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AQUIFER THERMAL ENERGY STORAGE SYSTEMS FOR NEARLY ZERO ENERGY BUILDINGS: A CASE STUDY ASSESSMENT FOR ROMANIAN CLIMATE CONDITIONS

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Abstract

The European Union's Energy Performance of Buildings Directive (EPBD), as amended by Directive (EU) 2024/1275, mandates the transition from nearly Zero Energy Buildings (nZEB), with very high energy performance and substantial renewable energy coverage, to Zero Emission Buildings, with an annual zero emissions balance. Aquifer Thermal Energy Storage (ATES) offers an environmental-friendly and cost-effective technology for supporting nZEB through seasonal thermal energy storage in groundwater aquifers. This paper assesses ATES feasibility for an office building in Bucharest, Romania (climatic zone 2), using dynamic simulations for both existing and nZEB-renovated configurations. The analysis reveals significant deployment barriers including shallow unconfined aquifers (7-10 m), regulatory constraints on groundwater reinjection, and pronounced heating-cooling demand imbalances characteristic of Romania's continental climate. The proposed system integrates ATES with solar thermal technology to mitigate demand asymmetry and enhance efficiency. Results indicate that successful ATES implementation in Romania requires updated legislation, site-specific hydrogeological assessment, and hybrid renewable configurations enabling balanced seasonal thermal storage.

Key words*: aquifer thermal energy storage (ATES), building energy efficiency, ground source heat pump, nearly zero energy buildings (nZEB), seasonal thermal storage.*

INTRODUCTION

The European building sector accounts for approximately 40% of total energy consumption and 36% of greenhouse gas emissions, making it a primary target for decarbonization efforts (Fleuchaus et al., 2018). The Energy Performance of Buildings Directive (EPBD), recently amended by Directive (EU) 2024/1275, establishes stringent requirements for nearly Zero Energy Buildings (nZEB), mandating that all new buildings comply with zero-emission standard by 2030, with public buildings required by 2028. The directive defines nZEB as buildings with very high energy performance where the nearly zero or very low amount of energy required should be covered to a very significant extent by renewable energy sources produced on-site or nearby. Because the directive sets no numeric thresholds for this definition, nZEB requirements and limit values are interpreted differently across Member States (Magrini et al., 2020).

Aquifer Thermal Energy Storage (ATES) represents a mature technology capable of meeting nZEB renewable energy requirements through seasonal thermal storage in groundwater aquifers. International experience demonstrates that ATES systems achieve thermal recovery efficiencies of 68-87% and reduce building energy consumption by 40-70% while cutting CO_2 emissions by up to 74% compared to conventional systems (Fleuchaus et al., 2018; Stemmle et al., 2021). Of the more than 2,800 systems operating worldwide, 85% are located in the Netherlands, with a further 10% in Sweden, Denmark, and Belgium, demonstrating technical maturity and economic viability with payback periods of 2-10 years (Fleuchaus et al., 2018).

Despite proven international success, ATES deployment in Central and Eastern Europe remains limited due to multiple barriers including regulatory constraints, limited hydrogeological data, and heating-cooling demand imbalances characteristic of continental

climates. Despite favourable geological conditions in western regions and substantial geothermal resources documented by Rosca and Antics (2004), Romania has not succeeded yet to fully exploit its ATES potential. The primary obstacles include obsolete groundwater legislation prohibiting thermal reinjection, insufficient aquifer characterization data, and limited institutional capacity in ATES-specific well construction requiring targeted technology transfer.

The continental climate of Romania presents unique challenges for ATES implementation. In Bucharest (climatic zone 2), annual heating demand typically exceeds cooling demand by a large margin (Tache et al. 2024; Petrişor et al., 2025), creating thermal imbalance that reduces ATES efficiency. This asymmetry contrasts with office buildings in temperate maritime climates where heating-cooling loads are more balanced. Recent work demonstrates that integrating high-temperature solar thermal collectors with underground seasonal heat storage can mitigate this thermal imbalance by injecting surplus summer heat into the subsurface, thus partially compensating for the heating-dominant load profile characteristic of continental climates (Bu et al., 2022).

Moreover, long-term numerical simulations indicate that persistent thermal imbalance leads to gradual aquifer temperature drift, reduced recovery efficiency, and potential regulatory constraints related to groundwater protection (Bloemendal & Hartog, 2018; Fleuchaus et al., 2018). In the Romanian context, where seasonal temperature amplitudes are high and heating seasons extend over 5–6 months, maintaining thermal equilibrium is particularly critical for system sustainability. Without corrective measures, thermal recovery efficiency can remain well below the 68-87% reported for well-operated installations: long-term monitoring of a doublet ATES system yielded average recovery efficiencies of only 47% and 60% for the warm and cold stores over the first three storage cycles, with annual energy and hydraulic imbalances producing thermal breakthrough between the warm and cold sides of the aquifer (Abuasbeh et al., 2021).

