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ARTICLE

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ENHANCING BUILDING ENERGY EFFICIENCY THROUGH THE IMPLEMENTATION OF RENEWABLE ENERGY SOURCES

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Abstract: Considering increasing sustainability requirements and the urgent need to reduce greenhouse gas emissions, improving the energy efficiency of buildings has become a key challenge in the construction sector. One of the most promising approaches involves the integration of renewable energy sources (RES) as alternatives to traditional, high-emission energy systems. This paper presents an analysis of the potential for using RES – such as solar, geothermal, and biomass energy – to enhance the energy efficiency of residential and public buildings. The economic and environmental benefits of implementing modern energy technologies are discussed, along with examples of technical solutions and hybrid system models. Legal, technical, and social aspects related to the implementation of such systems are also considered. The results of the analysis indicate that well-designed and properly managed RES systems can significantly reduce the demand for primary energy and CO_2 emissions while increasing the energy independence of buildings.

Keywords: renewable energy, RES, geothermal energy, wind and solar energy

1. Introduction

Building energy efficiency refers to the reduction of energy consumption while maintaining or even improving the thermal comfort, health, and well-being of occupants. It encompasses the use of advanced building materials, thermal insulation, energy-efficient systems (such as HVAC and lighting), and intelligent building management solutions. Enhancing energy efficiency not only lowers operational costs but also contributes to climate change mitigation and increased energy security.

Renewable energy sources (RES), such as solar, wind, geothermal, biomass, and hydropower, play a crucial role in improving energy performance in buildings. These sources are sustainable, have a low environmental footprint, and significantly reduce greenhouse gas emissions compared to fossil fuels Integrating RES into buildings – through technologies such as photovoltaic panels, solar thermal systems, ground-source heat pumps, or biomass boilers – allows for the partial or complete substitution of conventional energy sources. This integration not only supports decarbonization efforts but also increases the resilience and self-sufficiency of buildings in the face of growing energy demands and fluctuating energy prices [1].

2. Various types of renewable energy sources

Various types of renewable energy sources (RES) are increasingly being integrated into buildings to enhance their energy performance, reduce operational costs, and limit environmental impact. Photovoltaic (PV) systems, which convert solar radiation into electricity, are among the most widely adopted technologies, offering potential reductions in annual electricity bills of up to 70% [2]. These systems are often integrated into rooftops or building facades, sometimes combined with energy storage to increase self-consumption. Heat pumps, which extract thermal energy from the air, ground, or water, provide an efficient and low-emission alternative to traditional heating systems, with coefficients of performance (COP) typically ranging between 3 and 4. They are also capable of providing cooling during summer, making them suitable for year-round energy optimization.

Solar thermal collectors offer another effective solution, primarily for domestic hot water heating. When properly dimensioned and installed, they can meet 60–70% of the annual hot water demand, significantly lowering reliance on conventional energy sources. Biomass systems, using fuels such as wood pellets, firewood, or biogas, are commonly employed in detached houses and rural areas. Compared to fossil fuels, they contribute to a reduction in CO_2 emissions by up to 70%, especially when the biomass is sourced sustainably. Small wind turbines, although more location-dependent, can be highly effective in rural or coastal areas with adequate wind resources, offering energy independence and reducing grid dependence.

Beyond their direct energy benefits, the integration of RES supports climate change mitigation, energy diversification, and long-term economic savings. Additionally, hybrid systems that combine multiple sources – such as PV with heat pumps and battery storage – can enhance resilience and optimize energy use throughout the year. When combined with smart building technologies and energy management systems, RES enable buildings to become nearly zero-energy (nZEB) or even energy-positive, contributing to national and EU climate goals.

