ISSN 2720-3581

AGH

JOURNAL OF GEOTECHNOLOGY AND ENERGY

FORMERLY AGH DRILLING, OIL, GAS

2025, vol. 42, no. 4

WYDAWNICTWA AGH

KRAKÓW 2025

ISSN 2720-3581

JOURNAL OF GEOTECHNOLOGY AND ENERGY

FORMERLY AGH DRILLING, OIL, GAS

2025, vol. 42, no. 4

WYDAWNICTWA AGH

KRAKOW 2025

The “Journal of Geotechnology and Energy” (formerly “AGH Drilling, Oil, Gas”) is a quarterly published by the Faculty of Drilling, Oil and Gas at the AGH University of Krakow, Poland. Journal is an interdisciplinary, international, peer-reviewed, and open access. The articles published in JGE have been given a favorable opinion by the reviewers designated by the editorial board.

Editorial Team

Publisher

AGH University Press

Linguistic corrector: *Aeddan Shaw*
Technical editor: *Kamila Zimnicka*
Desktop publishing: *Munda*
Cover design: *Paweł Sepielak*

ISSN: 2720-3581
DOI: https://doi.org/10.7494/jge

Journal website: https://journals.agh.edu.pl/jge

Wydawnictwa AGH (AGH University Press)
al. A. Mickiewicza 30, 30-059 Kraków
tel. 12 617 32 28, 12 636 40 38
e-mail: redakcja@wydawnictwoagh.pl
www.wydawnictwo.agh.edu.pl

CONTENTS

Journal of Geotechnology and Energy | vol. 42 | no. 4 | 2025 | pp. 5–10

https://doi.org/10.7494/jge.2025.42.4.7715

ARTICLE

Elżbieta Halaj

AGH University of Krakow,
Faculty of Geo-Data Science, Geodesy, and Environmental Engineering, Poland
ORCID: 0000-0002-2411-3865
e-mail: ehalaj@agh.edu.pl

PRELIMINARY COMPARATIVE ANALYSIS OF UNDERGROUND THERMAL ENERGY STORAGE, SHALLOW AND DEEP GEOTHERMAL ENERGY SOLUTIONS FOR SUSTAINABLE DISTRICT HEATING IN POLAND

Date of submission:
26.10.2025

Date of acceptance:
13.11.2025

Date of publication:
31.12.2025

https://journals.agh.edu.pl/jge

Abstract: This paper explores shallow and deep energy technologies supporting Poland's district heating transition, focusing on aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), deep geothermal energy, and energy piles. Heating accounts for a major share of energy consumption and emissions in Poland, where district heating networks are essential for urban energy supply. National policies promote renewable energy integration and energy security, presenting opportunities for geothermal and underground thermal storage solutions. ATES and BTES offer seasonal heat storage by cycling thermal energy in subsurface aquifers and boreholes respectively, balancing variable heat demand and renewable supply. Deep geothermal energy provides stable base-load heat via extraction from deep reservoirs, contributing reliable renewable heat despite requiring significant investment and geological specificity. Energy piles represent an innovative technology, combining building foundation piles with embedded heat exchangers, enabling efficient ground heat use for heating and cooling without additional land or deep drilling. This method is especially suited for urban environments and contributes to cost-effective decarbonization. The paper compares technical principles, geological conditions, performance, economic and environmental aspects of these technologies, highlighting their complementary roles in enhancing heat network flexibility, efficiency, and sustainability. The findings inform strategic planning and policy development to optimize Poland's renewable heat infrastructure, supporting climate targets and energy independence for widespread adoption.

Keywords: underground thermal energy storage, geothermal energy, energy piles, district heating Poland

1. Introduction

Heating constitutes a significant portion of energy consumption and emissions in Poland, with district heating networks playing a vital role in urban energy supply. The integration of underground thermal energy storage and renewable heat sources is essential for improving flexibility, continuity, and sustainability.

The proposal of the *National Energy and Climate Plan 2030* [1] with a perspective until 2040 includes, among others:

- improving the country's energy security through the gradual independence of the sector from the purchase of fossil fuels and the use of local RES (renewable energy sources) deposits and waste heat,
- diversification of heat generation technologies in the district heating system and their adaptation to local conditions,
- development of heat storage in the district heating system,
- ensuring access to the power grid for heat pumps,
- lowering the temperature parameters of district heating networks.

These create significant opportunities for advancing geothermal technologies and underground thermal energy storage systems. Geothermal technologies utilize the earth's natural heat, offering a reliable and sustainable energy source that can reduce dependence on fossil fuels. Moreover, underground thermal energy storage allows excess heat to be stored during periods of low demand and then retrieved when needed, improving energy efficiency and grid stability. Together, these technologies can support local energy independence, lower emissions, and contribute to meeting climate goals.