Hybridization strategies - including integration with solar thermal collectors, photovoltaic-driven heat pumps, or auxiliary low-carbon heat sources - have been shown to restore annual energy balance and stabilize subsurface temperatures (Fleuchaus et al., 2018). The practical relevance of such measures is reflected in regulatory practice: monitored Dutch ATES systems show annual energy imbalances between −22% and +15%, and provincial legislation requires energy balance to be met over a 3-5 year period (Bloemendal & Hartog, 2018). In particular, solar-assisted ATES systems can inject surplus summer heat into the warm well, compensating for the higher winter extraction demand typical of continental climates. Parametric studies suggest that achieving a seasonal storage balance within ±10% significantly improves long-term efficiency and mitigates environmental risks (Bloemendal & Hartog, 2018).

For Romania, the high solar irradiation levels during summer (1,400–1,600 kWh/m²·year) create favorable conditions for such hybrid configurations, especially in urban areas like Bucharest where large roof surfaces are available on commercial and institutional buildings (Năstase et al., 2018; Prăvălie et al., 2022). Therefore, adapting ATES design to continental climatic conditions through hybridization and optimized operational control is essential to ensure technical feasibility, environmental compliance, and long-term performance stability.

This paper investigates ATES application feasibility for an office building in Bucharest, Romania, through hydrogeological assessment, dynamic building energy simulations, and system design analysis. The study evaluates both existing building performance and nZEB level renovation, identifying technical barriers specific to Romanian conditions and proposing solutions including hybrid renewable system integration. The research contributes to understanding ATES deployment potential in heating-dominated continental climates and provides guidance for Romanian policy development.

MATERIALS AND METHODS

Case Study Building and Location

The pilot building is an office facility located in climatic zone 2, Bucharest, Romania, constructed in the 1970s with ground floor plus

two levels. The building has a gross floor area of 864 m², with occupied office spaces totalling 366.80 m² (conditioned volume 1,281 m³). The building is currently connected to the district heating system for space heating.

Hydrogeological Investigation

Three exploratory wells (45 m depth) were drilled at the pilot site to characterize lithology and aquifer properties through soil sampling and granulometry analysis (Figure 1).

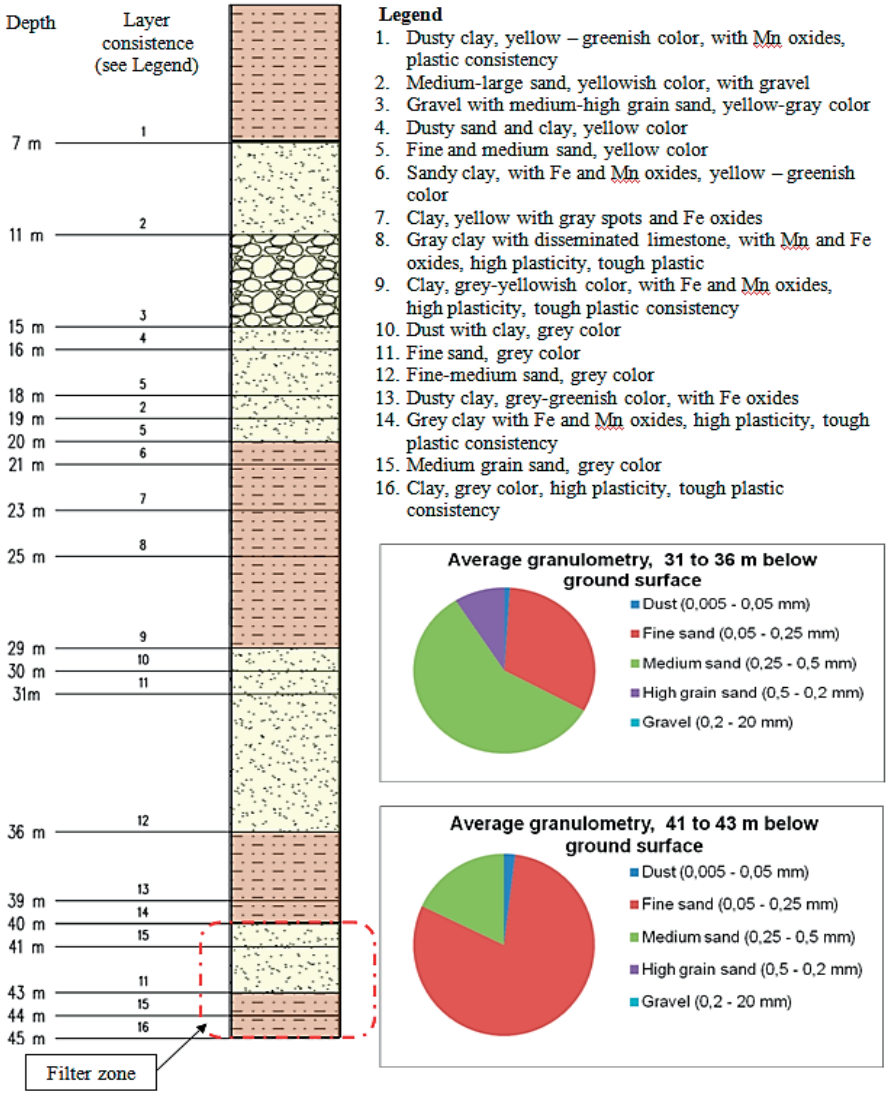


Figure 1. Site lithology, based on the 3 drills executed at the site. Lower right: breakdown for the composition of two different layers of the same aquifer

Site preparation and surface stabilization measures were implemented following erosion control protocols established for infrastructure applications (Olinic et al., 2024) to prevent surface runoff contamination during drilling operations. The investigation documented a confined secondary aquifer system at 30-45 m depth, comprising two distinct layers of 7 m and 3 m thickness respectively, yielding a combined aquifer thickness of 10 m - relatively shallow

compared to typical ATES implementations where 15-40 m are common.

