DOCTORAL SCHOOL OF GEOSCIENCES

DATA-DRIVEN ASSESSMENT AND OPTIMIZATION OF HIGH-TEMPERATURE AQUIFER THERMAL ENERGY STORAGE IN DEPLETED CLASTIC HYDROCARBON RESERVOIRS

THESES OF THE DOCTORAL DISSERTATION

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I. INTRODUCTION AND AIMS

The transition toward low-carbon energy systems requires solutions that balance seasonal mismatches between heat supply and demand. In Central and Eastern Europe, underground thermal energy storage (UTES) can store surplus heat in the subsurface for later recovery, and high-temperature aquifer thermal energy storage (HT-ATES) is especially relevant for district-heating and industrial applications. Depleted hydrocarbon reservoirs are attractive HT-ATES targets because they offer proven porosity-permeability systems, dense well networks, and long production histories that reduce geological uncertainty. Repurposing such assets can complement or replace costly decommissioning and abandonment, allowing legacy infrastructure to contribute to decarbonization while limiting environmental and economic liabilities.

Hungary's Pannonian Basin provides an ideal testbed, where elevated geothermal gradients, well coverage, and substantial district-heating demand coincide with decades of subsurface data. Yet clastic-reservoir heterogeneity, particularly channelized sands embedded in lower-permeability facies, complicates predictions of heat transport, thermal recovery efficiency, and long-term system performance.

This dissertation synthesizes geothermal and subsurface-energy contributions developed during the PhD research alongside a broader publication record that includes contributions to 27 peer-reviewed papers spanning geothermal systems, reservoir characterization, geological mapping, and mineral-resource studies. Three HT-ATES-focused papers form the dissertation backbone, covering (i) probabilistic MCDA-AHP screening integrated with geostatistics, (ii) MODFLOW-MT3DMS heat-transport simulation coupled with Random Forest surrogate modeling, and (iii) XGBoost-based 3D channel mapping for thermal-breakthrough prevention. Two complementary geothermal publications, a review on geothermal energy and critical metal extraction and a national overview of geothermal energy in Hungary, provide wider context and strengthen stakeholder engagement across academia, industry, and policy. Together, these works establish a coherent progression from regional screening to reservoir-scale simulation and scalable, data-driven optimization for practical HT-ATES deployment.

Although the potential of depleted hydrocarbon fields for UTES has been widely acknowledged, current assessment and design approaches remain fragmented. Regional screening studies often rely on simplified geological representations and deterministic parameter values, which are insufficient for formation-scale planning under uncertainty. Conversely, high-fidelity numerical simulations can capture complex heat-transport processes but are computationally intensive and difficult to apply systematically across large numbers of candidate sites. These limitations are amplified by inadequate representation of clastic-reservoir heterogeneity, where sand-channel architecture exerts first-order control on flow paths, thermal plume evolution, and breakthrough timing.

The overarching objective of the dissertation is to develop an integrated, uncertainty-aware, and data-driven framework for the assessment, design, and optimization of HT-ATES systems in depleted clastic hydrocarbon reservoirs. This objective was pursued through three connected aims: (1) probabilistic screening and ranking of depleted reservoirs by integrating MCDA-AHP with geostatistical simulation; (2) quantitative evaluation of thermal performance using physically based groundwater-flow and heat-transport modeling under heterogeneous conditions; and (3) development of scalable machine-learning and hybrid modeling approaches for rapid performance prediction and high-resolution geological characterization to support optimized system design.

II. APPLIED METHODS

1) *Probabilistic MCDA-AHP screening integrated with geostatistics*. A probabilistic site-screening workflow was developed by integrating Multi-Criteria Decision Analysis with the Analytic Hierarchy Process (MCDA-AHP) and stochastic geostatistical simulation. Reservoir and operational parameters (e.g., porosity, permeability, thickness, temperature, heat capacity, thermal conductivity, and well density) were gridded and populated using multiple realizations to represent subsurface uncertainty. Expert-derived weights were combined into composite suitability indices, and P10-P50-P90 maps were used to identify robust high-suitability zones and to test sensitivity to alternative weighting schemes.