ATES and BTES provide seasonal heat storage solutions that help balance fluctuating heat demand and renewable supply, whereas deep geothermal energy offers direct, base-load heat from the Earth's crust. Energy piles complement these technologies within foundation piles, allowing buildings to efficiently harness ground heat for seasonal heating and cooling without additional land use or deep drilling. Understanding the comparative advantages, limitations, and site-specific feasibility of these technologies can guide strategic planning for Poland's evolving heat infrastructure.

The paper compares technical principles, geological conditions, performance, economic and environmental aspects of these technologies, highlighting their complementary roles in enhancing heat network flexibility, efficiency, and sustainability.

2. Results and discussion

Aquifer thermal energy storage (ATES) is a technology that stores and recovers thermal energy by using subsurface aquifers – naturally occurring underground water-bearing layers. It works by extracting groundwater during one season, usually summer, where the water absorbs heat (cooling buildings or industrial processes) and then injecting this heated water back into the aquifer to store the thermal energy (Fig. 1). In the opposite season, typically winter, the process reverses by extracting the warm groundwater through wells to provide heat, often coupled with heat pumps, while reinjecting cooler water back into the system.

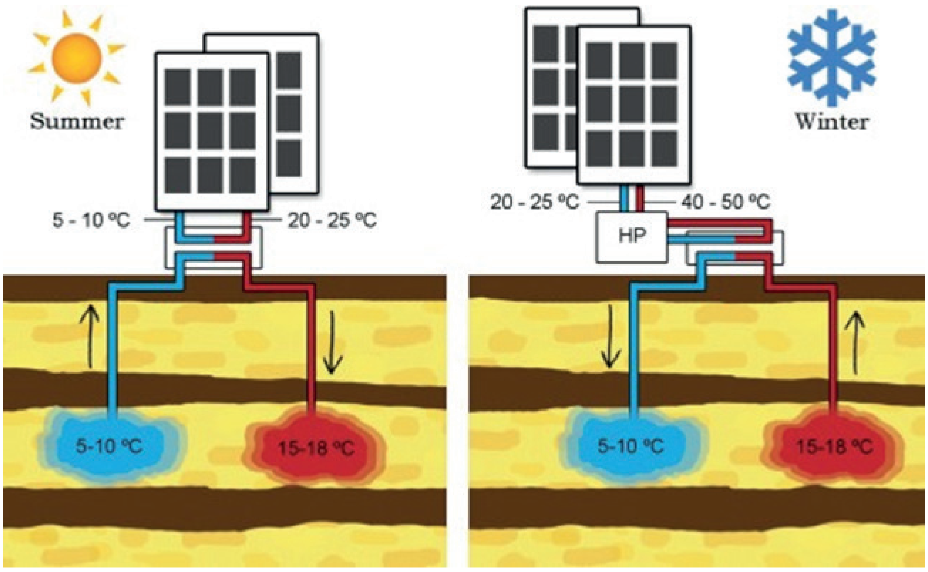


Fig. 1. The working scheme of a low-temperature seasonal ATES [2]

ATES typically operates seasonally, balancing heating and cooling demands through this cyclic exchange. It is considered an efficient, cost-effective way of reducing reliance on fossil fuels and leading to lower carbon emissions, especially for buildings where heating and cooling make up a large share of energy use. In order to be used in Poland, this technology requires suitable hydrogeological conditions such as permeable aquifers and adequate groundwater quality [3]. ATES systems can achieve higher efficiency than conventional heating and cooling technologies. Originating in Europe and widely adopted therein, ATES is used at over 1,000 sites, delivering sustainable energy benefits by leveraging natural underground thermal storage with minimal net water usage [4].

Borehole thermal energy storage (BTES) is a technology that stores thermal energy in the ground through vertical boreholes drilled into the earth (Fig. 2). These boreholes contain U-shaped pipes through which a heat-transfer fluid (usually water mixed with antifreeze) circulates in a closed loop. The system allows for the injection of excess heat or cold into the ground during periods of low demand and the recovery of this energy when needed, typically providing seasonal storage of thermal energy. This bidirectional system efficiently balances heating and cooling demands over the year.

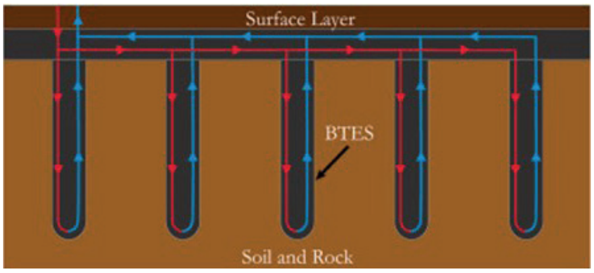


Fig. 2. Schematic illustration of borehole thermal energy storage system [5]

BTES is flexible and can be implemented in areas without specific groundwater conditions because it stores heat in the solid ground rather than relying on aquifers. It is particularly effective for large-scale installations where long-term thermal storage is required, such as district heating systems, where multiple buildings or facilities can benefit from the stored energy. This technology contributes to energy efficiency by enabling use of waste heat, solar thermal energy, or excess heat from industrial processes, thus reducing reliance on fossil fuels, and lowering greenhouse gas emissions [6]. BTES transforms the ground into a natural thermal battery, storing heat or cold for later use and providing a sustainable way to manage seasonal variations in energy demand.

