energy GmbH and INFRAS AG. Energieperspektiven 2050+ – technischer bericht. Technical report, Bundesamt für Energie (BFE), Bern, Switzerland, December 2021. Publikationsnummer 10783, Ausgabe vom 20.12.2021.