3. Benefits of using renewable energy sources

The implementation of renewable energy systems in buildings brings both economic and environmental advantages. One of the key benefits is the **reduction in building operating costs** – investments in renewable energy technologies, such as heat pumps, can typically pay off within 5 to 15 years, depending on the type and scale of the installation. In addition to financial savings, renewable energy sources contribute significantly to **reducing greenhouse gas emissions**. For an average household, modernization involving RES can lower CO_2 emissions by approximately 1–3 tons annually. To illustrate the impact: a conventional home without any renewable energy installations may emit around 4 tons of CO_2 per year, whereas a home equipped with RES technologies can reduce that to as little as 1–2 tons annually [6, 11]. This not only supports household sustainability but also contributes to broader climate change mitigation efforts.

3.1. Improved comfort

Renewable energy systems (RES) such as heat pumps can significantly enhance the thermal comfort of the occupants of buildings. These systems provide stable indoor temperatures throughout the year, regardless of external weather conditions. For example, heat pumps not only offer efficient heating during the winter months but also enable cooling during summer, acting as a versatile all-season solution. This results in improved living conditions and contributes to the overall well-being of residents by maintaining a consistent and pleasant indoor climate.

3.2. Reduced dependence on external energy sources

The implementation of renewable energy systems decreases reliance on conventional energy suppliers and imported fossil fuels. By producing energy on-site – through solar panels or other RES technologies – buildings become more self-sufficient and resilient to fluctuations in energy prices and potential supply disruptions. This independence is especially valuable in times of geopolitical instability or rising energy costs.

3.3. Benefits of using renewable energy sources

According to recent studies [4] integrating RES into buildings leads to a significant reduction in electricity consumption from the grid. One example is the application of photovoltaic (PV) systems:

- before modernization: 100% of electricity consumption sourced from the power grid;
- after modernization: 70% of electricity generated by RES, only 30% drawn from the grid.

This not only translates into lower energy bills but also contributes to reducing the building's carbon footprint. A diagram of the benefits of using RES is presented in Figure 1.

4. Challenges of implementing renewable energy systems

4.1. High initial investment costs

One of the most commonly cited barriers to the adoption of renewable energy systems (RES) are the high upfront costs. While the long-term operational savings are often significant – thanks to lower energy bills and reduced maintenance – many individuals, businesses, or municipalities struggle with the initial capital required for installation. These costs typically include: purchase of equipment (e.g., solar panels, batteries, inverters, heat pumps, or wind turbines), installation services by certified technicians, permits, inspections, and regulatory compliance, potential upgrades to existing infrastructure (e.g., roof reinforcement, new electrical wiring, integration with smart grid systems).

Although financial incentives such as subsidies, tax credits, and low-interest loans are available in many regions, they are not always sufficient to fully offset the investment or may not be accessible to all demographics. This barrier is particularly acute in low-income households or in developing countries, where access to financing is limited. An example of the estimated costs of installation ground-source heat pumps in Poland is presented in Table 1.

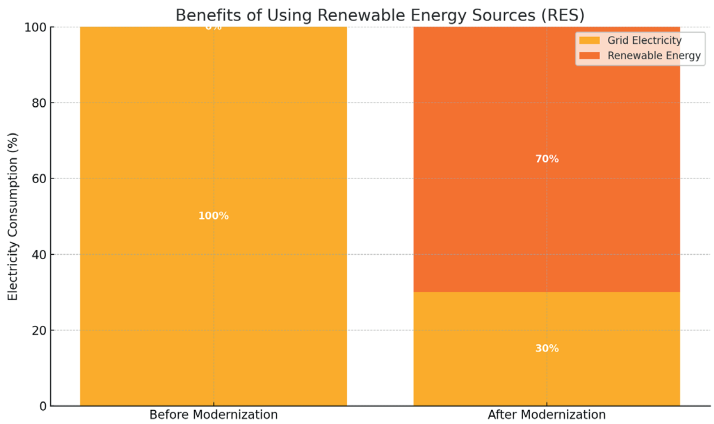

Fig. 1. Benefits of using renewable energy sources [1–3]

Table 1. Estimated installation costs of ground-source heat pumps in Poland (2020–2025) [6–10]