Energy Geostructures (EGs) are one of the most promising shallow geothermal solutions in the built environment. They are deployed by implementing tube heat exchangers in structures such as pile foundations, diaphragm walls, and tunnels, which are in direct contact with the soil to provide heating or cooling by using ground source heat pump [7].

Energy piles are a technology that integrates thermal energy storage within foundation piles constructed in the ground (Fig. 3). These concrete or steel piles contain embedded pipes through which a heat-transfer fluid (such as water with antifreeze) circulates in a closed loop. The system stores heat or cold in the pile structure and the surrounding soil, allowing buildings to use this stored thermal energy for heating or cooling via a connected heat pump. Energy piles enable efficient ground-source energy use without requiring additional land or deep boreholes.

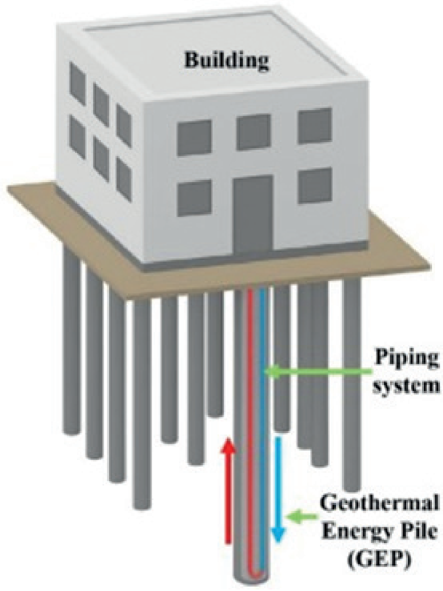


Fig. 3. Schematic view of energy piles [8]

This technology is particularly suitable for buildings that already require foundation piles, combining structural support with thermal energy storage. Energy piles offer a cost-effective and space-saving solution, especially in urban areas where land is limited. They function as seasonal or short-term thermal batteries, helping to balance heating and cooling demands and improve overall energy efficiency. By utilizing the existing foundation system, energy piles reduce installation costs and environmental impact compared to traditional geothermal solutions, contributing to reduced fossil fuel use and lower greenhouse gas emissions.

Geothermal energy is a renewable energy source derived from the heat stored within the Earth's crust. Deep geothermal involves tapping into underground reservoirs of hot water (or steam), usually located several kilometers below the surface. In Poland it is only used to provide space heating. The process begins with drilling wells into geothermal reservoirs, from which hot water is extracted.

These fluids can be used directly for heating buildings, greenhouses, some industrial processes as well as for recreational swimming pools [9]. Some existing boreholes that were drilled for other purposes, such as negative exploration of boreholes or depleted oil wells, are also considered for use as deep borehole heat exchangers [10].

Geothermal heating systems operate continuously, providing a stable and reliable source of energy unaffected by weather or seasonal changes. This makes geothermal energy an excellent solution for steady heating needs. The technology results in very low greenhouse gas emissions compared to fossil fuels, contributing significantly to carbon footprint reduction. Key requirements include suitable geological conditions of permeable rock formations with sufficient heat flow and favorable chemical composition [11, 12].

Technical Principles and Geological Conditions: ATES utilizes natural underground aquifers as thermal reservoirs by injecting and extracting heated or cooled groundwater seasonally. It requires permeable aquifers with sustainable groundwater flow which are locally available in some Polish regions, but also pose challenges in water quality management. BTES stores heat in closed borehole fields where the heat transfer fluid circulates through underground pipes embedded in rock or soil, making it less site-dependent and easier to deploy widely. Energy piles combine structural foundation piles with embedded geothermal pipes, allowing buildings to exchange heat with the ground through the piles themselves, making them adaptable to various geological conditions without compromising structural integrity. Deep geothermal energy exploits the naturally high temperatures at great depths – up to several kilometers deep – where geological structures and heat flow rates determine viability; Poland's low to medium geothermal gradients limit deep geothermal potential mainly to specific regions such as Podhale or the Polish Lowlands.

