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Conditions for the development of low-temperature aquifer thermal energy storage (LT-ATES) in Poland

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Abstract
We investigate the fundamental conditions for the effective deployment of Aquifer Thermal Energy Storage (ATES), focusing on low-temperature applications (LT-ATES) in Poland, identifying opportunities and challenges associated with implementing this technology within national hydrogeological and institutional settings. This study builds upon the findings of the project "Preliminary assessment of thermal energy storage potential in aquifers in Poland" completed in 2024, which provided the first comprehensive evaluation of LT-ATES potential. Our analysis encompasses key technical and regulatory determinants of sustainable system operation, emphasizing the necessity of full groundwater re-injection and rigorous site selection to safeguard water quality and prevent interference with medicinal and thermal water resources. Operational performance may be enhanced through advanced control strategies and systematic well maintenance. A SWOT analysis is applied to assess the strengths, weaknesses, opportunities and threats relevant to LT-ATES deployment in Poland. LT-ATES could play an important role in decarbonizing the national heating sector by supporting distributed systems, building clusters, and small district networks. The technology is increasingly recognized in strategic policy documents such as PEP2040 and the Geothermal Development Roadmap (2021). We conclude with policy recommendations to strengthen regulatory frameworks, increase awareness, and support nationwide implementation across Poland.

INTRODUCTION

Aquifer Thermal Energy Storage (ATES) has evolved over the past five decades from a theoretical concept into a significant element of green heating and cooling strategies. Initially developed in response to global energy concerns, ATES systems exploit the thermal capacity of subsurface aquifers to store and recover heat or cold across seasons. Their application has expanded rapidly in recent decades, particularly in western and northern Europe, where they now play an important role in sustainable energy transitions and carbon-neutral heating strategies (Marojević et al., 2025; Stemmle, 2025b; Köhler & Ganal, 2024).

The roots of ATES technology trace back to the 1960s and 70s, when researchers began to investigate the potential of underground water-bearing formations to serve as thermal reservoirs. The 1973 oil crisis catalysed interest in alternative and renewable energy storage methods, leading to pilot studies in Sweden, Germany and the United States. By 1978, one of the earliest demonstration systems was built in Uppsala, Sweden, designed to store solar heat in summer and recover it for space heating in winter (Lund, Freeston & Boyd, 2010; Andersson, 1985; Gehlin and Nordell, 2003; Fleuchaus et al., 2018).

These early systems, while operational, lacked robust modelling capabilities and suffered from thermal dispersion losses. Lee (2010) provided a foundational review of ATES operation, classification, and modelling approaches, highlighting the need for advanced hydrothermal simulations and robust doublet-well designs to prevent mineral precipitation at well screens and thermal short-circuiting, and to maximize recovery efficiency.

A key turning point in ATES development came in the 1990s, particularly in the Netherlands. The country's favourable geological conditions - widespread sandy aquifers at accessible depths between 20 and 150 metres – combined with proactive regulatory support and a growing emphasis on urban sustainability, made it a fertile ground for widespread implementation (Fleuchaus et al., 2028). Dutch engineers refined the doublet-well configuration, whereby one well stores heated groundwater (the so-called “warm well”) and the other stores cooled groundwater (the “cold well”). An important element of the ATES heating system is a heat pump. During wintertime, water, pumped via the hot well at a temperature of approximately 15-20°C, passes through the evaporator of the heat pump to raise the temperature of water circulating in buildings to the required level, usually in the range from 35 to 50°C. At the same time, the heat pump cools groundwater to approximately 10°C or lower. In the summertime, the cycle is reversed. Cooled groundwater is used for air-conditioning. After absorbing heat from the building, water is reinjected through the hot well (Fig. 1A). This operation pattern is called a cyclic regime due to the alternating direction of groundwater pumping between wells, and it requires groundwater to flow at a low velocity.

At high groundwater flow velocities (usually >100 m/year), a unidirectional system is most often used, where water is pumped in the direction of groundwater flow (Fig. 1B). Each well then serves as a production or injection well, regardless of the season. In the unidirectional regime, the temperature gradient between wells is lower than in the cyclic regime.

In both cases, if the water temperature in the cold well is low enough, it can be used directly to air-condition buildings via a water-to-air heat exchanger, bypassing the heat pump. This is known as free cooling.