Soil samples were collected during drilling and subjected to granulometric analysis in the laboratory to determine particle size distribution. The analysis revealed a significant presence of fine sand particles alongside coarser fractions, indicating moderate permeability conditions. The confined aquifer exhibits pressurized conditions with static water level rising to 11 m below ground surface, which is characteristic of artesian aquifers.

Groundwater temperature measurements were conducted in static well conditions using a calibrated PT100 resistance temperature detector at 5-meter depth intervals. Recorded temperatures were 13.18°C at 41 m depth and 12.98°C at 46 m depth.

A pumping test was performed with extraction from one well and reinjection distributed between two wells to evaluate aquifer hydraulic response. Due to project constraints including limited expertise availability and time restrictions, well screen placement was not optimally positioned. The filter zone was installed at 37-45 m depth, whereas optimal placement based on the granulometric data would have been at 29-36 m depth where higher permeability was indicated by coarser particle size distribution. The site lithology and aquifer configuration are illustrated in Figure 1.

Building Energy Simulation Methodology

Dynamic building energy simulations were performed using the RTU (from Romanian "Răspunsul Termic Unitar") method with one-hour time steps (Constantinescu, 2008; Petcu, 2009). The RTU method characterizes building elements thermal dynamics through the unit impulse response δ(t), enabling the determination of both intensive parameters (indoor temperatures) and extensive parameters (heat flow rates) under arbitrary climatic excitation via convolution with this unit thermal response (Skruch & Długosz, 2019; Constantinescu, 2020). The software tool implementing this method was developed and validated in earlier work (Petcu, 2009), and applied here to both existing and nZEB-renovated building configurations.

Critically for this study, the software operates with a finite heat source model: when available heating or cooling capacity is insufficient to maintain the setpoint temperature (20°C for heating and 25°C for cooling), it calculates the resulting indoor temperature deviation rather than assuming unlimited supply. This capability is essential for ATES feasibility assessment, where system thermal capacity is inherently constrained by aquifer properties and well design.

Hourly standard climate data (test reference year for Bucharest, Mc 001/6-2013) including outdoor air temperature and solar radiation on all building orientations were used as input. Software validation is documented through empirical validation using measured data from the Experimental Building INCERC Bucharest during cold and warm seasons 2008-2010 (Petcu et al., 2010), and numerical validation applying EN 15255:2008, EN 15265:2008, and ISO 13792:2012 for cooling load calculation, dynamic energy needs calculation, and summer internal temperature calculation respectively.

The building was simulated in two configurations: the existing building configuration with current envelope thermal properties, and the building renovated to nZEB standards. The existing building is characterized by limited thermal envelope performance typical of pre-renovation construction. The external walls present a thermal transmittance of 1.3 W/m²K, while the fenestration offers minimal insulation with a window U-value value of 3.2 W/m²K. The floor slab contributes to the thermal performance of the building envelope with a U-value of 2.5 W/m²K and the roof provides 0.77 W/m²K of thermal transmittance. Air leakage assessment indicates moderate infiltration with an airtightness level of n_{50} = 1.5 h^{-1}, reflecting gaps and thermal bridges typical of existing building stock. The building is currently serviced by connection to a district heating system for thermal conditioning.

In the nZEB renovation hypothesis, the thermal envelope performance is substantially enhanced across all structural components. The thermal envelope of the renovated building is assumed to reach U-values of 0.28 W/m²K for the insulated external walls, 1.3 W/m²K for the windows, 0.2 W/m²K for the floor slab, and 0.19 W/m²K for the insulated roof, resulting in a more thermally homogeneous envelope with reduced thermal bridging. Airtightness is set to

n_{50} = 0.5 h^{-1}, approaching passive building standards and substantially limiting uncontrolled air leakage. The renovated configuration assumes integration of renewable energy systems to meet nZEB requirements, replacing reliance on conventional district heating with technologies capable of meeting heating and cooling demands from renewable sources.