Year	Estimated cost (PLN)	Estimated cost (EUR)	Notes
2020	60,000–90,000	13,000–19,500	Including drilling and installation
2021	60,000–90,000	13,000–19,500	Stable prices
2022	60,000–90,000	13,000–19,500	High demand, no cost increase
2023	60,000–90,000	13,000–19,500	GSHP market growth (+28%)
2024	60,000–90,000	13,000–19,500	Drilling: 160–250 PLN/m
2025	60,000–100,000	13,000–22,000	Slight rise due to inflation

4.2. Technical constraints and location-specific issues

The feasibility of deploying renewable energy systems is highly dependent on the technical characteristics of the building or site, as well as its geographical location. Some of the main challenges include: *limited space availability*: In urban environments, rooftop space may be restricted or shared (e.g., in apartment buildings), making it difficult to install enough solar panels to meet energy demands. *Shading and orientation*: Trees, taller buildings, or structural features can cast shadows on solar installations, reducing efficiency. Additionally, optimal orientation and tilt are needed to maximize sunlight exposure.

Wind turbines require consistent and strong wind speeds to operate efficiently. In cities, wind conditions are often irregular due to obstructions and turbulence caused by buildings.

Some buildings may not be structurally sound enough to support the additional load of solar panels or heavy battery systems without reinforcement.

From the aesthetic side, local regulations or historical preservation codes may limit or prohibit visible modifications to rooftops or facades, especially in culturally protected areas.

In rural areas, while space is generally less of an issue, the lack of grid infrastructure or professional service providers can make installation and maintenance more complicated or expensive.

4.3. Seasonal and weather dependence

Renewable energy production is naturally variable. Solar energy, for example, is highly dependent on sunlight availability, which fluctuates with weather and seasons. This intermittency often requires **energy storage systems** (e.g., batteries) or **hybrid systems** with backup sources to ensure a stable supply – further increasing the overall system cost and complexity.

4.4. Maintenance and technical know-how

Although RES generally require less maintenance than traditional systems, they are not maintenance-free, for example: panels need to be cleaned and occasionally inspected, inverters have a limited lifespan and must be replaced after 10–15 years and battery systems may degrade faster depending on usage patterns.

Furthermore, many users lack the technical expertise to maintain or troubleshoot these systems themselves, necessitating professional services which may not always be locally available.

5. Subsidies and support programs

European Union programs supporting investments in renewable energy sources (RES) offer substantial financial assistance for the modernization of buildings using green technologies. In Poland, well-known initiatives include *Clean Air* (*Czyste Powietrze*) and *My Electricity* (*Mój Prąd*) [3, 5] and the others, which provide grants and rebates for installing solar panels, heat pumps, and improving energy efficiency. Table 2 presents a comparison of the main renewable energy funding programs available to households in Poland, including the scope of support, maximum funding amounts, and key eligibility criteria.

Table 2. Support programs for renewable energy in Poland (2025) [3, 5]

Program name	Eligible measures	Support level	Timeline / Notes
Mój Prąd 6.0	PV systems, battery storage, energy management systems, EV chargers	Up to PLN 16,000 per household	Open from Sep 2, 2024, to Aug 2, 2025, or until funds are depleted. Expanded scope beyond solar panels.
Czyste Powietrze 2025	Heat pump installation (non-gas), boiler replacement, insulation, building modernization	Up to PLN 170,000 (tiered by income)	Relaunched Mar 31, 2025. Requires energy audit and excludes gas systems.
Moje Ciepło	Heat pumps (air-to-water, ground-source), hybrid systems	Varies by technology and household income	Ongoing program under NFOŚiGW. For newly built, energy-efficient homes.
Ulga Termo-modernizacyjna	All RES-related upgrades and thermal modernization	Tax deduction up to 53,000 PLN per owner	Permanent income tax relief for single-family homeowners. Stackable with grants.
Energia dla Wsi	Rural RES installations, community cooperatives, agricultural buildings	Depends on project scope and location	Active from Feb 3 to Dec 19, 2025. Focus on rural energy autonomy.
BGK TERMO	Multi-family building RES systems (collective PV, heat pumps)	Covers up to 50% of net investment	For housing cooperatives, communities, and managers. Managed via BGK bank.

