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EXTENDED ABSTRACTS

Cost Drivers of Large Thermal Energy Storage in Switzerland: A Mixed-Methods Analysis Combining Quantitative Modelling and Case Studies

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Summary

Large-scale thermal energy storage (TES) is essential for decarbonised heat supply but remains subject to substantial cost uncertainty in early planning stages. This study analyses 93implementedTES projects based on harmonised Swiss reference costs to derive empirical scaling relationships and quantify residual cost dispersion across borehole thermal energy storage, tank thermal energy storage and pit thermal energy storage. Although scaling models explain a substantial share of cost variation, systematic deviations persist beyond capacity and technology effects. A mixed-methods framework links residual-based quantitative modelling with targeted qualitative case studies to interpret these deviations as structural cost drivers rather than statistical noise. The results provide a structured classification of cost uncertainty for early-stage techno-economic assessment of large-scale TES systems.

Keywords: thermal energy storage, cost drivers, cost scaling, investment costs, case studies, cost uncertainty, district heating

Field of application for the findings: Early-stage planning and techno-economic assessment of large-scale thermal energy storage systems in district heating and integrated heat supply systems.

Addressed audience: Researchers in solar and thermal energy systems, district heating planners, energy system analysts, utilities, engineering consultants, and public authorities involved in heat infrastructure planning.

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1. Introduction

Large-scale thermal energy storage (TES) is central to decarbonised heat supply, particularly in district heating networks (Guelpa & Verda, 2019). Early-stage planning requires technology selection under substantial cost uncertainty, while available investment data remain limited and heterogeneous. Recent work harmonises cost data and identifies scaling relationships across technologies (Lüchinger et al., 2025), yet substantial dispersion persists around these trends. This variation is commonly treated as statistical noise, although part of it reflects systematic structural differences between projects. This study introduces a mixed-method framework that links residual-based quantitative modelling with targeted qualitative case reconstruction to identify structural cost drivers. The objective is to systematically interpret cost dispersion and classify sources of cost uncertainty in early-stage planning. The analysis covers borehole (BTES), pit (PTES), and tank thermal energy storage (TTES), including non-pressurised and pressurised TTES configurations, within a Swiss planning context.

2. Methodological Approach

The methodological approach follows a sequential mixed-method logic in which quantitative modelling informs the targeted selection of qualitative case studies (Creswell & Plano Clark, 2017). Figure 1 illustrates the framework, combining quantitative analysis of a harmonised TES project database with qualitative case reconstruction. The database comprises realised large-scale TES projects compiled through literature review and complemented by expert input.

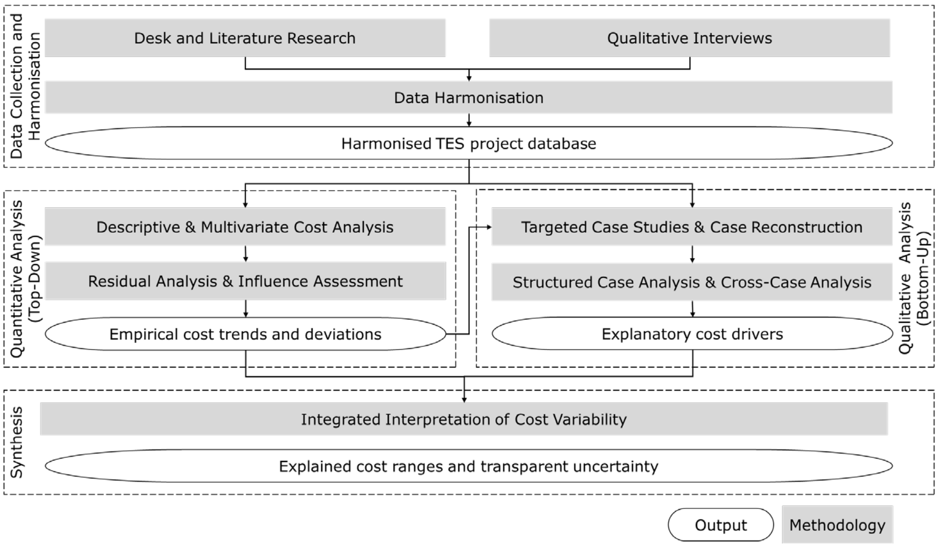

Fig. 1: Sequential mixed-method framework for early-stage cost assessment of TES systems. Quantitative analysis of a harmonised project database identifies cost trends and residual deviations that guide targeted case selection. Qualitative reconstruction explains structural cost drivers, and the integrated interpretation classifies cost variability and uncertainty.

