Spatial Multi-Criteria Play-Based Analysis for HT-ATES Systems Across the Swiss Molasse Plateau

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ABSTRACT

High-Temperature Aquifer Thermal Energy Storage (HT-ATES) is a promising technology for decarbonizing heat supply by balancing seasonal energy mismatches. This study develops a spatial multi-criteria play-based analysis (SMCPBA) to assess HT-ATES favorability across the Swiss Molasse Plateau (SMP). The framework integrates surface energy system criteria—industrial excess heat (IEH), heat demand density (HDD), and thermal networks (TN)—with subsurface geological data including aquifer depth, thickness, thermal properties, and fault-based permeability indicators. Two geological targets, the Cenozoic sediments and Upper Mesozoic carbonates, are evaluated. Aggregated favorability maps reveal that urban centers such as Geneva, Lausanne, and Zurich present optimal conditions for HT-ATES deployment due to high surface demand and geotechnical suitability.

1. INTRODUCTION

Heating and cooling account for approximately 50% of energy use in Europe, with fossil fuels still supplying 75% of that demand (European Commission report, 2016). In Switzerland, where fossil-derived heating oil and gas accounted for 68% of the heat supply as recently as 2016 (Narula et al., 2018), the transition toward sustainable alternatives is a national priority under the 2030 climate targets (United Nation report, 2015).

District Heating Networks (DHNs) offer a compelling solution for the integration of renewable and waste heat sources. When coupled with seasonal heat storage technologies, particularly Underground Thermal Energy Storage (UTES), these networks can significantly improve system flexibility. Among UTES types, High-Temperature Aquifer Thermal Energy Storage (HT-ATES) is uniquely positioned to support large-scale seasonal heating needs, especially in industrial and urban contexts where waste heat is available (Fleuchaus et al., 2018). The operational principle of HT-ATES involves alternating periods of heat injection and extraction through a well doublet connected to a permeable aquifer, allowing for seasonal storage and recovery of thermal energy. A schematic overview of this loading and unloading cycle is illustrated in Figure 1.

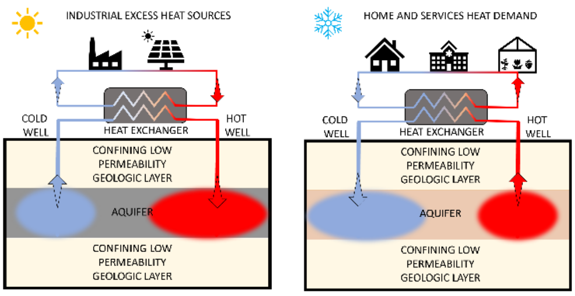

Figure 1: Schematic representation of ATES systems loading (left) and unloading (right) cycles.

However, HT-ATES deployment faces site-specific barriers related to subsurface geology, proximity to heat demand and sources, and legal or technical constraints (Kallesøe et al., 2019, Fleuchaus et al., 2020). A strategic, spatially explicit framework is needed to guide development efforts.

This study presents such a framework based on spatial multi-criteria play-based analysis (SMCPBA), applied to the Swiss Molasse Plateau—a region with rich geological data, high heat demand, and existing DHN infrastructure.

2. METHODOLOGY

2.1 Overview of the SMCPBA Framework

To evaluate the spatial favorability of HT-ATES systems across the Swiss Molasse Plateau (SMP), we developed a Spatial Multi-Criteria Play-Based Analysis (SMCPBA) framework. The approach integrates surface-based energy infrastructure and demand data with subsurface geological, thermal, and geomechanical information in a GIS environment using a 100x100 m grid resolution. A schematic of the assessment process is shown in Figure 2.

2.2 Surface Criteria and Proximity Analysis

Surface-level criteria include the spatial distribution of (i) Industrial Excess Heat (IEH), (ii) Heat Demand Density (HDD), and (iii) Thermal Network (TN) infrastructure. IEH maps were adapted from Zuberi et al, highlighting low-temperature (<150°C) waste heat sources from Swiss industry. HDD data was compiled from national building energy records and includes both residential and commercial sectors (Swiss Federal Office of Energy, 2022). TNs, which are necessary for practical integration of HT-ATES systems, were mapped using infrastructure datasets (BFE report, 2022).

Proximity-based Euclidean distance analysis was conducted to assess how well heat supply, demand, and network infrastructure align spatially. A Proximity-Adjusted Preference (PAP) scoring system (Boggia et al., 2018) was applied to each criterion, using distance-decay functions and expert-assigned weights to calculate a composite surface favorability index.

2.3 Subsurface Criteria and Play-Based Modeling

The subsurface component focuses on two key geologic units known for aquifer potential: the Cenozoic sediments and Upper Mesozoic carbonates. Geological surfaces, including the base and top contacts of these units, were extracted from the GEOMOL 3D geologic model (Guglielmetti and Moscariello, 2022) and seismic interpretations (Sommaruga et al., 2012). Depth and thickness maps were constructed for each target, and temperature was estimated by interpolating isotherms (25°C, 60°C, 90°C) from a regional thermal model constrained by 31 borehole temperature logs.