In addition to direct subsidies, tax incentives also play a significant role. Homeowners and building owners may deduct the costs of RES investments from their income taxes, making such projects more accessible and financially attractive.

The process of applying for funding to install renewable energy sources (RES) in Poland – such as photovoltaic systems, heat pumps, or energy storage – begins with selecting the appropriate support program, such as *My Electricity* (*Mój Prąd*), *Clean Air* (*Czyste Powietrze*), or *My Heat* (*Moje Ciepło*). The choice depends on the type of planned investment, the condition of the building (new or undergoing renovation), and the household's income level. The applicant then prepares the complete documentation, which typically includes the application form, a cost estimate, invoices or contractor offers, documents confirming property ownership, and in some cases, an income certificate as well as an **energy audit of the building**. The energy audit is particularly required in programs such as *Clean Air*, especially when applying for higher levels of support or when the investment involves comprehensive thermal modernization. Its purpose is to assess the energy efficiency of the building before the upgrade and to recommend optimal technical solutions eligible for funding. The application can be submitted electronically (e.g., via the gov.pl platform or dedicated program portals), in person at an office, or by mail. Once submitted, the application undergoes a formal and substantive evaluation. The funding authority (e.g., the Provincial Fund for Environmental Protection) may request additional information or conduct a technical inspection. Upon a positive decision, a grant agreement is signed. In refund-based programs, the applicant first completes the project – purchasing and installing the system – and then submits documentation confirming its completion (e.g., invoices, handover protocols). In some cases, a portion of the funds may be paid in advance, prior to installation. The final stage involves settling the grant and receiving the payment. The entire process may take several weeks to a few months, depending on the quality of the documentation, compliance with program requirements, and the availability of funds.

Although the application process can be time-consuming and administratively demanding, the **benefits of investing in RES are tangible** – including long-term savings on energy bills, improved energy efficiency, and greater independence from external energy suppliers.

6. Conclusions

Implementing renewable energy source (RES) technologies in buildings is a forward-looking investment that not only reduces utility bills but also supports environmental protection and sustainable development. Long-term financial savings and improved energy independence are among the most important benefits for property owners. Through systems such as photovoltaic panels, energy storage, and heat pumps, households gain the ability to produce and manage their own energy, often covering most or even all of their daily needs. This significantly reduces dependence on external electricity or heating suppliers and enhances resilience to fluctuating energy prices, power outages, and energy crises. Stored surplus energy can be used during periods of low production or high demand, ensuring energy continuity and security. Moreover, this autonomy contributes to a cleaner environment by lowering CO_2 emissions and reducing the overall ecological footprint. National and EU support programs – such as subsidies, grants, and tax incentives – play a crucial role in making these technologies more accessible, lowering the financial barrier to entry. In the long run, investing in RES enhances not only economic efficiency but also household stability, self-sufficiency, and environmental responsibility. Figure 2 presents a model of a self-sufficient household, illustrating a vision of the future centered around sustainable and energy-independent living.

Fig. 2. Model of a self-sufficient household

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

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ARTICLE

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THE INFLUENCE OF THE TRAJECTORY OF A BOREHOLE HEAT EXCHANGER ON THE POWER EXCHANGED WITH THE ROCK MASS

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Abstract: The article presents the influence of the trajectory of a borehole heat exchanger on the power exchanged with the rock mass. The focus is on the thermal parameters of rocks, which include thermal conductivity. This parameter can be determined using literature, laboratory tests or in-situ using a thermal response test. The design of the borehole heat exchanger as an inclined borehole maximizes the power exchanged with the rock mass by increasing the length of the borehole exchanger in the layer with the best thermal parameters. Mathematical calculations and thermal response tests show the advantage of inclined wells over vertical borehole heat exchangers in terms of the amount of power obtained from the rock mass.