2.1. Energy storage and supply capabilities

ATES and BTES are primarily seasonal storage technologies capable of storing excess heat during low-demand periods for later use, thus enabling better utilization of renewable and waste heat sources, and reducing peak loads in district heating systems. ATES typically offers higher storage capacity and operational efficiency but has site restrictions. BTES is versatile with moderate storage capacity and fewer hydrogeological constraints. Energy piles may serve a dual role by providing building foundations and acting as heat exchangers for seasonal thermal energy storage, which helps reduce heating and cooling loads efficiently. Deep geothermal energy provides a continuous and stable heat supply independent of surface conditions which is suitable for base-load operations but requires significant upfront drilling investment and risk management.

2.2. Economic and environmental aspects

ATES and BTES systems have moderate capital costs and can be integrated with existing infrastructure, offering cost-effective improvements in energy efficiency and emissions reductions. Deep geothermal involves higher investment but delivers reliable renewable heat with minimal emissions. Environmentally, ATES demands stringent groundwater protection to avoid contamination, BTES operates as a closed system minimizing environmental risks, and deep geothermal options generally lead to low emissions but have potential for induced seismicity and require sustainable reservoir management. By integrating geothermal functionality into structural piles, energy piles reduce installation costs compared to separate systems while promoting renewable energy use and minimizing environmental risks.

2.3. Integration and policy implications for Poland

The complementary use of ATES and BTES with deep geothermal energy can enhance Poland's heat network flexibility, renewable integration, and decarbonization. Energy piles offer a practical and scalable solution for Poland, especially in urban areas or sites unsuitable for traditional geothermal systems, complementing existing underground thermal technologies and supporting decarbonization goals. Existing pilot projects and mapping studies identify suitable sites and technical pathways. Policy support, regulatory frameworks, continuous resource assessment, financial incentives, and public engagement are necessary to advance technology adoption and scale benefits.

ATES and BTES are seasonal thermal storage technologies relying on shallow subsurface conditions and heat pumps, suitable for localized heating and cooling. Deep geothermal provides a continuous and high-temperature energy source ideal for both heat and electricity generation but requires significant investment and specific geology. Energy piles combine structural foundation elements with thermal storage at shallow depths, offering a cost-effective and space-saving solution for building heating and cooling. They are especially suitable where foundation piles are already necessary, enabling efficient ground-source energy use with lower installation costs.

The choice among these technologies depends on local geological conditions, energy demands, available space, and economic considerations.

Table 1 compares four shallow geothermal technologies: aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), energy piles, and deep geothermal energy.

ATES uses groundwater in natural aquifers to store heat and cold within the water itself. BTES, by contrast, stores thermal energy directly in the ground (rocks or soil) without relying on groundwater. Energy piles store heat in concrete foundation piles embedded in the ground, utilizing shallow depths typically between 5 and 30 m. Deep geothermal accesses heat from deep inside the Earth, usually from depths below 1000 m, harnessing naturally occurring high temperatures.

ATES wells are relatively shallow (>10 m), while BTES boreholes range from 30 to 100 m. Energy piles use even shallower depths (5–30 m), integrating thermal harnessing with structural foundation elements. Deep geothermal requires drilling much deeper, often over 1000 m, where temperatures exceed 20°C, compared to the 8–12°C groundwater temperature in ATES, 8–10°C ground temperature in BTES, and similar 8–12°C ground temperature for energy piles.

ATES and BTES are primarily used for seasonal heating and cooling of buildings and require heat pumps to transfer thermal energy efficiently. Energy piles serve heating and cooling needs integrated into building foundations and also require heat pumps. Deep geothermal can provide heating, sometimes needing high-capacity heat pumps depending on the system.

ATES requires permeable aquifers with good groundwater quality. BTES prefers soil where groundwater presence is minimal or absent. Energy piles need soils suitable for pile foundations with good thermal conductivity. Deep geothermal requires suitable permeable rock formations and favorable thermal conditions.

Table 1. Comparison of four thermal energy technologies: aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), energy piles, and deep geothermal energy

Features	ATES	BTES	Energy piles	Deep geothermal
Energy source	Groundwater in natural aquifers	Ground (rocks or soil)	Heat stored in foundation piles in the ground	Heat from inside the Earth
Storage type	Storage of heat and cold in water	Storage of heat (cold) in the ground	Storage of heat in concrete piles embedded underground	Direct use of geothermal heat
Borehole depth	>10 m	30–100 m	Shallow depth, typically 5–30 m	Usually above 1000 m
Initial temperature	Groundwater temperature usually 8–12°C	Ground temperature usually 8–10°C	Ground temperature usually 8–12°C	Temperature depends on location (>20°C)
Application	Heating and cooling buildings, requires heat pump	Heating and cooling buildings, requires heat pump	Heating and cooling buildings, integrated into foundations, requires heat pump	Mainly space heating, sometimes requires high-power heat pump
Geological requirements	Requires suitable aquifers with good permeability	Suitable for various soil types, groundwater presence undesired	Requires soils suitable for pile foundations, good thermal conductivity preferred	Requires suitable layers with good permeability and thermal conditions
Advantages	+ Low operating costs + No water quality impact + Stable energy source	+ Efficient use of energy + Good heat storage conditions + Low CO2 emissions	+ Utilizes existing foundation structures + Lower installation cost compared to deep boreholes + Minimizes additional land use	+ Expandable system + Suitable for large-scale use + Low CO_2 emissions
Disadvantages	- Requires suitable hydrogeological conditions - Requires well drilling - High initial costs	- Needs adequate permits - Less availability in dense urban locations - Requires borehole drilling	- Limited heat storage capacity compared to deep geothermal - Effectiveness depends on pile design and soil conditions	- High initial costs - Requires deep drilling and suitable geology
The prospects for the use in district heating networks in Poland	low	high	low	high