Fault structures were characterized based on their mechanical behavior under simulated stress fields (Valley and Miller, 2020), calculating slip tendency, dilation tendency, and Von Mises stress for each mapped fault segment. These three indicators were combined into a fault favorability index to assess the likelihood of secondary permeability. Petrophysical and thermal parameters (e.g., porosity, permeability, rock and fluid heat capacities) were sourced from well data and literature (Chevalier et al., 2010).

2.4 Subsurface-Constrained HT-ATES Capacity

The storage capacity of HT-ATES systems was calculated using established equations that model thermal energy storage within aquifers. Mass flow rate was determined under two scenarios:

- **Unconfined Case:** Based on reservoir porosity, density, and thermal capacity,
- **Stress-Constrained Case:** Limited by the allowable pressure given the local geostress field and aquifer permeability (Welsch et al., 2016).

Nominal charge capacity (P) was then calculated using fluid densities, heat capacities, and injection/production temperatures (Th = 90°C, Tc = 30°C), assuming a recovery efficiency derived from a modified Rayleigh number correlation (Barton et al., 1995). The final capacity was compared to local HDD to assess how much demand could theoretically be covered by a subsurface HT-ATES system.

2.5 Techno-Economic Model and LCOH

A Levelized Cost of Heat (LCOH) model was applied to estimate the cost-efficiency of deploying HT-ATES systems under varying subsurface conditions. The model includes capital expenditures (CapEx) such as well drilling (depth-dependent), surface facilities, and pumps, as well as operational expenditures (OpEx), energy costs, and system lifetime (20 years) assumptions based on HEATSTORE project guidance (Kallesøe et al., 2019).

Drilling costs were calculated using a quadratic depth-dependent formula calibrated for Swiss conditions. Pumping costs accounted for stress-limited pressure heads and efficiency losses. The LCOH was computed by discounting all life-cycle costs and dividing them by the total recoverable energy output over the system's operational lifetime.

2.6 Data Reliability Mapping

To address spatial uncertainty in geological interpretation and modeling, a data reliability index was developed. This index incorporated the density and quality of borehole and seismic data used in temperature and structural modeling. Seismic lines were classified into best, moderate, or poor categories based on lateral continuity and stratigraphic clarity (Sommaruga et al., 2012). Wells were categorized by their depth and number of isotherms they intersected (25°C, 60°C, 90°C). Areas with dense, high-quality data—such as Geneva, Lausanne, and Zurich—received higher reliability scores, while areas with sparse or low-quality data, particularly in the southeastern Plateau, were downgraded accordingly. This reliability index was used to modulate the final favorability maps to avoid overrating poorly characterized regions (Figure 3).

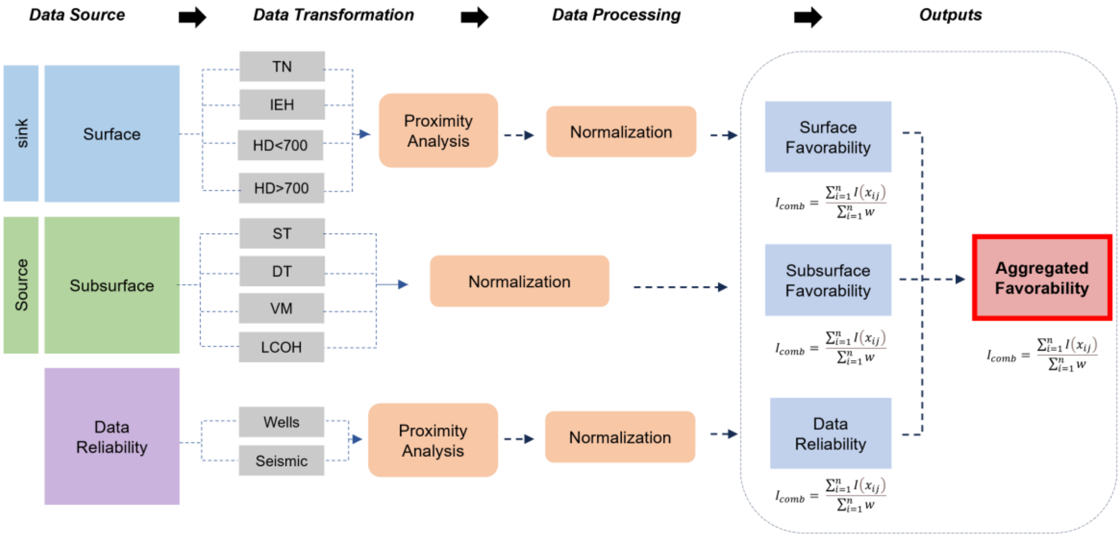

Figure 2: Overarching framework for the assessment of favorability in the SMP. TN: Thermal Network, IEH: Industrial Heat Excess, HD: Heat Demand, ST: Stress Tendency, DT: Dilation Tendency, VM: Von Mises Stress, LCOH: Levelized Cost of Heat