Keywords: borehole heat exchangers, inclined borehole, thermal conductivity, geoenergetics, drilling wells

1. Introduction

The term "borehole heat exchanger (BHE)" refers to a borehole equipped with heat exchanger pipes (usually U-shaped). A heat transfer medium flows through these pipes. The space between the pipes and the well's wall should be sealed with cement grout. The basic designs of BHE include: single U-tube, double U-tube, multi-U-tube, and centric systems [1–3]. To 200 m in depth, single U-tube systems are most frequently applied, while deeper installations are coaxial. The coaxial system is most profitable in the view of exploitation costs and the highest heating power. Any kind of construction can be applied in boreholes purposed for producing heat [4]. Many factors influence the correct design of ground heat pump systems (with BHEs). Important factors affecting the effectiveness of this system are presented in Table 1. Economic and energy factors are presented.

Table 1. Factors affecting the efficiency of BHEs heating or cooling installations [1]

Construction parameters	Natural parameters	Production parameters
– depth of the installation	– geothermal gradient	– basic heating loads
– diameter of the borehole	– thermal conductivity of rocks	– basic cooling loads
– diameter of pipes	– specific heat of rocks	– peak load value
– thermal resistivity of pipe materials	– porosity and saturation of rocks	– peak load time
– distance between pipes in the exchanger	– hydrogeodynamic conditions	– time in which heat sources regenerate in the rock mass
– thermal conductivity of cement slurry	– local climatic conditions	– temperature of the heat carrier

Most often, borehole heat exchangers are made as vertical wells. However, there is a technique that allows borehole heat exchangers to be made at an angle known as Geothermal Radial Drilling (GRD). It is characterized by drilling multiple diagonal boreholes from a single location. A specialized drilling rig is used to drill this type of borehole, which has its limitations. The drilled boreholes are diagonal (angle of 30 to 65 degrees), usually between 40 and 60 m long, whereas classic borehole heat exchangers are usually around 100 m or more. Another difference between GRD and conventional drilling (vertical heat exchangers) is the need to construct a start chamber. Its depth is usually between 1 and 2 m. The basics of this method were developed by Tracto-Technik in the late 1970s [5] and in 2006 the company developed a modern tool with intelligent solutions for this type of installation. It was Tracto-Technik that named this method Geothermal Radial Drilling [4, 6, 7]. Such an installation is located in the C research field of the Geoenergetics Lab (Faculty of Drilling, Oil and Gas, AGH University of Krakow).

This work involves comparing the works of borehole heat exchangers, both vertical and inclined boreholes (drilled individually, unlike GRD technology). BHEs made as inclined boreholes, each drilled from a separate station, are located in research field B of the Geoenergetics Lab. The Geoenergetics Laboratory has heat exchangers of the same design made as vertical exchangers in research field A.

2. Method section

The BHEs located in research fields A and B at the Geoenergetics Lab (Faculty of Drilling, Oil and Gas, AGH University of Krakow) will be analyzed. A sample vertical BHE was selected, while the other was constructed as an inclined borehole. Both boreholes have the same lithological profile, as shown in Table 2.

The comparative analysis was performed in two stages. The first stage consisted of an analysis of literature data. The second stage consisted of in-situ measurements performed as a thermal response test (TRT).

Based on the lithological profile, values of thermal conductivity λ for particular rock layers can be assumed based on literature. Next the average λ can be calculated. The next step is to calculate the values of the indicators [9] of unit power exchanged between the working medium and the rock mass based on the following formulas:

$$q = 20 \cdot \lambda \tag{1}$$

$$q = 13 \cdot \lambda + 10 \tag{2}$$

where:
q – unit energy flow rate [$W \cdot m^{-1}$],
λ – thermal conductivity of the rock (effective) [$W \cdot m^{-1} \cdot K^{-1}$].