2.4. Advantages

ATES stands out for low operating costs, no water quality impact during proper exploitation, and a stable energy source. BTES benefits from efficient energy use, good heat storage conditions, and low CO_2 emissions. Energy piles utilize existing foundation structures, offer lower installation costs compared to deep boreholes, and minimize additional land use. Deep geothermal is expandable, and suitable for extensive applications.

2.5. Disadvantages

ATES depends heavily on suitable hydrogeological conditions, requires well drilling, and has high initial costs. BTES needs wells and permits. Energy piles have limited heat storage capacity compared to deep geothermal and their effectiveness depends on pile design and soil conditions. Deep geothermal involves the highest initial costs and requires deep drilling in suitable geological formations.

2.6. Prospects for Poland

In 2022 around 82% of primary energy input to district heating systems comes from fossil fuels in Poland [13]. The integration of sustainable and low-temperature heat sources into existing district heating systems decarbonizes the heat supply but requires balancing heat source and network temperatures [14]. Shallow geothermal technologies are one of the most energy efficient and least GHG emitting available alternatives to provide space heating and cooling [15]. Among the listed technologies, the most probable uses in Poland will most likely be BTES (in terms of quantity) and geothermal energy (in terms of installed capacity).

The potential of BTES in Poland can be indicated by the popularity of BHE. Currently, in the PIG database, approximately 1700 objects are registered with BHE [16]. Although this number is not representative and is significantly underestimated this can be considered as of future BTES installations indicator.

The identified demand for seasonal heat storage in district heating systems in Poland is significant [17]. Seasonal thermal energy storage systems, and in particular borehole thermal energy storage (BTES) systems, are a key component in implementing the transition to renewable heat generation [18]. The potential of 5GDHC integrated with borehole thermal energy storage (BTES) can unlock the synergies between heating and cooling via a bidirectional thermal network [19]. According to [20] heat pumps will generate more than half of the heat for district heating systems in Baltic states. Approximately 45 new geothermal drillings (Fig. 4) received funds promises within National Fund for Environmental Protection and Water Management project [21].