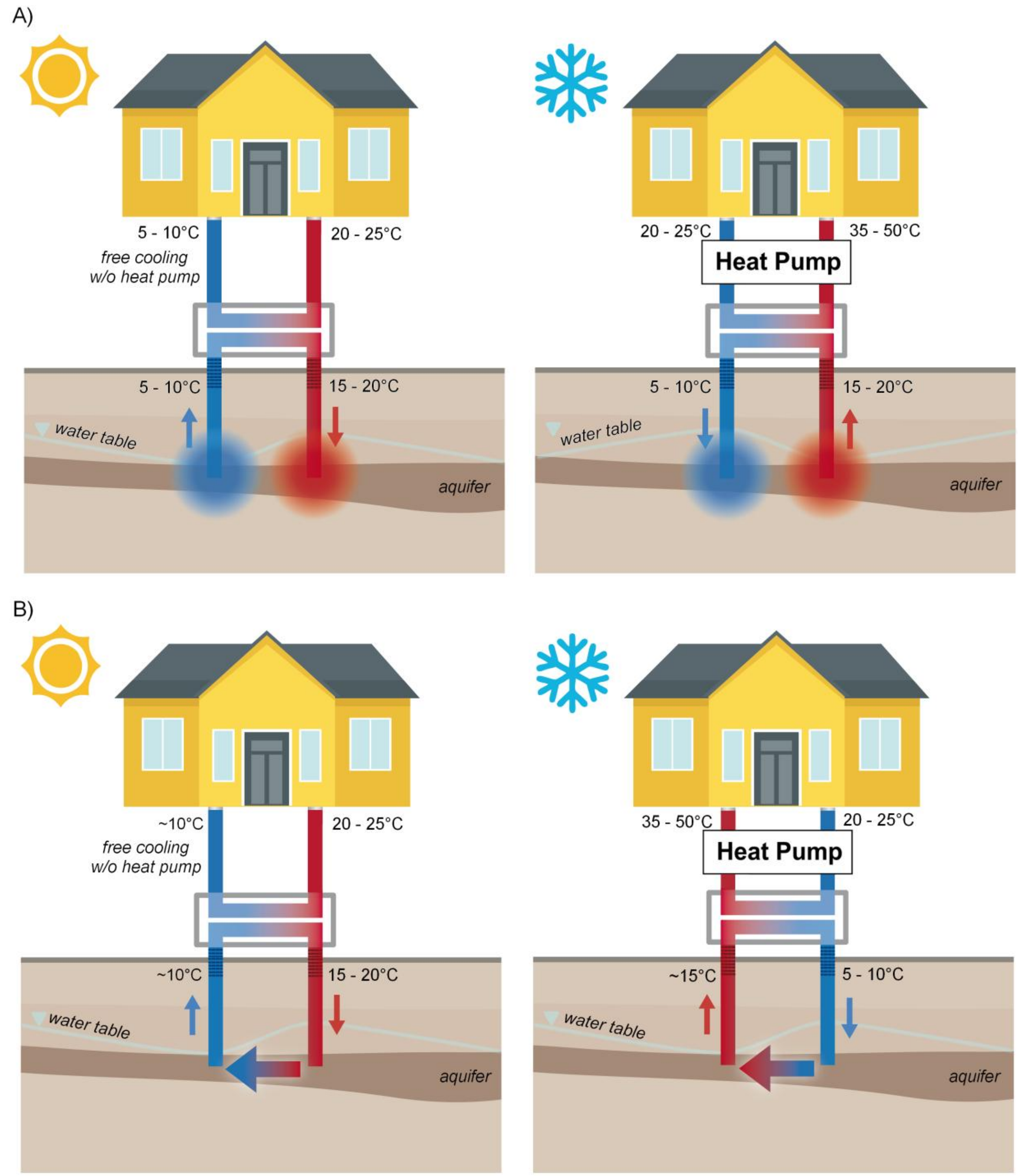


Figure 1. *Simplified scheme of LT-ATES systems operation in summer and winter seasons: A) cyclic regime, B) unidirectional regime*

By the early 2000s, several hundred ATES systems were already operating across Europe, mainly serving commercial facilities, hospitals, airports and university campuses. As deployment expanded, researchers began to focus more on subsurface processes and potential environmental effects. Bloemendal and Hartog (2018) made an important contribution by analysing how aquifer characteristics influence the thermal recovery efficiency of low-temperature ATES (LT-ATES) systems. Their study demonstrated that recovery performance strongly depends on parameters such as permeability, transmissivity and groundwater flow regime, as well as on operational practices aimed at maintaining thermal balance between heating and cooling seasons. They found that recovery efficiency can vary widely - from around 50% to over 90% - depending on the degree of alignment between system design, geological conditions, and thermal demand.

Ongoing research efforts have been instrumental in facilitating the adoption of ATES within integrated energy networks. In the 2010s, European utilities, municipalities and energy researchers began embedding ATES within broader renewable heating and cooling infrastructures. In the Netherlands, the *WarmingUP* project – a collaboration involving Deltares and dozens of other institutions – explored combining ATES with high-temperature district heating networks, aquathermal energy from surface water, and geothermal heat. The report by Deltares (2023) highlighted that ATES systems are not only efficient and durable but also invisible and space-efficient, making them ideal for deployment in dense urban environments where solar panels or wind turbines may not be feasible.

One of the defining developments of the 2010s was the introduction of medium- and high-temperature ATES (MT-ATES and HT-ATES) systems, capable of operating at 30–85°C. These systems allow storage of excess heat from solar thermal collectors, combined heat and power (CHP) plants, and geothermal sources for later use. The *ATES Factsheet v6***,** published by Water Europe (Kleyböcker et al., 2023) provides numerous examples, including a long-running HT-ATES in Neubrandenburg, Germany, storing geothermal heat since 1987, and the MT-ATES in Westland, Netherlands, storing CHP and solar energy since 2015. The report highlights recovery efficiencies ranging from 72% to 93%, depending on system design and aquifer characteristics.

While the technological maturity of ATES has improved over time, so did the understanding of its interaction with local hydrology and chemistry. Visser et al. (2015) investigated the long-term impacts of ATES on groundwater hydrochemistry and found that temperature changes can significantly influence microbial activity, redox potential, and solute mobilization. Such effects prompted stronger regulatory frameworks and environmental assessments, particularly in areas with sensitive aquifers or overlapping thermal zones.

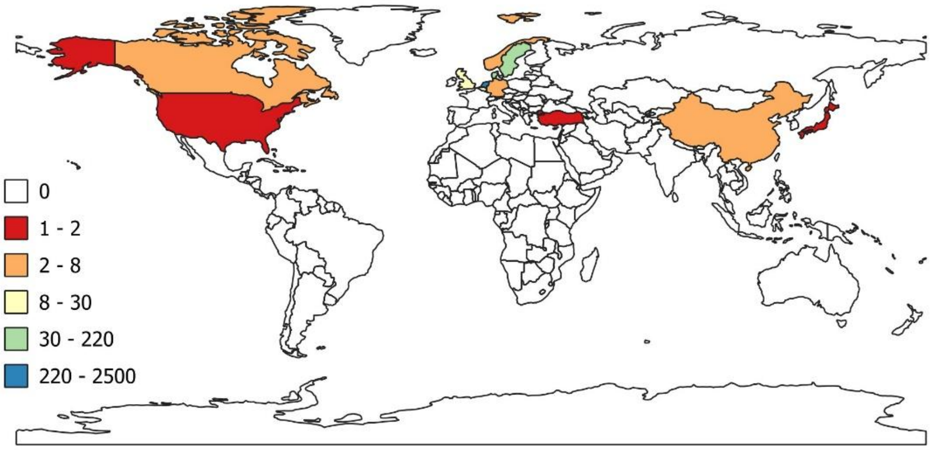
From an operational perspective, the recovery factor (RF), defined as the ratio between discharged and charged energy, emerged as a key performance metric. Todorov et al. (2020) conducted one of the most detailed studies of direct heating and cooling with ATES systems in Finland, showing that the RF stabilizes after three to four years of operation. Their work emphasized the importance of demand-side forecasting, dynamic control strategies and aquifer thermodynamics in optimizing performance.

Advances in digital monitoring and control systems also occurred during this period, improving thermal optimization. Pei et al., (2024) applied distributed temperature sensing (DTS) and ensemble-based simulations to monitor heat plume movement within aquifers in real time. This allowed for early detection of system inefficiencies (such as clogged well screens or thermal dispersion) and enabled operators to adjust flows dynamically to preserve high recovery rates.

In parallel, the role of ATES in broader climate strategies became increasingly prominent. The report by Deltares (2023) and Water Europe emphasized the synergy between ATES and energy neutrality targets, particularly in cities looking to decarbonize their building stock. HT-ATES, operating at 70–80°C, is now being developed for retrofit applications, where space and energy infrastructure constraints limit the viability of other renewable options. In these systems, ATES can replace gas boilers entirely, delivering high-grade heat from solar or geothermal sources with no direct emissions. An example of a HT-ATES project, including retrofit applications, has been documented in Neubrandenburg, Germany. The system was developed by converting existing geothermal heating infrastructure into an HT-ATES to seasonally store excess heat for district heating applications (Dobson et al., 2025). The HT-ATES retrofit system operated with formation temperatures around 50-55°C from the geothermal wells, and geochemical modelling suggested that injection temperatures could potentially be increased to about 90°C under favourable conditions (Dobson et al., 2025).Nowadays, ATES is firmly embedded in urban energy planning across northern and western Europe, with growing interest also in China, Canada and the United States. Its adoption is expanding into hybrid configurations - combined with borehole storage, geothermal plants, and heat pumps - and linked to smart-grid infrastructure that can balance thermal loads at the district or city scale (Stemmle et al., 2024; 2025a; Geerts et al., 2025; Marojević et al., 2025).