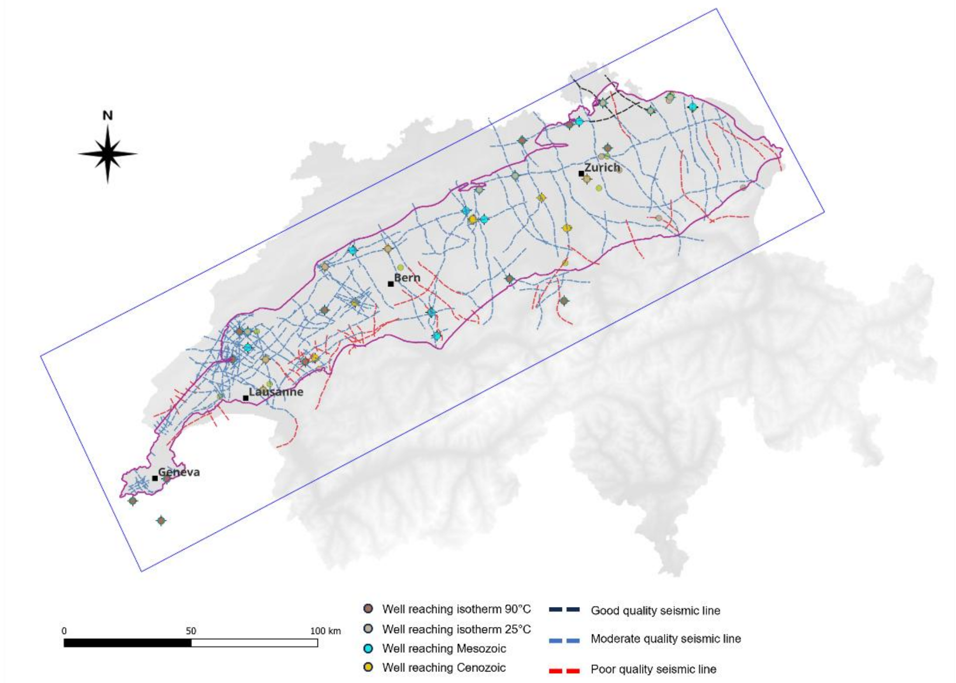

Figure 3: The datasets used for the 3D thermal and geologic models of the SMB include temperature data and 2D seismic data. Of the 29 wells analyzed, all reached the 25°C isotherm, 20 reached the 60°C isotherm, and 12 reached the 90°C isotherm. The 2D seismic data, acquired in Switzerland from the 1960s to the present, vary in quality. The best quality data, representing only 4 profiles (92 km or 2% of the total), exhibit good lateral continuity and clear stratigraphic reflections. The majority of the data, classified as moderate quality, include 190 profiles (3458 km or 80% of the total) with decent lateral continuity, though reflections are less clear. The poor quality data consist of 69 profiles (808 km or 18% of the total) with low to poor lateral continuity and difficult-to-recognize stratigraphic reflections.

3. RESULTS

3.1 Surface Criteria and Proximity Analysis

Proximity analysis showed that thermal networks (TNs) are the most spatially limiting factor due to their limited presence outside urban cores. Conversely, heat demand is broadly distributed and least restrictive. IEH shows intermediate coverage, favoring industrial clusters around major cities.

These results are visualized in Figure 4, where Geneva, Zurich, and Lausanne emerge as the most favorable urban areas with overlapping TNs, HDD, and IEH. These are key prerequisites for cost-effective HT-ATES deployment.

3.2 Subsurface Fault Analysis

Secondary permeability in fractured reservoirs is influenced by fault behavior under stress. By calculating slip tendency and dilation tendency based on regional stress simulations (Valley et al., 2020), and mapping Von Mises stress levels, we assessed the potential for enhanced transmissivity.

Strike-slip faults in the western and northeastern SMB exhibit the highest favorability due to their mechanical behavior. Thrust faults along the Alpine front are less favorable, partly due to insufficient data. Results are shown in Figure 5, where a composite fault favorability index highlights areas with structurally enhanced permeability.