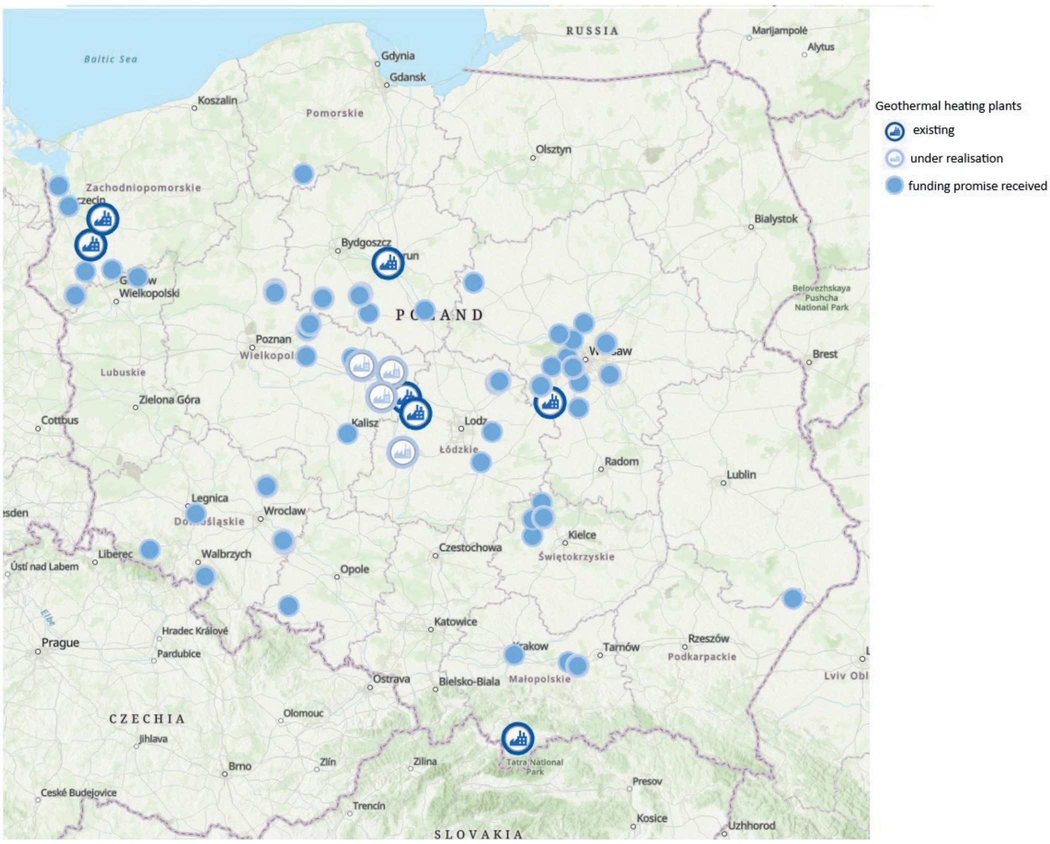


Fig. 4. Locations of existing and planned geothermal heating plant in Poland [21]

This indicates the great degree of interest in the aforementioned technology, especially from local governments. Unfortunately, this technology requires significant investment both during the drilling phase and at the stage of constructing the surface installation. Nevertheless, the variety of possible applications of this technology (district heating, recreation, agriculture, treatment) as well as the experience gained so far create significant potential for its use [22, 23].

ATES technology shows a decrease in capital costs per installed heating and cooling capacity with increasing capacity. Capital costs per installed capacity can be considered 300 €/kW [24]. Despite this, technology is highly dependent on hydrogeological conditions. The PIG report illustrates the potential of this technology in Poland [25]. As research shows, the largest cities in Poland are unfortunately located outside the areas with the best conditions for ATES [26].

Energy piles are a new and emerging technology in Poland. The utilization of dwellings' foundations as ground heat exchanger components has recently demonstrated the potential to generate significant cost reductions primarily attributed to the reduction in expenses associated with drilling and backfill material (grout) [27]. This technology has some potential however in view of the scope of zero-energy and passive buildings, especially considering new solutions and additives like new materials or PCMs [28–30].

Some indication of shifting towards mentioned technologies can be addressed in the Heating Plant of the Future project in Lidzbark Warmiński. In this demonstrative installation, heat pumps are integrated with three ground sources: air heat exchangers, a low-temperature ground storage (BTES), and a high-temperature water storage (PTES). The system is powered by electricity generated directly on-site from hybrid solar thermal collectors (PVT) and a nearby photovoltaic (PV) installation [31].

3. Conclusions

ATES, BTES, energy piles and deep geothermal energy represent critical underground thermal technologies, each with distinct characteristics suitable for Poland's district heating transition. Their strategic combination promises more resilient, efficient, and sustainable heat supply systems aligned with environmental and energy goals. Ongoing research, tailored infrastructure development, and coherent policies will be vital to unlocking their full potential for Poland's sustainable energy future.

Funding: Partial financial support was received from AGH University of Krakow statutory work No. 16.16.140.315/05.

Conflicts of Interest: The author of this paper declares no conflicts of interest.

References

[1] Ministry of Climate and Environment: *National Energy and Climate Plan*. https://www.gov.pl/web/climate/national-energy-and-climate-plan [in Polish: https://www.gov.pl/web/klimat/krajowy-plan-na-rzecz-energii-i-klimatu] [10.11.2025].

[2] Bloemendal M., Hartog N.: *Analysis of the impact of storage conditions on the thermal recovery efficiency of low-temperature ATES systems*. Geothermics, vol. 71, 2018, pp. 306–319. https://doi.org/10.1016/j.geothermics.2017.10.009.

[3] Hałaj E., Pająk L., Papiernik B.: *Simulation study of the Lower Cretaceous geothermal reservoir for aquifer thermal energy storage*. Environ Geochem Health, vol. 44, 2022. https://doi.org/10.1007/s10653-021-01130-7.

[4] Solecki M.L., Wojnarowski P., Wasilewski G., Machowski G., Stopa J.M.: *Possibilities of energy storage in geological structures in Poland*. In: Matematičke Metode i Nazivlje u Geologiji, Zagreb, 2022, https://www.bib.irb.hr/1203784/download/1203784.1203784.Matge [10.12.2024].

[5] Sadeghi H., Jalali R., Singh R.M.: *A review of borehole thermal energy storage and its integration into district heating systems.* Renewable and Sustainable Energy Reviews, vol. 192, 2024, 114236. https://doi.org/10.1016/j.rser.2023.114236.