GLOBAL LANDSCAPE OF ATES DEVELOPMENT AND TRENDS

Worldwide, and especially in western and northern Europe, ATES technology has gained traction in countries with temperate climates and suitable aquifer conditions, including the Netherlands, Belgium, Sweden, Germany, Denmark and the United States, Canada, and China outside of Europe (Figure 2).



Country	Installations
Netherlands	2500
Sweden	220
Denmark	55
Belgium	30
Great Britain	12
Norway	8
China	6
Canada	4
Germany	4
Japan	2
USA	2
Turkey	1

Figure 2. Estimated global distribution of ATES installations' (data source: Fleuchaus et al. 2018)

Global expansion of ATES has been primarily driven by a combination of urban decarbonization objectives, the increasing emphasis on waste heat recovery and seasonal storage, and its integration with complementary technologies such as solar thermal, shallow geothermal, and district heating networks. These factors have positioned ATES as a strategic component in sustainable urban energy transitions (Stemmle et al., 2024; Marojević et al., 2025).

Nevertheless, the adoption of ATES outside of Europe remains relatively limited (Fleuchaus et al., 2018). This is partly attributed to suboptimal aquifer conditions in some regions, but it is also largely due to the lack of governmental support and appropriate legal regulations in many countries. Institutional barriers, such as limited technical expertise and the absence of targeted financial incentives, further constrain deployment. Moreover, in areas where seasonal demand for both heating and cooling is not well balanced, the economic and operational viability of ATES systems is significantly reduced. Emerging economies with rapidly growing cities and rising energy demands (e.g., in Asia and the Middle East) represent untapped potential, but their development requires customized regulatory frameworks and technology adaptation (Stemmle et al., 2024; Gao et al., 2025; Marojević et al., 2025). The above also applies to Poland (Miecznik and Skrzypczak, 2019).

In Europe, ATES has become a central component of sustainable energy infrastructure, especially in regions aiming to phase out fossil fuels from heating and cooling systems. The continent leads the world in ATES deployment, with the Netherlands firmly established as a global pioneer. With more than 3000 operational systems as of 2025 (Bloemendal and Olsthoorn, 2025), the Dutch model has integrated ATES into new urban developments, commercial buildings and public facilities at scale. This success is attributed to the country's favourable geology, shallow, permeable sandy aquifers, and a progressive policy environment that includes clear permitting rules, thermal zoning, and robust integration into spatial and energy planning (Fleuchaus et al., 2018; Deltares, 2023). Projects are further supported by cutting-edge research institutions such as Deltares, which play a leading role in optimizing system design, improving monitoring techniques, and exploring high-temperature ATES (HT-ATES) for retrofitting older residential districts (Kleyböcker et al., 2023).

Germany also is continuing research and demonstration projects on ATES technology, particularly through its emphasis on medium- and high-temperature storage systems that pair well with waste heat from industrial processes and geothermal energy sources. The system in Neubrandenburg, for instance, has been in operation since the late 1980s and is one of the oldest continuously functioning HT-ATES systems in Europe (Kleyböcker et al., 2023). German research, such as that by Stemmle et al. (2025), continues to explore efficiency improvements, environmental impacts, and optimal integration with renewable heat networks. Across Scandinavia, countries like Sweden and Denmark focus heavily on seasonal integration of ATES with solar thermal energy, using the technology primarily to support large-scale district heating schemes. An excellent example of a large-scale LT-ATES system is in Stockholm Arlanda airport. One of the largest ATES systems in the world is used for cooling and pre-heating of ventilation in the buildings and for de-icing of aircraft parking stands (Midttømme et al. 2017). The volume of the aquifer beneath the boulder ridge known as Brunkebergsåsen is estimated at 200 million m^3. The average storage temperature in the cold zones is between 3 and 6 °C, while in the warm zones it is between 15 and 25 °C (~20 °C on average). The use of this aquifer for cooling and heating at the airport allows savings of about 19 GWh of energy, which is equivalent to the energy used by 2,000 single-family homes (Swedavia Airports, 2026). In Denmark, research is more focused on high-temperature ATES (HT-ATES), an example of which is the study of Pasquinelli et al. (2020). Based on three scenarios derived from a Petrel-based geostatistical model, finite-difference reservoir simulations indicate an average recovery efficiency of approximately 72% when injecting water at 90 °C into a highly porous and permeable aquifer with a background temperature of 55 °C. These results suggest that implementation of a high-temperature aquifer thermal energy storage (HT-ATES) system in the Gassum Formation within the Stenlille structure is technically feasible.

Despite these successes, the expansion of ATES across Europe remains uneven, owing to a combination of different factors, including regulatory fragmentation and limited institutional experience. In areas with fractured rock formations or high-salinity aquifers, technical challenges persist regarding heat retention and groundwater mobility. Additionally, EU regulations on groundwater use and environmental protection are interpreted differently across member states, resulting in variable legal frameworks and inconsistent support for ATES projects (Guglielmetti et al., 2021).

Urban density presents another layer of complexity. In cities like Amsterdam and Rotterdam, overlapping thermal plumes from adjacent ATES systems can lead to thermal interference if not properly managed. Dutch authorities have responded with aquifer zoning and strategic licensing to coordinate spatial distribution, but such frameworks are still underdeveloped in most European cities (Bloemendal and Hartog, 2018; Deltares, 2023). As interest in ATES grows, the need for integrated subsurface planning becomes increasingly urgent.

Another challenge lies in seasonal asymmetry, particularly in southern Europe, where cooling demand outpaces heating for most of the year. This imbalance complicates the design of thermally balanced systems and may necessitate hybrid configurations, such as combining ATES with borehole storage or phase change materials or integrating with waste heat from sewer networks (Elkhatat and Al-Muhtaseb, 2023).

Nevertheless, the European Union has provided vital support through funding major research and innovation programs such as PUSH IT, HEATSTORE and NextGen. These initiatives have helped standardize ATES performance metrics, assess environmental impacts, and facilitate knowledge exchange between countries (Guglielmetti et al., 2021; Szklarz et al., 2024). EU-backed research has also promoted ATES as a core element in broader strategies for urban climate neutrality, district heating decarbonization, and resilience to energy price shocks.

In summary, Europe's leadership in ATES is well-established, but its future growth hinges on addressing several structural challenges. These include the harmonization of groundwater regulations, improved aquifer mapping, and greater public-private collaboration to unlock financing and project development capacity. More broadly, Europe must ensure that its leadership extends beyond its northwest core, where ATES is already thriving, into emerging regions in central, eastern, and southern Europe, where the potential remains largely untapped. With the proper institutional frameworks, technical adaptations, and strategic investment, ATES could play a foundational role in Europe's journey to climate-neutral heating and cooling.