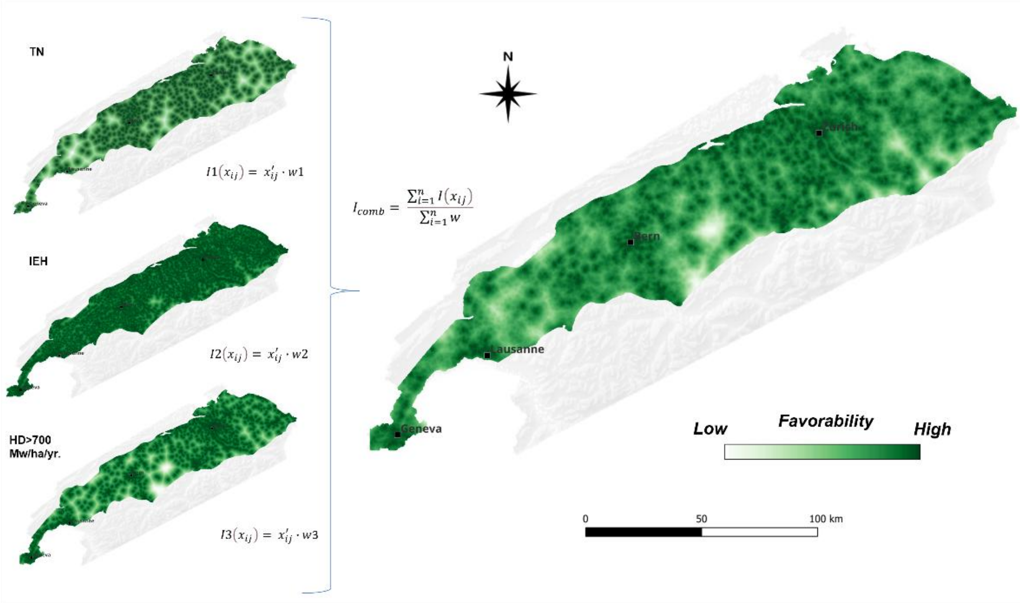

Figure 4: Favorability maps of the surface criteria

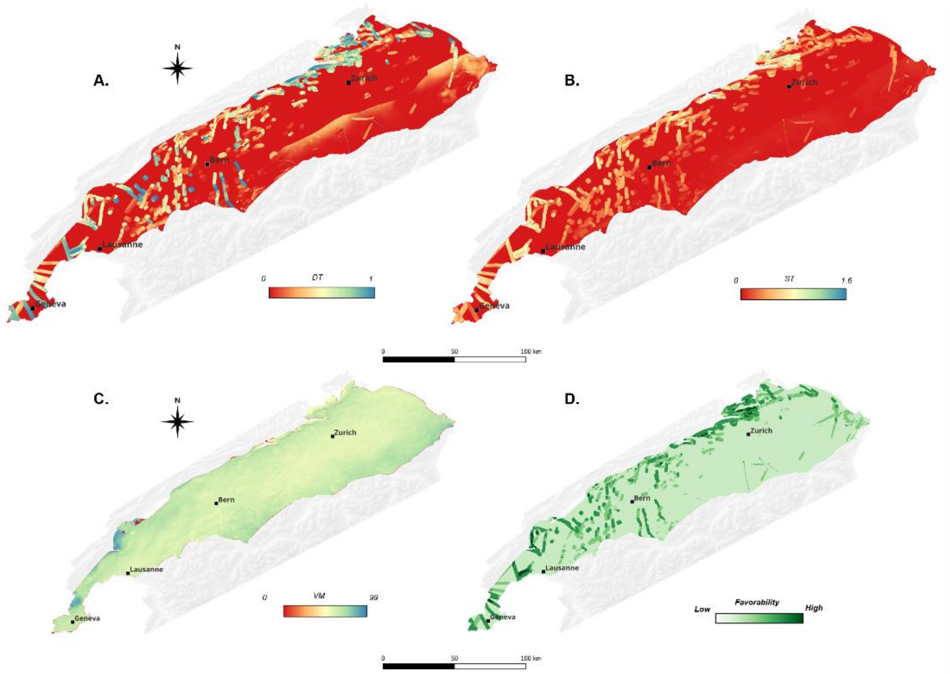

Figure 5: Fault analysis results. A. Dilation tendency rating. B. Slip tendency rating. C. Von Mises stress rating and D. Aggregated favourability for the three indicators.

3.3 Play-Based Subsurface Modeling

Geological modeling used seismic and well datasets to define the geometry of the Cenozoic and Mesozoic reservoirs. Petrophysical parameters were compiled from literature and borehole data (Chevalier e al., 2010, Guglielmetti et al., 2021). Isotherm depths (25°C, 60°C, 90°C) were interpolated using average geothermal gradients.

The Cenozoic sequence is thicker and more variable, while the Mesozoic carbonates are structurally more consistent and often fault-enhanced. These differences influence storage potential and thermal performance.

Cenozoic aquifers generally offer higher capacity due to greater thickness, while Mesozoic units, although thinner, can reach optimal temperatures for HT-ATES operation.

3.4 Levelized Cost of Heat (LCOH)

To assess the economic viability of HT-ATES systems, a Levelized Cost of Heat (LCOH) model was applied, calculating the average cost per megawatt-hour (CHF/MWh) of usable heat delivered over a 20-year system lifetime. The model includes capital costs (drilling, pumps, heat exchangers) and operational costs (pumping energy, maintenance, equipment replacement), with drilling costs estimated using a depth-dependent quadratic function adapted to Swiss sedimentary conditions (Kallesøe et al., 2019). Input assumptions include a waste heat supply cost of 35 CHF/MWh, electricity at 120 CHF/MWh, and a pump efficiency of 50%, following guidance from the HEATSTORE project (Kallesøe et al., 2019). Recoverable heat is constrained by aquifer properties and stress-limited pressure conditions, influencing system size and cost efficiency (Schout et al., 2014).