[6] Ahmed A.A., Assadi M., Kalantar A., Sapińska-Śliwa A., Sliwa T., Ahmed N., Rogozik S.: *Evaluating the techno-economic impact of decarbonizing buildings by using borehole heat exchangers in comparison to fuel-based systems*. Energy for Sustainable Development, vol. 76, 2023, 101262. https://doi.org/10.1016/j.esd.2023.101262.

[7] Rafai M., Salciarini D., Vardon P.J.: *The thermo-mechanical impact of long-term energy pile use*. Renew Energy vol. 244, 2025, 122693. https://doi.org/10.1016/j.renene.2025.122693.

[8] Gholami K., Guo Y., Fan C., Liu W.V.: *Optimizing the layout of geothermal energy piles to minimize ground temperature changes*. Energy and Buildings, vol. 349, 2025, 116569. https://doi.org/10.1016/j.enbuild.2025.116569.

[9] Halaj E.: *Geothermal bathing and recreation centres in Poland*. Environmental Earth Sciences, vol. 74, 2015, pp. 7497–7509. https://doi.org/10.1007/s12665-014-3740-5.

[10] Kunasz R., Śliwa T., Sapińska-Śliwa A.: *The concept of a deep borehole heat exchanger at the AGH University of Krakow Campus*. Journal of Geotechnology and Energy, vol. 42, no. 2, 2025, pp. 15–27.

[11] Halaj E.: *Characteristics and sustainable utilisation prospects of geothermal waters of the Liassic formations in the Mogilno-Lodz Trough, Poland*. Sustain Water Resour Manag, vol. 5, 2019, pp. 1537–1553. https://doi.org/10.1007/s40899-018-0235-7.

[12] Halaj E., Kepinska B.: *Conjunctive uses of the geothermal water resources from Lower Cretaceous formations in the Mogilno–Lodz trough, Poland*. Sustain Water Resour Manag, vol. 5, 2019, pp. 1479–1494. https://doi.org/10.1007/s40899-018-0284-y.

[13] URE: *District heating in numbers – 2022. Report of the Polish Energy Regulatory Office*, 2023, https://www.ure.gov.pl/en/about-us/reports/67,Reports.html [15.10.2025].

[14] Stock J., Schmidt T., Xhonneux A., Müller D.: *Optimisation of district heating transformation for the efficient integration of a low-temperature heat source*. Energy, vol. 308, 2024, 132461. https://doi.org/10.1016/j.energy.2024.132461.

[15] Figueira J.S., García Gil A., Vieira A., Michopoulos A.K., Boon D.P., Loveridge F., Cecinato F., Götzl G., Epting J., Zosseder K., Bloemendal M., Woods M., Christodoulides P., Vardon P.J., Borg S.P., Erbs Poulsen S., Andersen T.R.: *Shallow geothermal energy systems for district heating and cooling networks: Review and technological progression through case studies*. Renew Energy, vol. 236, 2024, 121436. https://doi.org/10.1016/j.renene.2024.121436.

[16] Boniewska K., Szlasa M., Jabłoński J., Plut J., Kutyna M.: *Development of shallow geothermal resource utilization in Poland: comparison of statistics from 2022 and 2023 based on CAG data*. In: *Symposium for Drillers. PORT PC, 18/03/2025*, Warsaw 2025 [unpublished].

[17] Kalina J., Tańczuk M., Jendryasek Ł.: *Planning energy transition and decarbonisation of district heating systems in Poland*. Energy, vol. 328, 2025, 136578. https://doi.org/10.1016/j.energy.2025.136578.

[18] Hagemann W., Weichmann J., Gernandt H., Krenzlin F., Schiffer J.: *Modeling and optimization of borehole thermal energy storage systems using physics-based neural networks*. Renew Energy, vol. 256, 2026, 123753. https://doi.org/10.1016/j.renene.2025.123753.

[19] Li X., Yilmaz S., Patel M.K., Chambers J.: *Techno-economic analysis of fifth-generation district heating and cooling combined with seasonal borehole thermal energy storage*. Energy, vol. 285, 2023, 129382. https://doi.org/10.1016/j.energy.2023.129382.

[20] Volkova A., Koduvere H., Pieper H.: *Large-scale heat pumps for district heating systems in the Baltics: Potential and impact*. Renewable and Sustainable Energy Reviews, vol. 167, 2022, 112749. https://doi.org/10.1016/j.rser.2022.112749.

[21] NFOSIGW: *Providing thermal waters in Poland programme*. www.gov.pl/web/nfosigw/poszukiwanie-wod-termalnych-z-dofinansowaniem-nfosigw [15.10.2025].

[22] Kepinska B., Hajto M.: *Geothermal Energy Use, Country Update for Poland, 2019–2021*. European Geothermal Congress 2022, Berlin 2022, https://www.egec.org/wp-content/uploads/2023/02/20-POLAND-EGC-2022-country-update.pdf [10.12.2024].