CURRENT STATE OF ATES RESEARCH AND POLICY IN POLAND

In Poland, the development of ATES, especially LT-ATES, remains in an early and exploratory phase, despite the country's favourable conditions for seasonal thermal storage and a high potential for the development of ATES technology explicitly suggested in international research. A landmark study by Bloemendal et al. (2015) from TU Delft identified Poland as one of the European countries with very favourable geological and climatic conditions for widespread ATES deployment. Their assessment highlighted the presence of extensive sedimentary basins and a suitable thermal demand profile, particularly in urban areas with high heating needs in winter and increasing cooling requirements in summer. Despite the global scale assessment, hence low resolution of maps, these authors noted that Poland holds significant promise for future ATES expansion if supported by proper institutional and regulatory frameworks.

This observation is supported by the preliminary assessment of Miecznik and Skrzypczak (2019) and recent initiatives undertaken by the Polish Geological Institute – National Research Institute (PIG-PIB). The PIG-PIB currently completed the project "*Wstępna ocena możliwości magazynowania energii cieplnej w poziomach wodonośnych na obszarze Polski (ATES)*" (*Preliminary assessment of the potential for thermal energy storage in aquifers in Poland*), carried out in 2023–2024. In addition, the local potential for the technology's use has been analysed in the Kościerzyna district case study (Lemoine, 2021). The results show that certain areas offer favourable hydrogeological conditions for LT-ATES systems with several megawatts of cooling capacity; however, they present this as a possibility for appropriate engineering research rather than for existing operational systems. Poland's climate, characterized by cold winters and increasingly hot summers, creates a strong natural demand for both heating and cooling, aligning well with the fundamental principles of ATES.

Additionally, the presence of extensive sedimentary basins, particularly in central and northern regions, suggests significant hydrogeological potential for aquifer-based storage. Studies of the Lower

Cretaceous aquifer in central Poland confirm favourable hydrogeological conditions for ATES but emphasize that the technology remains at the research and modelling stage (Hałaj et al., 2022). Despite these advantages, ATES technology has not yet been adopted in the Polish heating market.
The use of underground thermal energy storage technologies in Poland began to attract scientific interest about a decade ago. In addition to review articles on various underground heat storage technologies (Miecznik, 2016; Malina and Bujak, 2017), preliminary studies were undertaken to assess the suitability of selected hydrogeological structures in Poland for meeting the requirements for ATES installations. Particularly noteworthy are studies conducted on the young glacial areas of the Kashubian Lake District (Lemoine 2016, 2020, 2021) and the Żarnowiec Upland (Lemoine, 2018) in north-central Poland. In central Poland, investigations focused on Quaternary and Upper Cretaceous aquifers in Piotrków County (Bujakowski et al., 2016) and the city of Sochaczew (Skrzypczak et al., 2017), where Quaternary and potentially Oligocene formations were identified as prospective aquifers for ATES applications. A significant study contributing to the initial selection of areas meeting the hydrogeological criteria for ATES technology was by Miecznik and Skrzypczak (2019). These authors used publicly available hydrogeological data, including information obtained from 1324 boreholes of the groundwater observation and research network and 172 information sheets of uniform groundwater bodies. The authors took into account such parameters as: depth to the top of the aquifer; type of porosity of reservoir rocks; stratigraphy and lithology of the aquifer rocks (i.e. only sands and gravels were considered); type of the water table in the aquifer; the depth range of the accessed aquifer (its thickness); and the depth to the static water level. Groundwater body fact sheets can then be used for comparison with well data and also provide additional information on the range of hydraulic conductivity and transmissivity in a given groundwater body. The selection of wells that met the criteria for aquifer thermal energy storage enabled an initial assessment indicating that the greatest potential for ATES development exists primarily in northern and western Poland, which is in line with the results of the current study and the work presented by Bloemendal (2015). However, key parameters – such as groundwater velocity and potential single well discharge rates – were not considered in that earlier assessment. Encouragingly, the importance of ATES is beginning to be reflected in national policy documents. The technology is now included in the list of *Poland's National Smart Specializations* (pol. *Krajowe Inteligentne Specjalizacje – KIS*) under the thematic area of sustainable energy systems. Furthermore, development of ATES technology appears in the Multi-year *Program for the Development of the use of Geothermal Resources in Poland* (2021) (pol. "*Wieloletni program rozwoju wykorzystania zasobów geotermalnych w Polsce*") as a technology to be supported by the government during the next 15 years. This strategic document – commonly known among Polish geoengineers and policymakers as the "Geothermal Development Roadmap" – includes PLN 159 million (about EUR 38 million) that the government plans to allocate to subsidize the construction of ATES installations in Poland by 2040. However, at the request of the Ministry of Climate and Environment, this document will be revised in early 2026, so it can be expected that other funding amounts will be provided then. These inclusions mark a positive institutional signal that ATES is being increasingly recognized not only as a technological opportunity but also as a strategic asset for achieving national and EU-level climate and energy targets.
Recently, a series of thematic maps, including a map aggregating LT-ATES potential into three utility classes, has been published (Konieczyńska et al., 2025).