Spatial LCOH variation reflects geological depth, transmissivity, and heat storage potential. Lower LCOH values (<150 CHF/MWh) were found in the northern and central Swiss Molasse Basin, particularly around Zurich and Aarau, where aquifers are shallower and storage capacities are higher. Conversely, deeper or geologically complex areas—especially in the southern Plateau—tend to yield higher LCOH values.

These findings are illustrated in Figure 6, which shows LCOH distributions and modeled HT-ATES charge capacities for both the Cenozoic and Mesozoic reservoirs. The results highlight areas where technical suitability aligns with economic feasibility, supporting strategic decision-making for deployment.

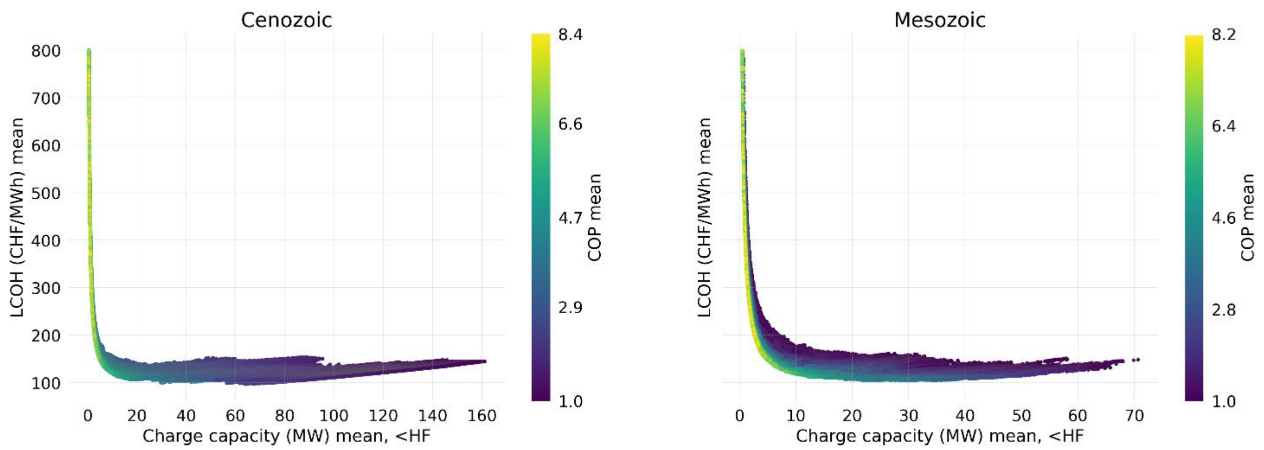

Figure 6: LCOH as a function of charge capacity for the Cenozoic and Mesozoic intervals. Data shown here are limited to LCOH values below 800 CHF/MWh. The data color describe the COP.

3.5 Subsurface Data Integration into the SMCPBA

In constructing the subsurface favorability component of the SMCPBA framework, we prioritized the absolute values of key geomechanical and techno-economic indicators rather than their spatial interrelations. Specifically, high values of Slip Tendency (ST), Dilation Tendency (DT), and Von Mises Stress (VM) were interpreted as proxies for enhanced fault reactivation potential and secondary permeability. These indicators were combined with the Levelized Cost of Heat (LCOH), where lower values indicate more economically viable conditions for HT-ATES deployment.

Each of these subsurface criteria was assigned a weight based on its relative contribution to overall favorability. These weights were derived using expert judgment and prior work on thermal storage suitability in similar sedimentary settings (Malczewski, 2006, Ferretti et al., 2011, Welsch et al., 2016, Kallesøe et al., 2019). The resulting composite scores were used to generate favorability maps for both the Cenozoic and Mesozoic reservoirs.

The resulting maps are presented in Figure 7, which show the spatial distribution of subsurface favorability for each reservoir. For the Cenozoic units (Figure 7B), the northern region of the Swiss Molasse Basin exhibits the highest favorability, shown in darker green tones. This zone combines favorable geomechanical characteristics—high ST, DT, and VM—with lower LCOH, indicating both technical and economic suitability for HT-ATES systems.

Similarly, the Mesozoic favorability map (Figure 7A) also highlights the northern SMB as the most favorable area. However, it is important to note that the data coverage and resolution for the Mesozoic reservoir are more limited than for the Cenozoic. Despite this, the available data still suggest that the northern portion of Results show that LCOH values <150 CHF/MWh are achievable in the central and northern Plateau, especially for the Cenozoic target (Figure 7). LCOH increases with depth due to drilling costs, but decreases the study area holds strong potential, with fault-enhanced zones likely contributing to better storage performance.

When comparing both maps, a clear spatial pattern emerges: the northern Swiss Molasse Basin consistently demonstrates higher subsurface favorability across both target reservoirs. This consistency reinforces the conclusion that this region should be prioritized for more detailed HT-ATES feasibility assessments and potential pilot deployment.

with higher capacity up to an optimal point, beyond which returns diminish.