RESULTS AND DISCUSSIONS

ATES System Design Considerations

Based on the pilot study findings and international best practices, the confined secondary aquifer at 30-45 m depth with 10 m combined thickness can be accessed through properly designed wells with a minimum spacing of 100 m between warm and cold wells to prevent thermal interference and ensure adequate thermal storage volume (Bloemendal et al., 2018; Birdsell et al., 2021). For small-scale ATES systems in similar geological conditions, international experience indicates design flow rates of 10-15 m^3/h per well (Bloemendal et al., 2014); however, the significant fine sand content and suboptimal well screen placement at the pilot site (installed at 37–45 m depth rather than the optimal 29-36 m depth indicated by granulometric analysis) restrict feasible extraction rates to approximately 2.9-5.8 m^3/h (0.8-1.6 l/s). A temperature differential of 5 K between extraction and reinjection was adopted as the design value for the aquifer circuit, based on hydrogeological assessment and recommendations from the MATES project's hydrogeological partner. This differential ensures reinjection temperatures remain within environmentally safe limits: approximately 8°C during winter (cold storage) and 18°C during summer (warm storage), consistent with the ranges recommended to balance heat pump efficiency with environmental protection and avoid exceeding 25°C, which may impact trace element mobility (Bonte, 2015). At the maximum feasible site flow rate of 1.6 l/s, this differential provides a thermal exchange capacity of approximately 33.4 kW at the aquifer, sufficient to meet the evaporator demand of the proposed heat pump system under design load conditions.

The proposed system employs water-to-water heat pumps with modular scroll compressors, enabling capacity modulation across multiple steps depending on load conditions. Performance analysis indicates COP values of 6.14 for small compressor operation, 5.91 for large compressor operation, and 5.35 at full capacity with both compressors engaged. The seasonal performance factor for the complete system, including circulation pumps and auxiliaries, ranges from 4.65 to 5.01 based on operational scenarios. To protect the aquifer from potential refrigerant contamination and allow controlled flow rate variation, the technological scheme (Figure 2) incorporates an intermediate heat exchanger circuit between the heat pumps and the underground circuit. A buffer tank enables temporary sensible heat storage to accommodate variable building demands without modifying underground water flow rate, while distribution employs low-temperature heating (35/30°C supply/return) and chilled water cooling (7/12°C supply/return) to maximize heat pump efficiency and ensure compatibility with aquifer temperature levels.

Building Energy Performance Analysis

Dynamic simulation results reveal substantial energy demand reduction through nZEB renovation. For the existing building configuration, annual specific energy consumption totals 181.41 $kWh/m^2 \cdot year$ for heating and 14.75 $kWh/m^2 \cdot year$ for cooling, based on the occupied area of 366.80 m^2. The pronounced heating-cooling imbalance characteristic of Bucharest's continental climate is evident, with heating demand exceeding cooling demand by a factor of approximately 12:1.