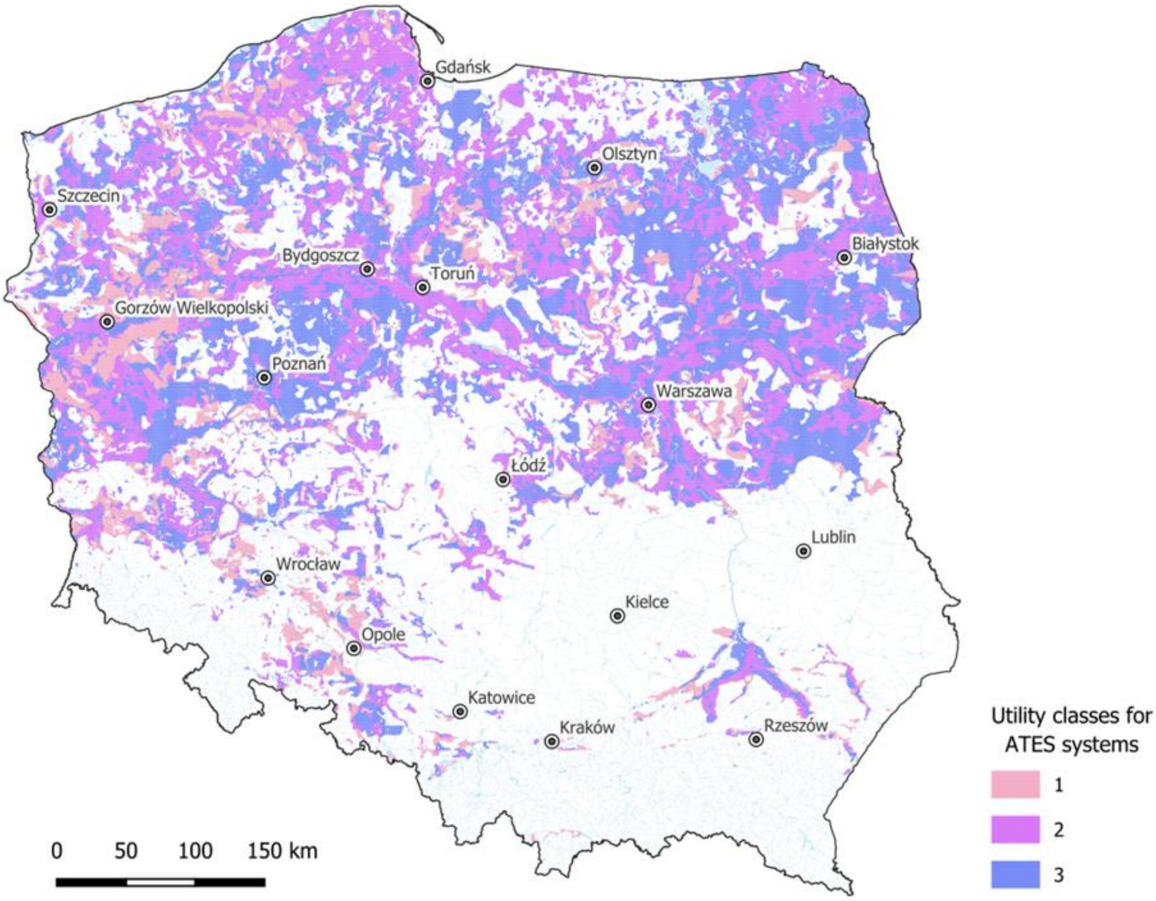


Figure 3. Classification of LT-ATES potential in Poland (1 – for systems up to 175 kW; 2 – for systems above 500 kW; 3 – mixed conditions, power adjustment by installation technical design, based on Konieczyńska et al., 2025)

The spatial distribution of ATES classes within the aquifers analysed showed a heterogeneous, mosaic-like pattern (Figure 3). This reflects the inherent variability in hydrogeological conditions across Poland. The map further illustrates the areas where LT-ATES systems could be initially prioritized for implementation in Poland.

One of the most compelling drivers for future ATES development in Poland is the country's need to decarbonize its heavily coal-dependent heating sector. Rising energy prices, combined with European Union mandates to reduce greenhouse gas emissions, are pushing both policymakers and energy providers to explore renewable and decentralized heat sources. In this regard, high temperature ATES (HT-ATES) could provide an efficient and long-term solution for storing excess heat from solar systems, waste heat from industrial processes, and/or residual heat of geothermal plants for later use in winter, potentially reducing the demand on fossil fuel-based district heating.

Moreover, EU funding mechanisms, such as the Horizon Europe, Interreg, Cohesion Fund programs or research networks such as Geothermica or COST Action are creating new opportunities for the financial and technical support of innovative thermal storage projects. These instruments have already catalysed the development of geothermal and heat storage initiatives in Poland (Table 1) and could be extended to support ATES feasibility studies and pilot projects. The PIG-PIB, along with AGH University of Kraków, MEERI PAS, and others, is increasingly active in energy transition research and could play a central role in adapting ATES models to local geological and climatic conditions and overall technical concerns.

Table 1. European research projects addressing UTES technology (non-exhaustive list)

Acronym	Title	Financing	Web site
PUSH IT	Piloting Underground Storage of Heat In geoThermal reservoirs	Horizon Europe	https://www.push-it-thermalstorage.eu/

ATES-SEUM	Aquifer Thermal Energy Storage for Southern European Urban Markets	Marie Skłodowska-Curie Actions (MSCA)	https://cordis.europa.eu/project/id/101149399
HEATSTORE	High-Temperature Underground Thermal Energy Storage	Geothermica	https://www.heatstore.eu/
NextGen	Towards a next generation of water systems and services for the circular economy	Horizon Europe	https://nextgenwater.eu
SAPHEA	Developing a single access point for the market uptake of geothermal energy use in multivalent heating and cooling networks across Europe	Horizon Europe	https://cordis.europa.eu/project/id/101075510
USES4HEAT	Underground Large-Scale Seasonal Energy Storage for Decarbonized and Reliable Heat	Horizon Europe	https://www.uses4heat.eu;
GeoPLASMA-CE	Shallow Geothermal Energy Planning, Assessment and Mapping Strategies in Central Europe	Interreg Central Europe	https://portal.geoplasma-ce.eu
Geothermal-DHC	Research network for including geothermal technologies into decarbonized heating and cooling grids	COST Action CA18219	https://www.geothermal-dhc.eu/ https://www.cost.eu/actions/CA18219

Despite these opportunities, several barriers continue to hinder the widespread adoption of ATES in Poland. The most critical of these is the absence of a clear legal and regulatory framework for seasonal thermal energy storage in aquifers. Without defined rules governing groundwater rights, thermal injection thresholds, and long-term monitoring obligations, investors and utilities face considerable legal uncertainty. This uncertainty is compounded by the limited awareness and technical experience with ATES among urban planners, heat network operators, and policymakers.

Furthermore, Poland's district heating infrastructure is among the largest in Europe, and remains largely centralized and coal-fired, especially in small and medium-sized towns. According to recent data, coal accounted for about 61.2% of fuel used in district heating in 2023 (URE, 2024). These systems are not yet well-adapted for integration with decentralized thermal storage units such as ATES, which are typically optimized for use at the building or district scale in more flexible networks. Modernization of these systems is ongoing but will require substantial investment and policy reform to create a more open and modular heating market based on low temperature grids. The significant challenge lies in aquifer characterization. Poland's publicly accessible hydrogeological mapping system is not specifically tailored for ATES feasibility. While deep geothermal resource mapping is relatively well developed, it does not provide sufficient data on shallow groundwater flow characteristics, critical for successful ATES system design. This knowledge gap makes it difficult to identify viable sites, and hampers the development of risk assessment protocols.

To address this situation, during 2023-2024 three Polish research institutions including the Polish Geological Institute – National Research Institute (PIG-PIB), the Mineral and Energy Economy Research Institute of the Polish Academy of Sciences (MEERI PAS), and the AGH University of Krakow (AGH University of Krakow), conducted a comprehensive review of available groundwater data to assess the national potential for utilizing freshwater aquifers as storage reservoirs for thermal energy, including both for heat and cold. As an outcome of this work, a Map of Low-Temperature Aquifer Thermal Energy Storage Potential was developed and published, identifying areas across Poland with hydrogeological conditions favourable for ATES implementation (Figure 3). This means that at least one of the aquifers present down to 200 m of depth meets the boundary conditions which make possible to store and deliver enough energy for heating and cooling demand in Poland's climatic zone. The main version of the map is available on https://geologia.pgi.gov.pl/mapy/?page=Podziemne-magazynowanie and contains approximate data on the main ATES favourable aquifer parameters, such as depth, thickness, transmissivity, single well discharge, hydraulic conductivity, groundwater flow velocity and assumed effective porosity used in flow velocity calculations[1]. These values cannot be applied to the scale of individual installations, the proper planning of which will always require detailed site investigation. However, the project outcomes pave the way for further ATES development in Poland. Especially since the project also included a detailed legal system review regarding ATES applications in usable groundwater layers. Many gaps and inconsistencies in the current regulation framework were identified, and proposals for changes and amendments were formulated.

LEGAL ASPECTS OF ATES IN POLAND

Aquifer thermal energy storage is not implemented in the Polish legal system. The only exception is found in the Act of 20 July 2017 - Water Law (consolidated text - Journal of Laws of 2025, item 960) in which "*heat accumulators in aquifers*" are named but not defined. No detailed regulations on the creation and use of such systems are stated, except for charging rules and rates, and possible restrictions presented later in the Discussion: How to Accelerate the Development of ATES Technology in Poland.