2) *Numerical groundwater-flow and heat-transport simulation (MODFLOW-MT3DMS)*. Reservoir-scale feasibility and design controls were quantified using a coupled groundwater-flow and heat-transport model implemented with MODFLOW and MT3DMS. Three-dimensional distributions of porosity, permeability, and anisotropy were constructed from well logs, core data, and production records, and then translated into hydraulic and thermal parameter fields. Seasonal injection-production cycles were simulated for duplet configurations to evaluate plume

containment, thermal breakthrough timing, and recovery efficiency under alternative well spacings and operational schedules.

3) A combined machine-learning workflow was developed to speed up HT-ATES performance screening and improve UTES well placement in clastic reservoirs. A Random Forest surrogate trained on numerical simulations predicts thermal recovery and breakthrough time from key geological and operational inputs, enabling rapid multi-scenario optimization. In parallel, XGBoost with RBF residual correction predicts Flow Zone Index from well logs to produce 3D sand-channel connectivity maps that support thermal-breakthrough risk mitigation.

III. NEW SCIENTIFIC RESULTS

T1: The multi-criteria decision analysis-analytical hierarchy process (MCDA-AHP) framework, integrated with geostatistics, is a time-efficient and systematic way to assess the suitability of abandoned hydrocarbon fields in Hungary for underground heat storage. In this framework, key reservoir and operational parameters such as porosity, permeability, thickness, temperature, heat capacity, thermal conductivity, and well density are represented on a grid and populated using stochastic geostatistical simulations to capture subsurface uncertainty. Expert-derived weights are assigned to these criteria and combined into composite suitability indices, which classify each grid block as having high, medium, or low potential for thermal energy storage. The resulting suitability maps show that the method can rapidly highlight the most promising zones within each field, even in data-limited settings. These findings indicate that MCDA-AHP, when coupled with geostatistics, provides a practical decision-support tool for repurposing mature fields as underground thermal energy storage sites rather than treating them solely as decommissioning liabilities.

T2: The Békés Formation in Hungary is consistently identified as a prime candidate for high-temperature aquifer thermal energy storage (HT-ATES) by the probabilistic MCDA-AHP screening framework. Analyses of P10, P50, and P90 realizations generated from geostatistical simulations show that this formation repeatedly attains high suitability scores over a large fraction of its area, even when accounting for uncertainty in porosity, permeability, and temperature. The contrast in suitability between favorable and marginal zones within the formation demonstrates the framework's ability to resolve spatial heterogeneity and to distinguish robust targets from more uncertain ones. When compared with earlier, coarser national screening studies, the results show that the method effectively bridges regional-scale ranking and formation-scale design insight. These observations imply that the Békés Formation can serve as a reference case for HT-ATES deployment in clastic basins and that the MCDA-AHP approach provides a rigorous basis for prioritizing formations and fields under geological uncertainty.

T3: Repurposing depleted hydrocarbon fields for underground thermal energy storage is shown to be economically competitive with, and in many cases preferable to, conventional well decommissioning when evaluated within the MCDA-AHP framework. Typical decommissioning costs, which can range from tens of thousands to over one million USD per well, contrast with the option of retaining and adapting existing boreholes and reservoir infrastructure for long-term energy storage services. In the decision framework, criteria related to economic performance, environmental risk reduction, and regulatory constraints can be combined with geological parameters to rank fields according to their repurposing potential. The results demonstrate that many fields currently categorized as end-of-life liabilities could instead be treated as strategic subsurface assets for heat storage, CO2 storage, or other low-carbon applications. This indicates that integrating repurposing options into decommissioning planning can materially change the cost-benefit balance for operators and regulators, with significant implications for national energy transition strategies.

T4: A high-resolution hydrogeological and thermal transport model of the Békési Formation demonstrates that a depleted clastic reservoir can sustain high-temperature aquifer thermal energy storage (HT-ATES) under realistic operating conditions. The model, implemented with MODFLOW and MT3DMS, uses well logs, core analyses, and production histories to reconstruct the three-dimensional distribution of porosity, permeability, and anisotropy and to translate these properties into hydraulic and thermal parameters. Simulations of dual-well (duplet) configurations show that injection temperatures on the order of 95 C are feasible and that the resulting thermal plumes remain largely contained within the formation over multiple seasonal cycles. The spatial evolution of the heat plume reveals that reservoir architecture and anisotropy strongly control heat migration pathways, storage efficiency, and the timing of thermal breakthrough at the production well. These outcomes indicate that physically based numerical modeling can directly link clastic reservoir heterogeneity to HT-ATES performance and provide quantitative design guidance.