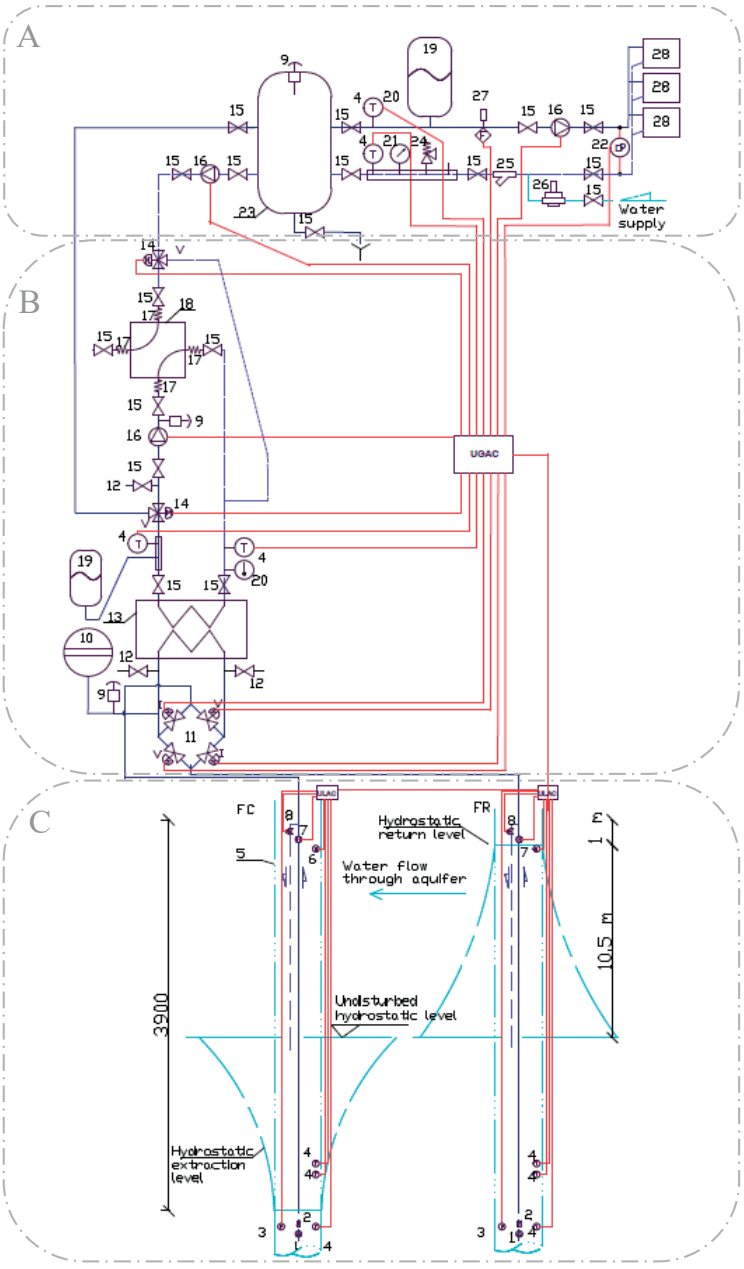


Figure 2. Technologic scheme for a heating / cooling system using ATES (A - distribution system and building related equipment, B - heat pump and other equipment from heat station, C - aquifer)
LEGEND: 1. Immersion water pump; 2. Clapper check valve; 3. Pressure transducer; 4. Temperature transducer; 5. Water well PVC pipe; 6. Water level sensor; 7. Water meter with pulse output; 8. Electric Solenoid Valve Water; 9. Air separator; 10. Water hammer arrestor; 11. Electric Solenoid Valve Water; 12. Bleeder; 13. Plate Heat Exchanger; 14. Three-way Valve with electric actuator; 15. Ball cock; 16. Circulation pump; 17. EPDM Rubber Joint to reduce the vibration; 18. Heat pump; 19. Expansion Vessel; 20. Thermometer; 21. Manometer; 22. Pressure drop transducer; 23. Water buffer tank; 24 Over pressure valve; 25. Inline Y filter; 26. Water Pressure Regulator; 27. Water flow sensor; 28. Fan coil unit; FC – Warm well; FR – Cold well; ULAC – Local acquisition and control unit; UGAC – General acquisition and control unit; I – Winter; V – Summer

Following nZEB renovation, annual heating demand decreases to 63.99 kWh/m²·year (65% reduction) while cooling demand reduces to 9.14 kWh/m²·year (38% reduction), though the heating-cooling asymmetry persists at a ratio of 7:1. Peak demands are also substantially reduced, with maximum hourly heating load dropping from 28.5 kW to 12.3 kW and peak cooling load from 9.8 kW to 6.7 kW (Figure 3). These lower peaks make the renovated building suitable for heat pump-based systems, but this suitability comes with a critical design constraint that must be addressed explicitly.

The ATES-coupled system operates as a low-entropy heating and cooling circuit, with thermal agent parameters close to the conditioned space temperature - 35/30°C for heating and 7/12°C for cooling.

This reduced temperature lift is precisely what enables the high COP values (5.35-6.14) reported for the heat pump configuration, as thermodynamic efficiency increases with decreasing temperature differential between source and sink. However, the same characteristic makes the distribution system technically demanding. The small driving temperature difference between the agent and the indoor environment - approximately 14 K on the heating side at design conditions - severely limits the capacity of conventional terminal units. Standard fan coil units are typically rated at higher supply temperatures (40-45°C), and their performance at 35°C supply is not covered by manufacturer specifications; capacity must therefore be estimated through corrected characteristic curves rather than catalogue data. This constraint becomes particularly acute during peak heating loads, where insufficient terminal unit surface area leads directly to failure to maintain setpoint. Radiant heating systems are better suited to these low-temperature conditions but introduce their own thermal inertia challenges in buildings with variable occupancy schedules. Both the engineering calculations and the physical implementation of such a system therefore require specialized expertise - the high system-level efficiency must not obscure the significant technical risk at the terminal unit level.

The annual energy demands for both building configurations are illustrated in Figure 3.

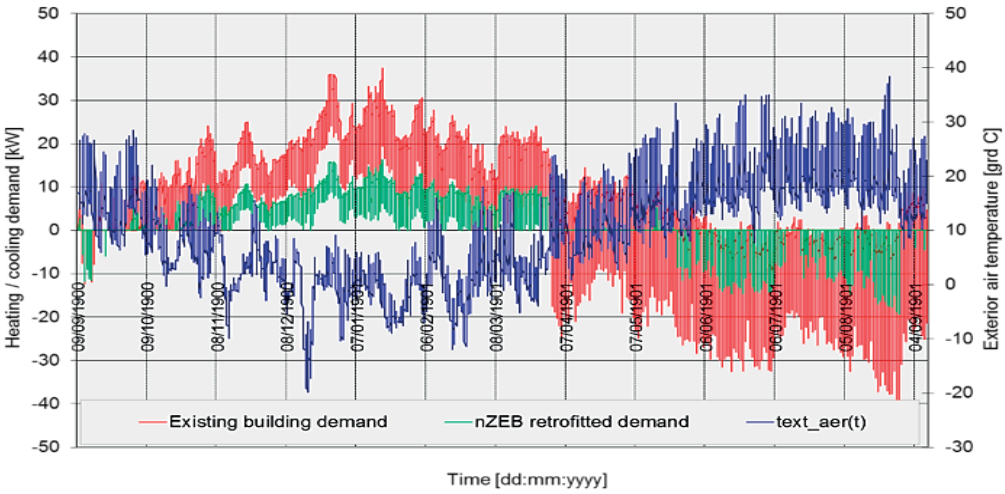


Figure 3. Energy demand of the pilot area, for existing building and the building renovated at a nZEB level

Aquifer Characteristics and ATES Suitability Assessment

The hydrogeological investigation identified characteristics that present both opportunities and limitations for ATES implementation. The measured combined aquifer thickness of 10 m falls below the typical 15-40 m thickness recommended for optimal ATES performance (Fleuchaus et al., 2018). Because the plume height is fixed by the aquifer thickness, a thin

aquifer also constrains the plume aspect ratio available for limiting heat losses to the confining layers (Tang & Rijnaarts, 2023), potentially limiting thermal storage volume and requiring careful system design to prevent thermal breakthrough between wells.