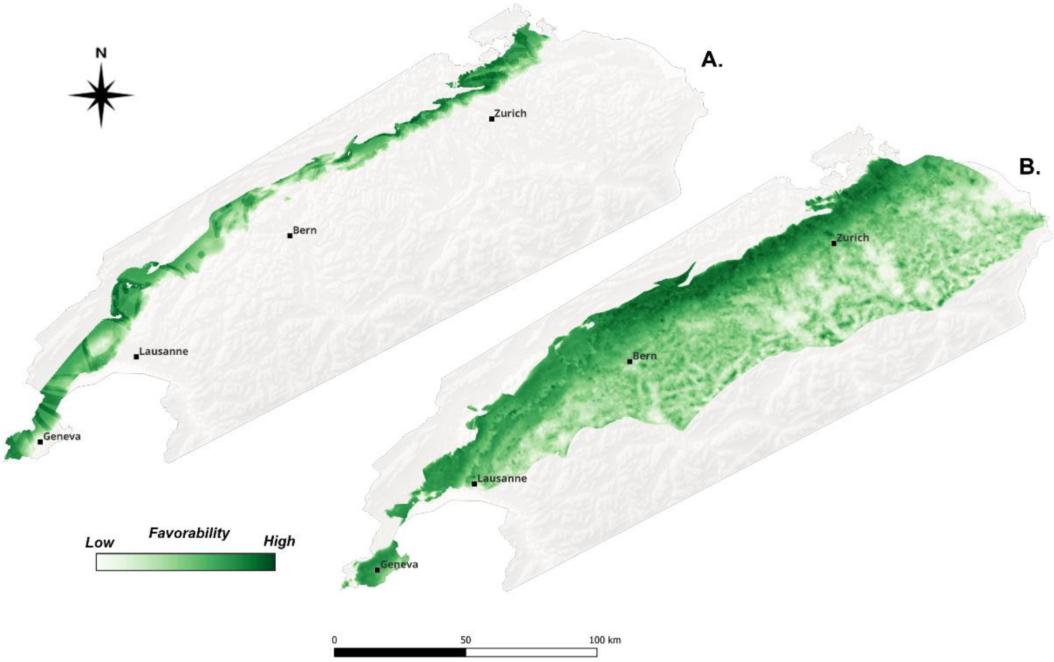

Figure 7: Subsurface favorability combining fault characterization and LCOH calculations. A : Mesozoic reservoir; B: Cenozoic reservoir.

3.6 Aggregated Favorability Mapping

The final stage of the SMCPBA involved synthesizing the individual surface and subsurface favorability layers into a single, spatially explicit aggregated favorability map. This integration step aimed to identify regions where the technical, infrastructural, and economic conditions align to support the development of HT-ATES systems.

To compute the aggregated favorability, each input layer—surface criteria (IEH, HDD, TN), subsurface geomechanical indicators (ST, DT, VM), and LCOH—was normalized and weighted according to its relative influence, as determined through the Analytical Hierarchy Process (AHP) and expert consultation. In addition, a spatial reliability index was applied to modulate scores based on the density and quality of underlying seismic and borehole data, ensuring that areas with high favorability but low data confidence were appropriately down-weighted.

The resulting aggregated maps for both the Mesozoic and Cenozoic reservoirs are presented in Figure 8. These maps reveal a clear pattern: the highest favorability zones are concentrated in and around the major urban centers of Zurich, Geneva, and Lausanne. These areas exhibit strong surface alignment (high demand, dense TN infrastructure, and waste heat availability), as well as structurally favorable subsurface conditions and relatively low LCOH values.

Notably, these zones also benefit from a high density of reliable geological and thermal data, which increases the confidence of the analysis.

In contrast, regions in the southern and southeastern portions of the SMB exhibit lower aggregated favorability. While some areas show good subsurface characteristics, they are often constrained by poor surface infrastructure or sparse data coverage, which introduces higher uncertainty into the assessment.

When comparing the two reservoir types, the Cenozoic system offers broader spatial favorability, largely due to its greater areal extent and generally thicker aquifers. However, the Mesozoic reservoir demonstrates more localized high-potential zones, often associated with fault-enhanced permeability and elevated temperatures. The overlap of high-scoring areas in both systems—particularly in the northern SMB—underscores the robustness of the integrated analysis and highlights these locations as top candidates for follow-up site-specific studies.

The aggregated favorability mapping not only identifies "hotspots" for HT-ATES development but also serves as a strategic planning tool. By incorporating techno-economic metrics and data confidence layers, this final output allows stakeholders to prioritize regions for further investigation and de-risk early-phase investments in energy storage infrastructure..