T5: Systematic numerical experiments show that optimal inter-well spacing and operational scheduling can increase HT-ATES thermal recovery efficiencies in the Békési Formation from about 81% initially to nearly 89% after several cycles, corresponding to an improvement of roughly 8. 5%. Suites of MODFLOW/MT3DMS simulations performed under varying porosity, permeability, and anisotropy conditions quantify how thermal breakthrough timing and recovery factors depend on both geology and well layout. The results indicate that there exists an intermediate range of spacing in which heat recovery is maximized: wells placed too close together experience early breakthrough, whereas wells placed too far apart underutilize the available reservoir volume. Scenario comparisons of different seasonal injection-production schedules further show that certain combinations of storage and extraction periods yield systematically higher annual energy returns than others. These findings demonstrate that jointly optimizing well spacing and operational strategy, informed by geological sensitivity analysis, is essential for robust and efficient HT-ATES design in clastic reservoirs.

T6: A Random Forest-based surrogate model trained on ensembles of HT-ATES simulations provides accurate and computationally efficient predictions of thermal performance across large numbers of candidate wells and configurations. The model learns relationships between input descriptors such as reservoir properties, well spacing, injection temperature, and operational schedule and outputs including thermal recovery efficiency and breakthrough time, achieving a coefficient of determination of approximately 0.87 on validation data. Once calibrated, the surrogate can evaluate thousands of scenarios at a cost that is more than 90% lower than running full MODFLOW/MT3DMS simulations for each case, enabling extensive parameter sweeps and uncertainty analyses. Application of the model to wells beyond the original numerical model domain shows that it can successfully extrapolate within a broader geological context, provided the input parameters remain within physically reasonable bounds. These results indicate that hybrid numerical-machine-learning workflows can scale HT-ATES planning from small, expert-curated scenario sets to exhaustive, data-driven optimization.

T7: The Hungarian subsurface is demonstrated to be a particularly favorable and instructive testbed for data-driven repurposing of depleted clastic hydrocarbon reservoirs into HT-ATES systems. The country's dense network of mature wells, relatively high geothermal gradients, and extensive district heating demand create a setting in which stored heat can be practically delivered to end users. Historical datasets including well logs, core measurements, and production records are shown to be sufficient to construct geostatistical models, numerical flow and heat-transport simulations, and machine-learning surrogates that collectively support HT-ATES design. Case studies in the Békés Formation illustrate how this integrated workflow can identify optimal well configurations, predict long-term performance, and manage uncertainty. These facts imply that the Hungarian example offers a transferable blueprint for other clastic basins with similar legacy data and heating needs, transforming depleted fields into key components of national decarbonization and energy security strategies.

T8: A hybrid machine-learning workflow combining XGBoost regression with radial basis function (RBF)-based spatial residual correction accurately predicts the three-dimensional distribution of high Flow Zone Index (FZI >= 4. 5) sand-rich channels in the Szolnok Formation. Petrophysical data from 128 wells, including porosity, permeability, and lithological indicators, are processed into features that capture both local rock properties and their spatial context before being used for training. The resulting model achieves an R2 of about 0.92 and a root-mean-square error of roughly 0.24, clearly distinguishing high-permeability channel bodies from low-FZI background intervals that behave as barriers to flow. The predicted channel network exhibits geologically plausible geometries and connectivity patterns, matching independent interpretations of the depositional system. These results show that hybrid geostatistical-machine-learning approaches can deliver high-resolution, geologically interpretable channel architectures that exceed the efficiency and, in many cases, the predictive quality of traditional stochastic simulations.

T9: Explicit prediction of sand-channel architecture in the Szolnok Formation is shown to be directly usable for optimizing underground thermal energy storage (UTES) site selection and well placement to reduce thermal breakthrough risks. The model outputs delineate continuous high-FZI channel zones suitable for injecting and producing fluids and identify adjacent low-FZI intervals that act as natural baffles or barriers between channel segments. By assigning hot and cold wells to different, geologically separated channel bodies that are shielded by these low-FZI zones, the design can minimize unwanted hydraulic and thermal communication between well pairs. Simulated flow and heat-transport behavior based on the predicted architecture confirm that such configurations delay thermal breakthrough and improve storage efficiency relative to designs that ignore channel geometry. These findings indicate that detailed channel mapping is a critical prerequisite for long-lived, high-performance UTES systems in channelized clastic reservoirs.