The confined aquifer conditions with artesian pressure offer advantages including reduced pumping energy requirements and natural protection from surface contamination. However, the pressurized nature requires careful well design to prevent uncontrolled discharge and ensure reliable reinjection capabilities. The granulometric analysis indicating significant fine sand content increases the risk of well screen clogging through particle migration and potential iron precipitation, which has been documented in other ATES systems (Possemiers et al., 2014). Preventive measures including proper well development, controlled injection velocities, and periodic monitoring would be essential for long-term operation.

The elevated groundwater temperatures (13.18°C at 41 m depth, 12.98°C at 46 m depth) exceed the regional average multiannual temperature of 10.7°C (SR 4839:2014) by approximately 2.5 K. This thermal anomaly is consistent with established patterns of groundwater thermal behaviour: at depths of 10-20 m, groundwater temperatures typically stabilize at 1-2 K above local mean annual temperatures, with further gradual increases below these depths due to geothermal gradient (Lee, 2013). The measured temperatures therefore reflect the combined influence of natural geothermal warming and potentially urban heat island effects documented in other urban areas (Benz et al., 2016; Böttcher & Zosseder, 2022), though the geothermal potential of the pilot area has not been comprehensively characterized. These elevated baseline temperatures provide advantageous conditions for heat pump operation, reducing temperature lift requirements during heating mode.

Groundwater Quality Assessment

Water quality analysis performed at the Bucharest pilot site revealed elevated concentrations of dissolved minerals that pose operational challenges for ATES implementation. Iron concentration measured 0.80 mg/l, exceeding the maximum contaminant allowable value by a factor of four and approaching the threshold above which iron oxide precipitation induces significant injection well clogging (Possemiers et al., 2014; Burté et al., 2019). Manganese was measured at 0.42 mg/l, exceeding its allowable limit by a factor of 8.4. While manganese contributes less to clogging than iron, the simultaneous presence of both elevated iron and manganese increases the risk of combined mineral precipitation during thermal cycling. Beyond inorganic parameters, urban aquifers in Bucharest may be subject to persistent organic pollutant contamination from historical industrial activities, though recent monitoring shows declining trends in urban soil contaminants such as polychlorinated biphenyls (Sandu et al., 2025), suggesting gradual improvement in urban environmental quality.

ATES System Performance Assessment

For the pilot building with occupied area of 366.80 m², the annual heating energy demand of 63.99 kWh/m²·year translates to approximately 23,470 kWh total annual heating requirement, while cooling demand of 9.14 kWh/m²·year corresponds to approximately 3,350 kWh annual cooling requirement. This pronounced imbalance (ratio 7:1) presents significant challenges for ATES thermal balance.

The heat pump system performance with seasonal performance factor (SPF) of 4.65 to 5.01 demonstrates the potential for highly efficient operation when coupled with ATES thermal storage. The modular compressor configuration allows optimization of part-load performance, with single compressor operation achieving COP values up to 6.14 during low-demand periods. This operational flexibility is particularly valuable for accommodating variable building loads and maximizing energy efficiency throughout the heating and cooling seasons.

The heating-cooling asymmetry has direct consequences for long-term ATES performance. A sustained mismatch between seasonal cooling injection and heating extraction produces a continuous thermal drift of the aquifer around the wells: the storage volume gradually cools until a new quasi-stationary regime is reached, characterized by asymmetric thermal plumes and a progressive reduction of the available

temperature contrast between warm and cold wells (Sommer et al., 2013; Fleuchaus et al., 2018; Godinaud et al., 2025).

From an environmental and regulatory perspective, such imbalance – particularly on the cooling side – is generally permissible in urban contexts. Regulatory frameworks are primarily concerned with excessive groundwater warming rather than moderate cooling, and life cycle assessments confirm that ATES yields substantial greenhouse gas reductions - up to 74% for heating compared with oil- and gas-fired systems, and up to about 59% for cooling relative to conventional techniques under the present electricity mix, rising to some 97% under a projected 2050 electricity mix (Stemmle et al., 2021). The dominant environmental impacts are attributable to operational electricity demand, which is responsible for over 95% of water use, global warming potential and acidification impacts, rather than to aquifer temperature changes (Ni et al., 2020). The critical consequence of persistent imbalance is therefore thermodynamic, not environmental: reduced temperature contrast translates directly into declining heat recovery efficiency and lower heat pump performance over successive annual cycles. Field monitoring of an imbalanced LT-ATES system documented a progressive decrease in the temperature difference on the ATES side - from approximately 3 K down to 1.8 K over four cooling seasons despite an available ΔT of 8 K - confirming that performance degradation under imbalanced operation exceeds what hydrogeological dispersion alone would produce (Abuasbeh et al., 2021). Numerical simulations corroborate this: thermally balanced doublet operation produces stable, symmetric plumes and sustained performance over decades, whereas imbalanced scenarios show enlargement of the warm plume, reduction of the cold plume, and progressive warming of the screened interval (Bozkaya et al., 2018; Godinaud et al., 2025).