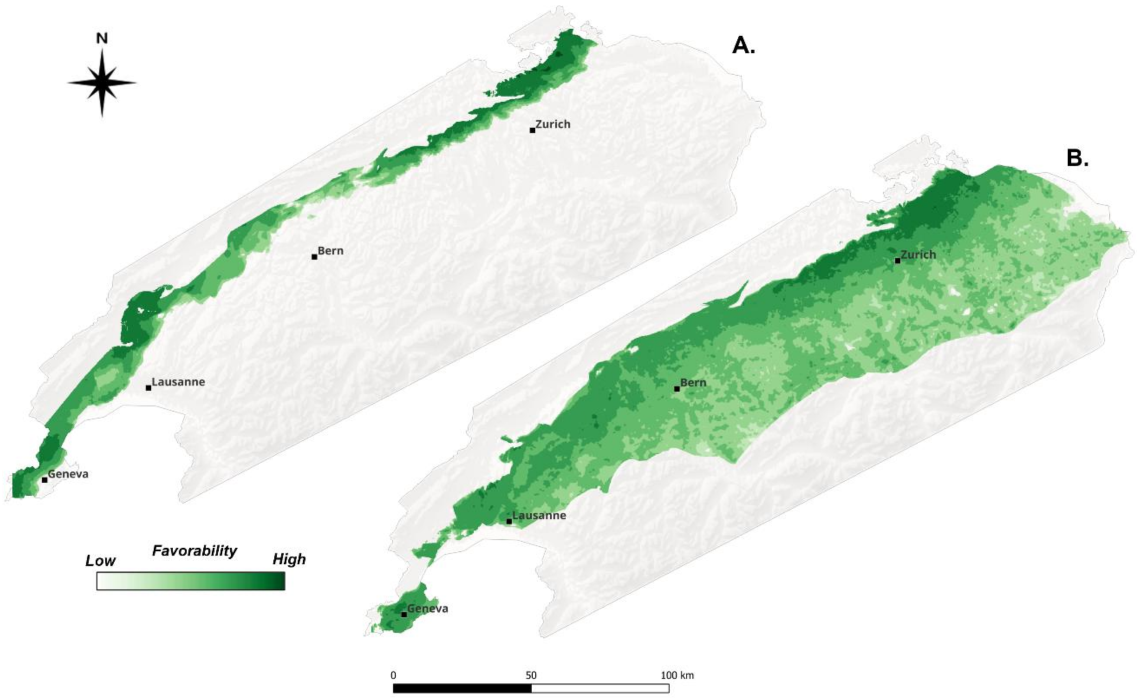

Figure 8: Aggregated favorability maps. A: Mesozoic reservoir ; B : Cenozoic reservoir

4. DISCUSSION

Critical considerations have be addressed and are discussed to ensure the robustness and applicability of the results:

Optimistic Estimations vs. Specific Location Analysis

The GIS-based analytical estimations provide an initial assessment, that cannot substitute location specific studies. For instance, the proximity analysis used a consistent 10-kilometer radius to assess thermal networks, heat demand, and industrial excess heat, which seems acceptable for initial screenings. However, specific geological and hydrological conditions at individual sites can significantly vary especially the Cenozoic reservoir which is known to be more heterogeneous than the Mesozoic reservoirs. This fact could alter the feasibility and performance of HT-ATES systems. Thus, while the results indicate high potential in areas like Geneva, Lausanne, and Zurich, detailed site-specific analyses are necessary to validate these findings and ensure realistic estimations.

Resolution Limitations and Data Gaps

The study is using a 100m x 100m raster gridding across the entire Swiss Molasse Plateau and assumes homogeneous subsurface properties within each grid point. This coarse resolution, while valuable for an initial screening, does not capture finer-scale variations particularly relevant for the subsurface heterogeneity that are essential for precise decision-making. The methodology is particularly useful for highlighting regions with high potential, guiding subsequent detailed studies to develop accurate development plans. Additionally, it helps identify areas deemed unfavorable, prompting further exploration to address data gaps and uncertainties. This can uncover new opportunities in regions initially overlooked due to insufficient data, enhancing the overall understanding of HT-ATES feasibility across the Plateau.

Methodological Scaling

The scalability of the methodology is a significant strength, allowing it to be adapted to various data resolutions and geographic extents. In regions with detailed subsurface data, the approach can be downscaled for finer-grained analysis, whereas an upscaled methodology might be necessary for areas with less comprehensive data to maintain analytical robustness. This flexibility ensures the methodology's applicability across different contexts and datasets, enhancing its utility and accuracy.

Further Investigation of Low-Hanging Fruits

The MCA has identified several high-potential areas for HT-ATES development, particularly in the northern Swiss Molasse Plateau. These areas, characterized by favorable conditions such as high heat demand, proximity to thermal networks, and industrial excess heat availability, represent "low-hanging fruits" for further investigation. Prioritizing these regions for detailed feasibility studies and pilot projects can provide valuable insights and expedite the practical implementation of HT-ATES systems, offering tangible examples of their viability.

5. CONCLUSION

This study introduces a robust and scalable spatial multi-criteria play-based analysis (SMCPBA) framework to assess the favorability of High-Temperature Aquifer Thermal Energy Storage (HT-ATES) systems, with a regional focus on the Swiss Molasse Plateau (SMP). By integrating surface energy system criteria—such as industrial excess heat, thermal demand, and network proximity—with detailed subsurface geological, thermal, and structural data, the methodology offers a comprehensive approach for identifying optimal zones for seasonal underground heat storage.