The Act of 9 June 2011 - Geological and Mining Law (consolidated text - Journal of Laws of 2024, item 1290) introducing special regulations for "*the use of the Earth's heat*", with no definition of its meaning, caused confusion as regards which administrative procedure is valid for use of groundwater for thermal energy storage and use. Thermal energy storage, though possible in aquifers and with direct use of groundwater as the energy carrier, is not considered as a hydrologeology-related issue in this Act, which causes inconsistences with administrative procedures required by the Water Law.

A lack of definition for thermal energy storage, including underground tankless heat storage, groundwater returned intake, and not including heat storage in renewable energy source installations, are only some further legal problems identified within the extensive European and Polish regulations relevant and needed for ATES systems development in Poland.

Given the current legal uncertainties and the lack of detailed regulations regarding ATES implementation in Poland, it is crucial to assess the broader potential and limitations of this technology. A structured SWOT analysis provides a useful framework to identify the strengths, weaknesses, opportunities and threats associated with LT-ATES in the Polish context. This analysis aims to support strategic decisions for its development, considering both the nascent legal framework and the country's pressing energy and environmental challenges.

SWOT ANALYSIS OF LT-ATES IN POLAND

The origins of SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis trace back to the mid-1960s research at the Stanford Research Institute, where Robert Franklin Stewart and his colleagues developed the SOFT approach (Satisfactory, Opportunity, Fault, Threat), a precursor to SWOT, as part of long-range strategic planning efforts. Although Albert S. Humphrey (2005) later popularized the terminology within management practice, archival research identifies Stewart as the originator of the conceptual framework that evolved into the modern SWOT categorization (Puyt et al., 2023).

A SWOT analysis is a strategic assessment framework originally developed in organizational and business studies to systematically evaluate internal strengths and weaknesses alongside external opportunities and threats. In energy and technology studies, it is widely used to support structured decision-making by identifying key factors that influence the feasibility, risks and development pathways of emerging solutions.

For the purposes of this article, the concept of SWOT analysis has been adopted to systematically assess the potential of LT-ATES in Poland's heating and cooling sector, considering technological, regulatory and market-related factors. In this paper, the categories are defined as follows: "Strengths" refer to internal attributes of LT-ATES that enhance its adoption and performance; "Weaknesses" denote internal limitations or barriers inherent to the technology or its deployment context; "Opportunities" comprise external conditions or trends that could facilitate the expansion of LT-ATES; and "Threats" encompass external challenges, risks or obstacles that may hinder its development. This structured approach allows for a comprehensive evaluation of LT-ATES, highlighting both the potential benefits and the constraints within the Polish context.

Despite the country's growing interest in renewable and low-carbon energy systems, the Polish market for underground thermal energy storage remains poorly developed. Conventional district heating systems, still largely dependent on fossil fuels, struggle to meet increasing energy efficiency and decarbonization requirements set by the European Union. Consequently, there is an urgent need to identify and evaluate innovative technologies that can enhance the operational flexibility, sustainability and resilience of heat supply systems.

[1] more in Konieczyńska et al., 2025

ATES represents one of the most promising yet underutilized solutions capable of transforming the way thermal energy is managed. By enabling the seasonal storage of heat and cold within aquifers, ATES can significantly improve the efficiency of district heating networks and integrated energy systems, allowing for better use of waste heat and renewable sources. However, the implementation of such systems in Poland is constrained by technical, legal and economic barriers, as well as by a general lack of awareness and experience in this field.

The purpose of conducting a SWOT analysis was therefore to comprehensively evaluate the strengths, weaknesses, opportunities and threats associated with the deployment of LT-ATES technology under Polish conditions (Table 2). The analysis aims to support decision-makers, planners and investors in understanding both the potential and the limitations of this technology, and to identify the measures necessary for its broader adoption. In the context of energy transition, increasing energy efficiency, and the modernization of district heating, ATES could play a strategic role in achieving national and European climate goals.

Table 2. SWOT assessment of LT-ATES development in Poland

<table>
<tr><th colspan="2">Internal Factors</th></tr>
<tr><th>Strengths</th><th>Weaknesses</th></tr>
<tr><td>• Energy efficiency: The technology enables effective use of waste heat and the storage of thermal energy from renewable sources.
• Scalability: LT-ATES systems can be adapted to various needs, from local district heating networks to large individual buildings.
• Environmental benefits: Reduction of CO_2 and other air pollutants through decreased demand for fossil fuels and lower primary energy use during peak heat demand periods.
• Low operational costs (OPEX): Once operational, ATES systems involve relatively low maintenance costs. Automated operation and the lack of fossil fuel consumption during storage and recovery reduce expenses.
• Short payback period (<10 years) as the installation scale increases[2].
• Reduction of grid load: By storing surplus heat and cold, LT-ATES systems can help reduce stress on the energy grid during peak demand periods.</td><td>• High initial costs (CAPEX): Geological and hydrogeological surveys, system design, modeling, and construction of LT-ATES installations are capital-intensive.
• Technological risk: Potential adverse changes in aquifer permeability (natural or induced by improper operation) may negatively impact system efficiency.
• Limited experience: In Poland, the technology is still relatively unknown, with a small number of specialists and contractors experienced in ATES system optimization and energy design.
• Regulatory complexity: The lack of dedicated regulations and an inconsistent legal framework make the investment process complicated and time-consuming.
• Complex water use pricing system.
• Instability of aquifer resources: Aquifers in Poland are often unstable or limited in availability, which may hinder implementation.</td></tr>
<tr><th>Opportunities</th><th>Threats</th></tr>
<tr><td>• Rising importance of renewable energy: EU energy transition goals promote technologies that enhance energy efficiency and reduce emissions.
• Inclusion of LT-ATES in the "Long-Term Program for the Development of Geothermal Resource Utilization in Poland" and in the National Smart Specializations (KIS), enabling access to funding for pilot projects.
• Financial support: Availability of national and EU grants for the development of energy storage technologies, including LT-ATES.</td><td>• Geological and hydrogeological conditions: Considerable variation in these conditions across Poland may limit ATES applicability.
• Lack of awareness: Insufficient knowledge levels among policymakers and society may slow down technology deployment.
• Technological competition: Development of alternative energy storage technologies, such as thermal batteries (PTES[3], BTES[4], HWTs[5], TCS[6]) and other heat storage systems.
• Technical challenges: Possible clogging of wells and heat exchange installations may significantly reduce LT-ATES system</td></tr>
</table>

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[2] Based on the experience from countries with mature ATES market (Herrmann et al. 2026, Schüppler et al. 2019, Fleuchaus et al. 2018)
[3] Pit Thermal Energy Storage
[4] Borehole Thermal Energy Storage
[5] Hot Water Tanks
[6] Thermochemical Heat Storage

• Growing demand for green heat: Driven by decarbonization requirements in the heating sector (e.g., EU Energy Efficiency Directive – EED), need for innovative solutions such as ATES. • Support for local energy independence and integration with smart energy networks: LT-ATES can become part of smart grids, optimizing thermal and electrical energy management within integrated systems. It can be combined with heat pumps, waste heat sources, solar heat collectors, and theoretically, photovoltaics or wind energy, enhancing system efficiency.	efficiency and, in severe cases, result in complete operational failure. • Political unpredictability: Changes in energy policy and regulation may affect investment profitability. • Economic factors: Costs associated with thermal energy used in such systems.
External Factors	

DISCUSSION: ACCELERATING THE DEVELOPMENT OF ATES TECHNOLOGY IN POLAND BASED ON SWOT ANALYSIS

The analysis of strengths, weaknesses, opportunities and threats associated with ATES technology highlights both the considerable potential of this solution and the numerous challenges hindering its widespread implementation in Poland. To enable stable development of ATES systems, coordinated actions are required across several key areas: policy, regulation, financing, education, and technical capacity building.