The integration of solar thermal collectors offers a practical solution to achieve thermal balance. International experience demonstrates that ATES systems achieve high seasonal performance in heating-dominated climates, and that supplementary heat injection is the accepted lever for maintaining long-term balance. Vanhoudt et al. (2011) documented three years of monitored operation of an ATES-heat pump system at a Belgian hospital, achieving a seasonal performance factor of 5.9 for heating and a 71% reduction in primary energy use compared with gas boilers and conventional chillers.

For the Bucharest pilot building, evacuated tube collectors could provide supplementary heat injection during summer cooling season to reduce thermal imbalance. The sizing of such a solar thermal system would need to balance the heating-cooling asymmetry, potentially requiring collector areas and storage capacities determined through detailed optimization considering building loads, available roof area, seasonal solar irradiance patterns, and system integration requirements. This hybrid renewable configuration would facilitate meeting EPBD requirements for on-site renewable energy generation while enabling sustainable ATES operation.

Beyond system-level solar thermal augmentation, imbalance can be managed through multi-well configurations and optimized well placement accounting for ambient groundwater flow, aquifer thickness, and urban constraints, which help maintain higher heat recovery factors even under imperfectly balanced loads (Sommer et al., 2013; Li et al., 2024; Petrova et al., 2025) and, in aquifers with high flow velocities (of the order of 100 m/year), an additional upstream extraction well acting as a hydraulic barrier can more than double thermal recovery efficiency relative to a conventional doublet (Ohagen et al., 2025). At urban scale, coordinated planning of multiple ATES systems allows excess cold from individual installations to be offset by excess heat from others, improving overall aquifer balance and increasing deployment density by approximately 30% (Sommer et al., 2015; Bloemendal et al., 2018; Beernink et al., 2022). Contemporary design guidelines therefore treat thermal imbalance as a manageable design variable rather than a hard constraint, emphasizing active balance management through control strategies and additional thermal sources as the key lever for maintaining long-term system viability (Bozkaya et al., 2018; Abuasbeh et al., 2021).

Regulatory and Institutional Barriers

The primary impediment to ATES deployment in Romania is Water Law no. 107/1996 (with subsequent amendments), which regulates reinjection of extracted water into aquifers. Contemporary operational experience with discharge quality compliance in Romanian wastewater treatment facilities demonstrates that meeting natural receptor standards requires continuous technological adjustment and monitoring (Dracea et al., 2022), principles equally applicable to ATES thermal discharge management. The legislation was designed primarily for mining and industrial wastewater discharge, establishing strict prohibitions on reinjection into the same aquifer from which water was extracted. This regulatory framework does not differentiate between contaminated industrial wastewater and closed-loop thermal energy storage where groundwater contacts only inert heat exchanger materials.

International regulatory frameworks provide alternative models that could guide Romanian policy development. The Netherlands employs a performance-based permitting system where ATES installations must demonstrate that thermal impacts remain within acceptable limits and that annual thermal balance is maintained (Bloemendal et al., 2014). German regulations, while more restrictive, still explicitly permit ATES systems under appropriate monitoring and control conditions (Stemmle et al., 2021).

The absence of ATES-specific technical standards in Romania creates additional uncertainty for potential investors. Key gaps include lack of well design specifications, monitoring requirements, operational protocols, and decommissioning procedures. The development of Romanian national standards based on established international protocols would facilitate systematic ATES deployment while ensuring environmental protection.

Institutional capacity represents another significant barrier. Limited Romanian experience exists with ATES-specific well construction techniques, and hydrogeological expertise for thermal storage applications is scarce. Professional training programs and technology transfer initiatives modelled on Dutch and German experience would be necessary to build domestic technical capacity for this renewable energy technology.

Comparison with International ATES Experience

The Bucharest pilot study findings align closely with recent assessments in other European countries facing similar regulatory and technical challenges. Noethen et al. (2025) identified substantial ATES potential in German regions despite regulatory barriers limiting implementation, while Jackson et al. (2024) report that ATES in the United Kingdom currently meets less than 0.01% of national heating demand although the technology could in principle serve about 61% of it. Similar to the Bucharest case, these studies demonstrate that technical feasibility exists but institutional frameworks remain underdeveloped.

The heating-cooling imbalance documented for Bucharest (ratio 7:1 for renovated building) is more severe than typical Dutch office buildings (ratio 1.5-2.5:1) but comparable to heating-dominated climates in Sweden and northern Germany. The proposed solar thermal integration strategy has precedent in Swedish and Belgian applications where seasonal storage systems achieve thermal balance through coordinated operation with solar collectors.