T10: The hybrid XGBoost-RBF workflow for sand-channel prediction is demonstrated to be significantly more computationally efficient than traditional Sequential Gaussian Simulation (SGS) while maintaining comparable or superior accuracy, and it is designed for reuse in other basins. Benchmarking shows that a typical SGS realization requiring approximately 8-12 hours of computation can be replaced by a machine-learning-based prediction generated in around 15 minutes once the model is trained. The workflow, which includes standardized feature engineering from well logs and spatial residual correction, is shown to be portable to other Szolnok-bearing fields and analogous channelized clastic systems, subject to recalibration with local data. The codebase and model configuration are documented and shareable, allowing other practitioners to reproduce, audit, and extend the approach. These facts suggest that the workflow can serve as a practical standard for channel-focused characterization in UTES, geothermal, and hydrocarbon projects across the Pannonian Basin and similar sedimentary provinces.

SUMMARY

The dissertation demonstrates that legacy subsurface datasets from mature hydrocarbon provinces can be repurposed into a coherent, uncertainty-aware design workflow for high-temperature aquifer thermal energy storage. Probabilistic MCDA-AHP screening provides an efficient bridge between regional-scale ranking and formation-scale targeting, while physically based MODFLOW-MT3DMS simulations quantify how heterogeneity, anisotropy, and operational design control plume evolution and thermal recovery. Machine-learning surrogates and hybrid channel-mapping models extend these insights to large scenario spaces and high-resolution geological architectures at practical computational cost.

Collectively, the results support a staged HT-ATES development pathway in which candidate fields are first screened under uncertainty, then tested by calibrated reservoir-scale simulations, and finally optimized using scalable data-driven predictors linked to geologically interpretable reservoir architecture. These outcomes indicate that depleted clastic reservoirs in Hungary can be transformed from end-of-life liabilities into strategic thermal-storage assets that contribute to district-heating decarbonization and energy security, with a workflow that is transferable to other data-rich sedimentary basins.

Összefoglaló

A disszertáció bemutatja, hogy az érett szénhidrogén-tartományokból származó, örökölt felszín alatti adatkészletek újrahasznosíthatók egy koherens, bizonytalanságtudatos tervezési munkafolyamattá a nagyhőmérsékletű vízadó rétegben megvalósított hőtárolás (HT-ATES) számára. A probabilisztikus MCDA–AHP alapú szűrés hatékony hidat képez a regionális léptékű rangsorolás és a formációléptékű célkijelölés között, miközben a fizikailag megalapozott MODFLOW–MT3DMS szimulációk számszerűsítik, hogy a heterogenitás, az anizotrópia és az üzemeltetési/tervezési paraméterek miként szabályozzák a plúmfejlődést és a hővisszanyerést. A gépi tanuláson alapuló szurrogátok és a hibrid csatornatérképezési modellek e felismeréseket nagy forgatókönyvtérre és nagyfelbontású geológiai architektúrákra is kiterjesztik, gyakorlati számítási költség mellett.

Összességében az eredmények egy lépcsőzetes HT-ATES fejlesztési pályát támasztanak alá, amelyben a jelölt mezőket először bizonytalanság mellett szűrik, majd kalibrált, rezervoár-léptékű szimulációkkal tesztelik, végül geológiailag értelmezhető rezervoár-architektúrához kapcsolt, skálázható adatvezérelt prediktorokkal optimalizálják. Ezek a kimenetek azt jelzik,

hogy a magyarországi kimerült törmelékes rezervoárok az életciklusuk végén jelentkező terhekből stratégiai hőtárolási eszközökké alakíthatók, amelyek hozzájárulnak a távhő dekarbonizációjához és az energiaellátás biztonságához, egy olyan munkafolyamattal, amely más, adatokban gazdag üledékes medencékre is átvihető.