1. Strengthening Policy and Regulatory Support

The effective deployment of ATES systems in Poland faces several barriers, including high initial investment costs, technological uncertainties, and a lack of regulatory clarity. These challenges are further compounded by limited national experience, a complex system of payments for water usage, and variable hydrogeological conditions that restrict suitable locations. Therefore, strengthening policy and regulatory support is essential to create a more favourable environment for ATES development, reduce investor risk, and accelerate the integration of this technology into Poland's heating and cooling sector. This will be achieved only with:

- Development of legal and technical guidelines tailored for ATES systems, clearly defined permitting framework, monitoring requirements, and environmental safeguards.
- Introduction of ATES into national and regional energy strategies, such as *district heating modernization programs* and *local energy transition plans*.
- Enhanced integration of ATES within long-term geothermal and renewable energy development policies, including the *Long-Term Program for the Development of Geothermal Resources in Poland* and the *National Smart Specializations (KIS)*.

Based on the SWOT analysis and a dedicated national project commissioned by the Ministry of Climate and Environment, the main gaps and inconsistencies identified in the legal system relate to the absence of clear legal definitions of ATES and underground thermal energy storage in general, ambiguities in administrative procedures governing groundwater pumping and reinjection for thermal purposes, and inconsistencies between water law, geological regulations, and renewable energy frameworks. These gaps create uncertainty regarding permitting procedures, environmental responsibility, and the acceptable use of productive (including drinking-water) aquifers for thermal energy storage, which discourages both researchers and potential investors. Proposed changes include introducing explicit legal definitions of ATES and LT-ATES, clarifying permitting procedures, harmonising groundwater protection and energy regulations, and providing guidance on acceptable temperature thresholds and monitoring requirements for aquifer-based storage. Although these regulatory barriers and proposed amendments have been formally identified and are currently under procedural consideration, detailed documentation cannot yet be disclosed for formal reasons.

Nevertheless, outlining these issues and directions for change is highly relevant for the international community, as similar legal and institutional challenges have been reported in other countries at an early stage of ATES deployment. Including this discussion strengthens the SWOT analysis and provides transferable insights for policymakers, developers, and researchers working on ATES implementation beyond Poland.

Clear and supportive regulation would not only reduce investment uncertainty but also encourage municipalities and private investors to consider ATES as a viable component of sustainable energy systems.

2. Expanding financial incentives and pilot projects

High initial capital expenditure (CAPEX) remains one of the strongest deterrents for investors. Therefore, it is crucial to:

- Establish dedicated funding mechanisms and grant programs at least at the national level (EU level highly recommended) to support feasibility studies, pilot installations and demonstration projects.
- Provide preferential loans or tax incentives for investments integrating ATES with renewable heat sources or heat pumps.
- Encourage public–private partnerships (PPP) that can share financial and operational risks between local governments, energy companies and research institutions.
- Consider abolishing charges for the use of groundwater for energy purposes under a full reinjection regime.

Successful pilot projects would showcase the practical benefits of ATES and build investor confidence, paving the way for broader adoption across Poland. To maximize their impact and ensure technical success, such pilots should be in areas with favourable hydrogeological conditions that allow stable and efficient system operation. One promising example is the Kościerzyna moraine island. According to Lemoine (2020), this area offers good potential for seasonal heat and cold storage, with several-megawatt cooling capacity possible under appropriate engineering conditions. Other potential pilot locations could also be considered. Urban areas, preferably those with small or medium-sized district heating networks, where integration with ATES would be technically and economically feasible, could prove to be the best option. The selection of such sites is now possible based on the recently completed national project led by the Polish Geological Institute – National Research Institute (PGI-NRI, 2024).

3. Building knowledge and technical capacity

Limited experience and a shortage of specialists remain challenges for the development of the Polish ATES market. While Polish experts have extensive experience with ground-source heat pump systems (GSHP), their practical knowledge of large-scale groundwater-based energy storage and extraction systems is still relatively limited. To address this, actions should include:

- Establishing training programs and certification schemes for engineers, hydrogeologists and HVAC designers focused on ATES design, operation, and maintenance.
- Promoting academic–industry collaboration to conduct applied research, model performance under Polish geological conditions, and develop optimization tools.
- Raising public and decision-maker awareness through targeted communication campaigns, conferences, and demonstration events emphasizing the environmental and economic benefits of ATES.

These measures would help to professionalize the market and ensure high-quality system design and operation, reducing the risk of technical failures.

4. Leveraging synergies with renewable and smart energy systems

ATES technology can become a strategic component of integrated, low-carbon energy systems if properly connected with other renewable technologies. The following steps are recommended:

- Promote hybrid solutions combining ATES with heat pumps, solar heat collectors, photovoltaic installations and waste heat recovery.
- Integrate ATES into smart grid, smart city initiatives and energy communities, allowing for better balancing of energy demand and supply.
- Encourage the use of ATES for district heating decarbonization, where stored renewable heat can supplement or replace fossil-fuel-based sources.

Such integration would maximize energy efficiency and contribute to national goals of carbon neutrality and energy independence.

5. Managing geological, environmental and technical risks

In many regions, groundwater levels fluctuate significantly, and the permeability or hydraulic connectivity of aquifers can vary over time (Guzy et al., 2025; Krogulec et al., 2022; Miecznik and Skrzypczak, 2019). Such hydrogeological variability may limit the capacity of the system to store and recover heat effectively. Consequently, these conditions can hinder large-scale implementation of ATES technologies and require detailed local assessments before deployment.

Given the variability of geological and hydrogeological conditions in Poland, careful site selection and monitoring are essential. Authorities should:

- Create a nationwide register of underground thermal energy storage facilities with operational parameters to prevent overuse of resources and provide data for mapping the actual conditions for subsurface thermal energy storage.
- Establish standards for system design and groundwater protection, including requirements for sealing, monitoring and remediation where necessary.

- Support research on adaptive system design for different geological settings, including shallow and medium-depth aquifers.

This approach would minimize environmental risks and improve confidence in the long-term stability of ATES operations.