Cost harmonisation follows Lüchinger et al. (2025). Investment costs are converted to a common Swiss reference context using purchasing power parities (World Bank Group, 2025) and Swiss construction cost indices (BFS, 2025). Civil engineering indices are applied to BTES and PTES, and building construction indices to TTES, ensuring comparability across countries and time periods. The quantitative analysis characterises cost ranges and estimates technology-specific scaling relationships between storage capacity and investment costs. Residual deviations from these trends indicate structural cost drivers not captured by size effects and guide the selection of representative cases. The qualitative analysis reconstructs selected projects with pronounced deviations to examine technical design, system integration, procurement strategies, and contextual conditions. Quantitative and qualitative findings are then integrated to classify cost variability and uncertainty in early-stage planning of large-scale TES systems.

3. Preliminary Results

The harmonised database comprises 93 realised large-scale thermal energy storage projects with validated investment costs, including 41 additions beyond Lüchinger et al. (2025), which expand coverage particularly for TTES and BTES. For quantitative modelling, 79 projects provide consistent key parameters: 24 BTES, 10 PTES, and 45 TTES. Owing to structural differences, TTES are analysed separately as non-pressurised ($n = 29$) and pressurised ($n = 16$) systems. The sample spans a broad range of capacities, investment levels, and technical contexts. Across technologies, scaling relationships between system size and investment costs emerge. For BTES, costs scale with total borehole length, yielding an exponent slightly above proportionality and a 90% dispersion factor of about 2.8. PTES show consistent volume-based scaling with deviations between factors of 2 and 2.5. For TTES, separate volume-based models for non-pressurised and pressurised systems yield robust fits ($R^2 \approx 0.75$–0.79), while dispersion remains within a factor of 2 to 3. Size effects therefore explain a substantial share of variation but not the full cost spread. Figure 2 presents the scaling model for non-pressurised TTES. Despite the robust volume–cost relationship, systematic deviations from the fitted trend persist, indicating additional structural drivers. Based on residual analysis, five projects with distinct directions and magnitudes of deviation and high model leverage are selected for qualitative reconstruction. The same procedure is applied across technologies, revealing consistent deviation patterns that indicate additional technical and contextual cost drivers.

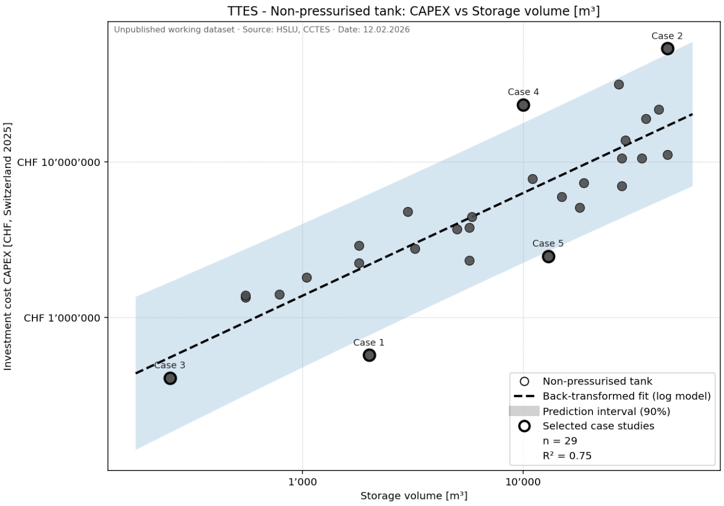

Figure 2: Logarithmic regression of storage volume and total investment costs (CAPEX, adjusted to Swiss 2025 price levels) for non-pressurised TTES. The dashed line shows the median trend and the shaded area the 90% prediction interval. Highlighted points denote selected case studies. Analyses for other TES types are not shown.

4. Outlook

The selected case studies are systematically reconstructed to identify the structural drivers underlying the observed cost deviations. A substantial share of the relevant project information is already available in prepared but not yet fully evaluated form and is now analysed in detail. The analysis focuses on technical design decisions, structural requirements, system integration, ground and site conditions, and procurement and implementation strategies. The objective is to isolate factors not explicitly represented in the quantitative scaling models but that materially contribute to cost variability. Cross-case comparison identifies recurring patterns and technology-specific characteristics. On this basis, a structured classification of cost uncertainty is developed that distinguishes between size-dependent, technological, and contextual drivers. This approach complements the quantitative scaling analysis and increases transparency regarding observed cost ranges in early-stage planning of large-scale thermal energy storage systems.

5. References

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6. Appendix

Table 1: List of Abbreviations

Definition	Abbreviation
Borehole thermal energy storage	BTES
Pit thermal energy storage	PTES
Tank thermal energy storage	TTES
Thermal energy storage	TES