The results consistently highlight urban centers such as Geneva, Lausanne, and Zurich as the most favorable locations for HT-ATES deployment. These areas benefit from a confluence of surface-level readiness and subsurface suitability, including available infrastructure, high heat demand, and structurally favorable aquifer conditions. Additionally, regions with high-quality seismic and borehole data offer greater confidence in model predictions and project viability.

A key strength of this framework lies in its adaptability. It can be applied at various spatial resolutions and is transferable to other sedimentary basins with comparable data availability. Moreover, by including a data reliability index and incorporating economic metrics such as the Levelized Cost of Heat (LCOH), the framework balances technical potential with practical feasibility.

While this regional screening provides a strategic basis for planning and prioritization, it must be complemented by local-scale feasibility studies, including hydrogeological testing, environmental assessment, and stakeholder engagement. Nonetheless, this work lays the groundwork for accelerating HT-ATES adoption and supports the broader transition to resilient, low-carbon heating systems across Switzerland and other high-demand regions in Europe.

REFERENCES

Barton, C.A., Zoback, M.D., and Moos, D.: *Fluid flow along active faults*, *Geology*, 23(8), Boulder; (1995), 683–686.Author, A., Author, B., Author, C. and Author, D.: Example of a journal publication, *Journal*, xx, city, (year), 153-166.

Boggia, A., Cortines Garcia, F., and Cortés, J.: *Spatial multicriteria analysis for sustainability assessment*, *Land Use Policy*, 71, Amsterdam; (2018), 281–292.

Bundesamt für Energie (BFE): *Dokumentation Geodatenmodell Thermische Netze*, *BFE Report*, xx, Bern; (2022), 1–34.

Chevalier, G., Diamond, L.W., and Leu, W.: *Potential for deep CO_2 sequestration in Switzerland*, *Swiss Journal of Geosciences*, 103(3), Basel; (2010), 427–455.

European Commission: *An EU Strategy on Heating and Cooling*, *European Commission Report*, xx, Brussels; (2016), 1–30.

Ferretti, V.: *A Multicriteria Spatial Decision Support System for siting landfills in Italy*, *Journal of Multi-Criteria Decision Analysis*, 18(5–6), New York; (2011), 231–252.

Fleuchaus, P., Godschalk, B., and Blum, P.: *Risk analysis of HT-ATES*, *Renewable and Sustainable Energy Reviews*, 133, Amsterdam; (2020), 110–125.

Fleuchaus, P., Godschalk, B., Stober, I., and Blum, P.: *Worldwide application of aquifer thermal energy storage – A review*, *Renewable and Sustainable Energy Reviews*, 94, Amsterdam; (2018), 861–876.

Guglielmetti, L., and Moscariello, A.: *Hydrochemical characterization in Geneva Basin*, *Energies*, 15(10), Basel; (2022), 3497.

Guglielmetti, L., and Moscariello, A.: *Use of gravity data for geothermal exploration in Geneva Basin*, *Swiss Journal of Geosciences*, 114(1), Basel; (2021), 15.

Kallesøe, A.J., Sigurdsson, H., and Carreon, M.: *UTES – State-of-the-art, examples, lessons (HEATSTORE D1.1)*, *Geothermica Project Report*, xx, Brussels; (2019), 1–78.

Malczewski, J.: *GIS-based multicriteria decision analysis: a literature survey*, *International Journal of Geographical Information Science*, 20(7), London; (2006), 703–726.

Narula, K., Roulleaux Dugage, J., and Fishman, T.: *Strategies for decarbonizing the Swiss heating* *system*, *Energy*, 169, Amsterdam; (2019), 1119–1131.

Schout, G., Drijver, B., Gutierrez-Neri, M., and Hassanizadeh, S.M.: *Analysis of recovery efficiency in HT-ATES*, *Hydrogeology Journal*, 22(1), Berlin; (2014), 281–291.

Sommaruga, A., Eichenberger, U., and Marillier, F.: *Seismic Atlas of the Swiss Molasse Basin*, *Matériaux pour la Géologie de la Suisse*, 44, Bern; (2012), 1–128.

Swiss Federal Office of Energy: *Thermische Netze: Nachfrage Wohn- und Dienstleistungsgebäude*, *BFE Statistics Report*, xx, Bern; (2022), 1–50.

United Nations: *Paris Climate Agreement*, *International Legal Materials*, 55, New York; (2015), 740–755.

Valley, B., and Miller, S.A.: *Play-fairway analysis for deep geothermal resources in Switzerland*, *World Geothermal Congress Proceedings*, xx, Reykjavik; (2020), 1–9.

Welsch, B., Schilling, F., and Müller, C.: *Characteristics of medium deep borehole thermal energy storage*, *International Journal of Energy Research*, 40 (13), Chichester; (2016), 1855–1868.

Zuberi, M.J.S., Krogmann, U., and Brunner, P.H.: *Excess heat recovery in Swiss industry*, *Applied Energy*, 228, Amsterdam; (2018), 390–408.

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