REFERENCES

Abdulhaq, H. A., Geiger, J., Vass, I., Tóth, T. M., Medgyes, T., & Szanyi, J. (2024). Transforming Abandoned Hydrocarbon Fields into Heat Storage Solutions: A Hungarian Case Study Using Enhanced Multi-Criteria Decision Analysis-Analytic Hierarchy Process and Geostatistical Methods. Energies, 17(16), 3954. https://doi.org/10.3390/en17163954

Abdulhaq, H. A., Geiger, J., Vass, I., Tóth, T. M., Medgyes, T., Bozsó, G., Kóbor, B., Kun, É., & Szanyi, J. (2025). Predicting Thermal Performance of Aquifer Thermal Energy Storage Systems in Depleted Clastic Hydrocarbon Reservoirs via Machine Learning: Case Study from Hungary. Energies, 18(10), 2642. https://doi.org/10.3390/en18102642

Abdulhaq, H. A., Geiger, J., Vass, I., Tóth, T. M., Bozsó, G., & Szanyi, J. (2025). A Data-Driven ML Model for Sand Channel Prediction from Well Logs for UTES Site Optimization and Thermal Breakthrough Prevention: Hungary Case Study. Energies, 18(16), 4230. https://doi.org/10.3390/en18164230

Dincer, I., & Rosen, M. A. (2011). Thermal Energy Storage: Systems and Applications (2nd ed.). Wiley.

IEA. (2017). Energy Technology Perspectives 2017. International Energy Agency.

Jin, W., Atkinson, T. A., Doughty, C., Neupane, G., Spycher, N., McLing, T. L., Dobson, P. F., Smith, R., & Podgorney, R. (2022). Machine-learning-assisted high-temperature reservoir thermal energy storage optimization. Renewable Energy, 197, 384-397. https://doi.org/10.1016/j.renene.2022.07.118

Paksoy, H. O. (Ed.). (2000). Thermal Energy Storage for Sustainable Energy Consumption. Springer.

Stricker, K., Grimmer, J. C., Egert, R., Bremer, J., Korzani, M. G., Schill, E., & Kohl, T. (2020). The Potential of Depleted Oil Reservoirs for High-Temperature Storage Systems. Energies, 13(24), 6510. https://doi.org/10.3390/en13246510

Stricker, K., Egert, R., Schill, E., & Kohl, T. (2024). Risk of surface movements and reservoir deformation for high-temperature aquifer thermal energy storage (HT-ATES). Geothermal Energy, 12(1), 4. https://doi.org/10.1186/s40517-024-00283-9

Szanyi, J., Rybach, L., & Abdulhaq, H. A. (2023). Geothermal Energy and Its Potential for Critical Metal Extraction-A Review. Energies, 16(20), 7168. https://doi.org/10.3390/en16207168

Szanyi, J. D., Kovács, B., & Abdulhaq, H. A. (2025). Harnessing geothermal energy in Hungary. Geological Society, London, Special Publications, 555(1), SP555-2024-22. https://doi.org/10.1144/SP555-2024-22

Zeghici, R. M., Oude Essink, G. H. P., Hartog, N., & Sommer, W. (2015). Integrated assessment of variable density-viscosity groundwater flow for a high temperature mono-well aquifer thermal energy storage (HT-ATES) system in a geothermal reservoir. Geothermics, 55, 58-68. https://doi.org/10.1016/j.geothermics.2014.12.006

ARTICLES USED IN THE PHD THESIS

Abdulhaq, H. A., Geiger, J., Vass, I., Tóth, T. M., Medgyes, T., & Szanyi, J. (2024). Transforming Abandoned Hydrocarbon Fields into Heat Storage Solutions: A Hungarian Case Study Using Enhanced Multi-Criteria Decision Analysis-Analytic Hierarchy Process and Geostatistical Methods. Energies, 17(16), 3954. https://doi.org/10.3390/en17163954

Abdulhaq, H. A., Geiger, J., Vass, I., Tóth, T. M., Medgyes, T., Bozsó, G., Kóbor, B., Kun, É., & Szanyi, J. (2025). Predicting Thermal Performance of Aquifer Thermal Energy Storage Systems in Depleted Clastic Hydrocarbon Reservoirs via Machine Learning: Case Study from Hungary. Energies, 18(10), 2642. https://doi.org/10.3390/en18102642