Managing geological, environmental, and technical risks in ATES systems extends not only to design and operation aspects but also to the protection of groundwater resources, including those classified as mineral waters under Polish law. The storage of heat and cold in aquifer systems represents a direct interaction with the groundwater environment, as the aquifer itself serves as the storage space, while groundwater acts as the energy carrier. Due to the obligation to protect groundwater resources, it is recommended that any system using them directly should be designed sustainably, meaning that water withdrawn from the aquifer must be fully re-injected into the same aquifer. Withdrawals of water, especially significant ones, for purposes other than heat exchange should, if necessary, take place outside the storage zones, where water retains its natural temperature and chemical equilibrium with the aquifer material. For this reason, ATES systems should not be located in groundwater recharge zones of existing or planned drinking water intakes.

The Water Law (consolidated text - Journal of Laws of 2025, item 960) in Article 130 has already foreseen a possibility for the prohibition or restriction of activities involving the siting of heat pumps and aquifer heat storage systems within the protection zones of groundwater intakes, due to the risk of compromising the *"suitability of the captured water or the efficiency of the intake."* According to Article 140, such prohibitions to protect water from degradation may also be established in protected areas defined under Article 139, i.e., those established under local laws. It should be assumed that such restrictions must result from local aquifer use conditions and justified concerns that, in these circumstances, ATES systems could adversely affect groundwater quality or resources.

In addition, managing ATES-related risks must take into account reservoirs of medicinal or thermal waters, which are legally considered mineral deposits and should maintain stable chemical composition and physical properties, including temperature. It is therefore highly unlikely that low-temperature storage systems in usable aquifers could negatively impact such waters, which are mostly found at depths greater than 200 m b.g.l., i.e. the boundary depth assumed for LT-ATES. Waters located at shallower depths in Inowrocław, Kołobrzeg, Świnoujście, Wieniec-Zdrój, and Kotowice are already covered (except for the last one) by extraction licenses and are designated as mining areas reserved for geothermal or therapeutic water exploitation. Any drilling within these areas requires the approval of the relevant mining authority following an assessment of the project's potential impact on the deposit. Such approval should not be granted if the planned works could threaten the stability of the chemical composition and/or temperature of the exploited waters.

Thus, managing geological and technical risks in ATES development must integrate not only technical and environmental safeguards but also the legal framework for groundwater and mineral water protection, ensuring that energy storage systems are developed sustainably and without compromising Poland's valuable subsurface water resources.

Managing geological and technical risks in ATES systems also requires addressing potential threats to system performance, among which clogging of installations used for storing and recovering thermal energy from aquifers is one of the most critical. This process can gradually reduce system efficiency and, in severe cases, lead to operational failure. Clogging mechanisms are typically divided into biological, chemical and physical types (Baveye et al., 1998; Vandevivere and Baveye, 1992), which often occur simultaneously and interact with one another. Temperature variations influence the solubility of mineral phases and can trigger precipitation of solids, particularly when redox (oxidation–reduction) conditions change. These processes increase the risk of clogging in surface heat exchangers and around well screens, especially during the early stages of system operation. Over time, as ATES systems circulate the same groundwater, the risk of precipitation tends to decrease; maintaining isolation from atmospheric oxygen helps preserve the groundwater natural redox potential and prevent the formation of less soluble mineral phases. The installation of surface filtration units can further protect the well screen zones and extend the system's lifetime.

Additionally, other forms of subsurface and groundwater use, such as the development of new water intakes, mine or construction dewatering systems, or nearby closed-loop borehole thermal energy storage (BTES) installations – may alter the local hydraulic regime and negatively affect ATES performance. Therefore, again, it is essential to maintain a comprehensive national register/database of all underground thermal energy storage and utilization systems to support coordinated planning and minimize the risk of hydraulic or thermal interference between installations.

CONCLUSIONS

Aquifer Thermal Energy Storage (ATES) represents a technologically mature and scalable solution for sustainable heating and cooling, with demonstrated success across northern and western Europe. Its integration into smart urban infrastructures, hybrid thermal networks, and carbon-neutral energy planning has shown substantial environmental and economic benefits. In Poland, however, the market for ATES remains at an early stage of development, constrained by a combination of regulatory ambiguity, technical barriers, and limited institutional experience.

The nationwide assessment of ATES potential in Poland should be regarded as indicative and cannot replace detailed local evaluations. Each installation requires a site-specific analysis of geological and hydrogeological conditions, as hydrodynamic and hydrochemical factors have a decisive influence on both the efficiency and long-term stability of the system. Sustainable operation requires the full re-injection of groundwater and careful site selection to protect water quality and avoid interference with drinking water sources. In regions where natural aquifer properties are less favourable, advanced technical measures, such as controlled recharge strategies, improved well design, or adaptive monitoring systems, may be necessary to ensure sustainable operation.

The SWOT analysis conducted for the Polish context highlights both the strategic opportunities and the existing limitations of ATES development. Among the most significant strengths are the technology's high energy efficiency, scalability, and environmental benefits, particularly the potential to reduce CO_2 emissions and lower primary energy consumption in heating networks. Conversely, weaknesses such as high initial investment costs (CAPEX), regulatory complexity, and the scarcity of specialized expertise currently impede progress. External factors further influence market dynamics: while growing demand for renewable heat and EU decarbonization policies create favourable opportunities, geological variability, low public awareness, and competition from alternative storage technologies pose continuing threats and challenges.

To foster intensive ATES deployment in Poland, a coordinated approach is required. Establishing clear and standardized permitting frameworks, improving the national mapping and classification of aquifer resources, and supporting large-scale demonstration projects would provide the empirical foundation for market confidence and policy formulation. At the same time, education and training programs for engineers, hydrogeologists and system designers are essential to build technical capacity and ensure high-quality implementation. Financial incentives, such as grants, low-interest loans, and Public-Private Partnerships (PPPs), could further alleviate the capital intensity of initial projects.

To overcome these challenges, Poland will need to: undertake a multi-pronged strategy, similar to the one launched at the end of 2021 for geothermal energy, to establish a regulatory environment conducive to subsurface thermal storage; invest in hydrogeological surveys and digital aquifer databases; incentivize early-stage ATES demonstration projects; and integrate ATES into the broader goals of the Clean Air Programme and the National Energy and Climate Plan.

Ultimately, the effective adoption of ATES in Poland could play an important role in achieving national and European energy transition goals. By enhancing the flexibility and efficiency of district heating systems, strengthening local energy security, and reducing environmental impacts, ATES offers a credible pathway toward low-carbon and resilient urban energy systems. The integration of ATES with heat pumps, renewable energy sources and smart grids would also contribute to the broader vision of sustainable urban development, supporting both environmental protection and long-term public health benefits. In line with PEP2040, which emphasizes modernization of distribution infrastructure, the promotion of heat storage technologies, and the shift toward low-emission heating systems, ATES deployment fits squarely within Poland's strategic energy transformation agenda. With its natural advantages and growing institutional interest, Poland has the potential to become a regional leader in ATES, but only when the appropriate legal, financial and technical pathways are established.

Resource-related and other technical aspects, together with the identification of prospective locations, will be addressed in future research and presented in a subsequent scientific publication.

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