The shallow aquifer depth identified in Bucharest (10 m combined thickness) presents greater challenges than typical Dutch ATES installations (15-40 m aquifer thickness) but remains within technically feasible ranges. Al-Madhlom et al. (2019) proposed a multi-criteria site selection method (AHP combined with the DRASTIC index) specifically for shallow groundwater conditions, confirming that such settings require more conservative design approaches and careful thermal management.

Study Limitations

One should acknowledge several limitations of this pilot investigation. The hydrogeological characterization was based on three exploratory wells within a limited site area, providing insufficient data to fully characterize aquifer heterogeneity and regional groundwater flow patterns. A more comprehensive assessment would require additional wells, long-term pumping tests, and seasonal temperature monitoring to validate ATES feasibility for commercial-scale implementation.

The dynamic building simulations employed standard test reference year climate data and

assumed operational patterns based on typical office occupancy. Climate change projections indicate potential shifts in heating-cooling ratios for Central Europe (Godinaud et al., 2025), which could affect long-term ATES thermal balance. Future studies should incorporate climate scenarios to assess system performance under evolving conditions.

The system design considerations and performance estimates presented in this study are based on simulation results and international best practices adapted for Romanian conditions rather than operational data from a functioning pilot installation. Actual implementation would require comprehensive feasibility studies including detailed performance monitoring, cost-benefit analysis, and long-term operational experience to validate the projected system performance and economic viability.

CONCLUSIONS

This study demonstrates that Aquifer Thermal Energy Storage (ATES) technology presents technically feasible opportunities for supporting nearly Zero Energy Buildings (nZEB) in Romanian continental climate conditions, though significant regulatory and technical barriers currently impede implementation. The pilot assessment for an office building in Bucharest revealed that nZEB renovation reduces annual energy demand by 65% for heating and 38% for cooling, making the building suitable for integration with renewable ATES-based systems.

The hydrogeological investigation documented a confined secondary aquifer at 30-45 m depth with 10 m combined thickness across two layers (7 m and 3 m) separated by a clay deposit. The aquifer exhibits favorable characteristics including moderate hydraulic conductivity and elevated ambient temperatures (13.2°C) that benefit heat pump operation. However, the aquifer thickness falls well below optimal ranges typical of international ATES installations, necessitating conservative design approaches and careful thermal management.

The elevated iron and manganese concentrations documented at the pilot site illustrate a broader challenge for ATES deployment in Romania. These values were obtained from a single site; Romanian aquifers across different geological regions may exhibit substantially different mineral profiles. Successful ATES deployment at national scale requires a systematic hydrogeochemical pre-screening of candidate aquifers, analogous to the regional water quality survey methodology developed by Allen (1983) for the United States. Recent assessments of groundwater contamination risks in Romania confirm the urgency of such systematic screening, revealing widespread vulnerability to multiple contaminants including nitrates, arsenic, and coliforms affecting over 670,000 individuals in rural areas alone (Ivanescu & Sandu, 2025). Allen's framework identified groundwater chemistry - particularly total dissolved solids, iron content, and carbonate saturation - as the primary determinants of long-term well injectivity and system reliability, concluding that freshwater with TDS below 500 mg/l in quartz sand aquifers represents the most favorable condition for low-temperature ATES. No equivalent national-scale screening exists for Romania, despite the fact that groundwater mineral content likely constitutes the most significant technical challenge for widespread ATES deployment in the country.

The pronounced heating-cooling demand imbalance characteristic of Bucharest's continental climate (ratio 7:1 even after nZEB renovation) represents the primary technical challenge for ATES deployment. This asymmetry would progressively cool the aquifer over multiple annual cycles, degrading system performance unless addressed through supplementary heat sources. Integration of solar thermal collectors offers a practical solution to achieve thermal balance, as demonstrated by successful international implementations in similar heating-dominated climates.

The heat pump system performance analysis indicates seasonal performance factors (SPF) of 4.65 to 5.01, demonstrating potential for highly efficient operation when properly integrated with ATES thermal storage. The modular compressor configuration enables optimization across variable load conditions, achieving COP values ranging from 5.35 to 6.14 depending on operational mode.

Romania's current regulatory framework poses the most significant barrier to ATES implementation, with Water Law no. 107/1996 prohibiting thermal reinjection without differentiation

between contaminated wastewater and closed-loop thermal storage. Development of ATES-specific regulations modeled on international performance-based permitting, combined with technical standards for well design and operation, would facilitate deployment while ensuring environmental protection.

Successful ATES implementation in Romania requires coordinated action on multiple fronts including: (1) legislative revision to permit thermal energy storage with appropriate monitoring requirements, (2) development of national technical standards based on international best practice, (3) pilot demonstration projects to build domestic expertise and generate operational data, (4) professional training programs for ATES design and operation, and (5) hydrogeological assessment campaigns to map aquifer suitability in major urban areas.

The research demonstrates that with appropriate institutional frameworks and hybrid system configurations integrating ATES with solar thermal technology, this renewable energy storage approach can significantly contribute to achieving Romania's nZEB targets and building sector decarbonization goals while providing reliable, cost-effective heating and cooling services.

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