[23] Gryszkiewicz I., Socha M.: *Balance and management of thermal water deposits and geothermal energy resources in Poland*, 2024. https://www.pgi.gov.pl/images/wody-mineralne/pliki/bilans_i_zagospodarowanie_zasobw_z_wd_termalnych_oraz_energii_geotermalnej_w_polsce_wg_stanu_na_31.12.2023_r_copy.pdf [10.12.2024].

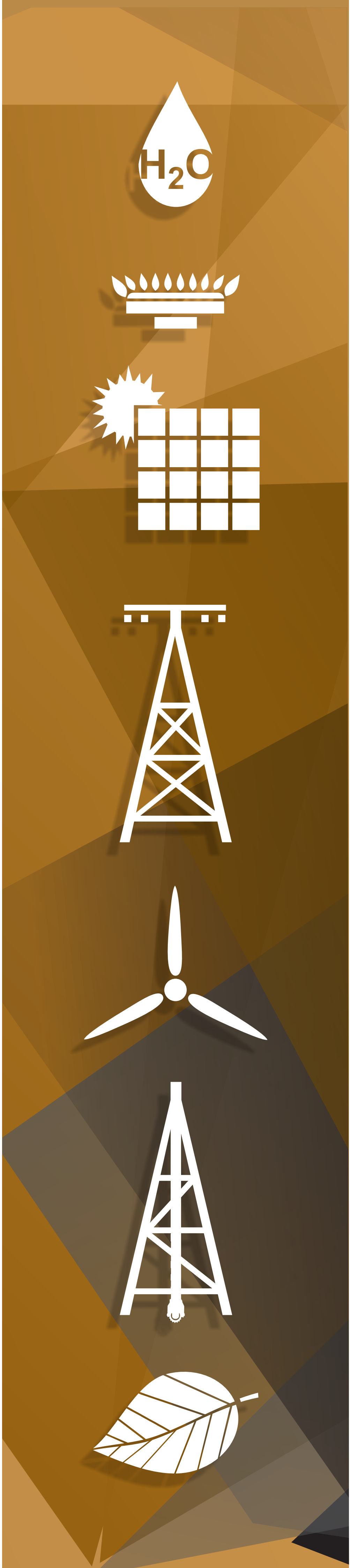
[24] Herrmann M., Fleuchaus P., Godschalk B., Verbiest M., Niemi Sørensen S., Blum P.: *Capital costs of aquifer thermal energy storage (ATES): a review*. Renewable and Sustainable Energy Reviews, vol. 226, 2026, 116202. https://doi.org/10.1016/j.rser.2025.116202.

[25] PGI: *Preliminary assessment of the possibility of storing thermal energy in aquifers in Poland (ATES)*. www.pgi.gov.pl/srodowiskowa/bloki-tematyczne/ates/mapa-potencjalu.html [14.11.2025].

[26] Halaj E., Bloemendal M.: *Possibilities for Aquifer Thermal Energy Storage (ATES) in main Polish cities*. In: European Geothermal Congress 2025, 2025. https://europeangeothermalcongress.eu/wp-content/uploads/2025/11/Halaj-et-Bloemendal.pdf [10.12.2024].

[27] Aresti L., Alvi M.R., Cecinato F., Fan T., Halaj E., Li Z., Okhay O., Poulsen S.E., Quiroga S., Suarez C., Tang A.M., Valancius R., Christodoulides P.: *Energy geo-structures: A review of their integration with other sources and its limitations*. Renew Energy, vol. 230, 2024, 120835. https://doi.org/10.1016/j.renene.2024.120835.

[28] Sliwa T., Sapińska-Śliwa A., Wysogląd T., Kowalski T., Konopka I.: *Strength Tests of Hardened Cement Slurries for Energy Piles, with the Addition of Graphite and Graphene, in Terms of Increasing the Heat Transfer Efficiency*. Energies, vol. 14, no. 4, 2021, 1190. https://doi.org/10.3390/en14041190.
[29] Faraj K., Khaled M., Faraj J., Hachem F., Castelain C.: *Phase change material thermal energy storage systems for cooling applications in buildings: A review*. Renewable and Sustainable Energy Reviews, vol. 119, 2020, 109579. https://doi.org/10.1016/j.rser.2019.109579.
[30] Sharma A., Tyagi V.V., Chen C.R., Buddhi D.: *Review on thermal energy storage with phase change materials and applications*. Renewable and Sustainable Energy Reviews, vol. 13, 2009, pp. 318–345. https://doi.org/10.1016/j.rser.2007.10.005.
[31] *The Heating Plant of the Future project*. cieplowniaprzyszlosci.pl, 2024 [14.11.2025].


H2O