Abdulhaq, H. A., Geiger, J., Vass, I., Tóth, T. M., Bozsó, G., & Szanyi, J. (2025). A Data-Driven ML Model for Sand Channel Prediction from Well Logs for UTES Site Optimization and Thermal Breakthrough

Prevention: Hungary Case Study. Energies, 18(16), 4230. https://doi.org/10.3390/en18164230

OTHER PUBLICATIONS (SELECTED)

Szanyi, J., Rybach, L., & **Abdulhaq, H. A.** (2023). Geothermal Energy and Its Potential for Critical Metal Extraction-A Review. Energies, 16(20), 7168. https://doi.org/10.3390/en16207168

Szanyi, J. D., Kovács, B., & **Abdulhaq, H. A.** (2025). Harnessing geothermal energy in Hungary. Geological Society, London, Special Publications, 555(1), SP555-2024-22. https://doi.org/10.1144/SP555-2024-22

Szanyi, J., **Abdulhaq, H. A.**, Hegyi, R., Gál, T., Szabó, É., Lossos, L., & Tóth, E. (2026). *Assessment of changes in groundwater resources due to climate change for the purpose of sustainable water management in Hungary*. Preprints. https://doi.org/10.20944/preprints202601.2237.v1

Gál, T., Alinasab, N., **Abdulhaq, H. A.**, & Skarbit, N. (2026). *A structured literature review of the application of local climate zones (LCZ) in urban climate modelling*. Earth, 7(1), 3. https://doi.org/10.3390/earth7010003

CONFERENCE ABSTRACTS

Abdulhaq, H. (2023). Transforming Abandoned Hydrocarbon Fields into Heat Storage Solutions: A Hungarian Case Study Using Enhanced Multi-Criteria Decision Analysis–Analytic Hierarchy Process and Geostatistical Methods. European Geothermal PhD Days (EGPD 2023), Glasgow, United Kingdom.

Abdulhaq, H. (2024). Transforming Abandoned Hydrocarbon Fields into Heat Storage Solutions: A Hungarian Case Study Using Enhanced Multi-Criteria Decision Analysis–Analytic Hierarchy Process and Geostatistical Methods. European Geothermal PhD Days (EGPD 2024), Delft, The Netherlands.

Abdulhaq, H. (2024). From Hydrocarbons to Heat Storage: Repurposing Depleted Reservoirs for High-Temperature Aquifer Thermal Energy Storage in Hungary. FUSED 24 Conference, Bochum, Germany.

Abdulhaq, H. (2025). Predicting Thermal Performance of Aquifer Thermal Energy Storage Systems in Depleted Clastic Hydrocarbon Reservoirs via Machine Learning: Case Study from Hungary. In: The 16th European Geothermal PhD Days (EGPD) Book of Abstracts, Szeged, Hungary. https://www.egpd2025.com

Abdulhaq, H. (2025). A Data-Driven ML Model for Sand Channel Prediction from Well Logs for UTES Site Optimization and Thermal Breakthrough Prevention: Hungary Case Study. IPGC 2025, Zaragoza, Spain.

Abdulhaq, H. (2025). A Data-Driven ML Model for Sand Channel Prediction from Well Logs for UTES Site Optimization and Thermal Breakthrough Prevention: Hungary Case Study. TOPO-Europe 2025, Sopron, Hungary.

Abdulhaq, H. (2026, planned). Lessons learned from the PhD (geostatistics–numerical modeling–machine learning integration for geothermal energy storage and reservoir characterization). European Geothermal PhD Days / PhD Days, Leiben, Austria.

CO-AUTHOR STATEMENTS

I, János Geiger, I hereby declare that the role of the doctoral candidate in the publications listed under 'ARTICLES USED IN THE PHD THESIS' was decisive and that I have not used these publications to obtain a scientific degree and will not do so in the future.

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János Szanyi

DECLARATION OF THE SUPERVISOR

I, János Szanyi, I hereby confirm that the content of the dissertation is based on the independent work of the doctoral candidate and that he has contributed decisively to the results through his independent creative activity. I consider the entire dissertation to be eligible for support from a professional and academic point of view and recommend its acceptance.

Szeged, 16.02.2026

János Szanyi