For the above case, the value of the unit power exchanged between the working medium and the rock mass calculated using formula 1 is 40.78 $W \cdot m^{-1}$, and using formula 2 is 36.51 $W \cdot m^{-1}$. Therefore, the average power exchanged with the rock mass, calculated on the basis of literature data, is 38.65 $W \cdot m^{-1}$

Table 2. Lithological profile for fields A and B of the Geoenergetics [8]

Length of the inclined borehole depending on the drilling angle [m]					
No.	**Top [m]**	**Bottom [m]**	**Thickness [m]**	**Lithology**	**Thermal conductivity [W·m⁻¹·K⁻¹]**
1	0.0	2.2	2.2	Anthropogenic ground (dark grey filled with debris)	1.600
2	2.2	2.6	0.4	Aggregate mud	1.600
3	2.6	4.0	1.4	Slightly and dusty clayey sand	1.000
4	4.0	6.0	2.0	Fine Sand	1.200
5	6.0	15.0	9.0	Sand and slag mix, slag	1.800
6	15.0	30.0	15.0	Grey clay	2.200
7	30.0	78.0	48.0	Gray claystate	2.100
–	–	–	–	Average	2.039

In the case of borehole heat exchangers, the main parameter is the thermal conductivity of the layers in which the heat exchanger is installed. Each layer has a thermal conductivity coefficient within a defined range. The thermal conductivity values of rocks can be found in literature or specialized software. Table 3 presents selected thermal conductivity values of rocks based on the Earth Energy Designer industry software.

Table 3. Thermal conductivity of various minerals and rocks based on specialized Earth Energy Designer software

Name	**Minimum thermal conductivity [W·m⁻¹·K⁻¹]**	**Maximum thermal conductivity [W·m⁻¹·K⁻¹]**	**Recommended thermal conductivity [W·m⁻¹ · K⁻¹]**
Amphibolite	2.14	3.55	2.90
Andesite	1.73	2.22	2.20
Arkose	2.54	3.73	2.90
Basalt	1.33	2.29	1.70
Breccia	2.26	4.11	2.80
Clay - dry	0.40	0.90	0.40
Clay - wet	0.90	2.22	1.60
Claystone	1.05	3.02	2.20
Coal	0.26	0.63	0.30
Conglomerate	1.35	3.70	2.80
Diorite	1.97	2.87	2.60
Dolomite	2.83	4.34	3.20
Dunite	3.98	4.73	4.20
Eclogite	2.32	4.19	2.90
Gabbro	1.72	2.53	1.90
Gneiss	1.89	3.95	2.90
Granite	2.10	4.07	3.40
Granodiorite	2.03	3.34	3.30
Gravel - dry	0.39	0.52	0.40
Gravel - saturated	1.80	1.80	1.80
Gypsum	1.29	2.80	1.60
Lamprophyre	2.43	3.41	2.60
Limestone - massive	2.46	3.93	2.80
Marble	1.28	3.08	2.60

Table 3. cont.

Name	Minimum thermal conductivity [W·m^{-1}·K^{-1}]	Maximum thermal conductivity [W·m^{-1}·K^{-1}]	Recommended thermal conductivity [W·m^{-1} · K^{-1}]
Marl	1.75	3.46	2.10
Marl – clayey	1.46	2.52	2.00
Marl – dolomitic	1.89	3.90	1.89
Pegmatite	2.89	3.31	3.00
Peridotite	3.79	5.27	4.00
Quartzite	3.60	6.62	6.00
Rhyolite	3.06	3.37	3.30
Salt	5.28	6.38	5.40
Sand – dry	0.27	0.75	0.40
Sand – dry – compacted	1.11	1.25	1.20
Sand – moist	0.58	1.75	1.00
Sand – saturated	1.73	5.02	2.40
Sandstone	1.28	5.10	2.30
Serpentinite	2.30	4.31	3.00
Shale	1.50	2.60	2.10
Silt – dry	0.38	1.00	0.40
Silt – wet	1.00	2.30	1.80
Siltstone	1.31	3.52	2.40
Syenite	1.70	3.48	2.60

By selecting the average or recommended value for a given layer, one can calculate the weighted average thermal conductivity along the length of the BHE installed in that rock mass. By making an inclined borehole, the thermal conductivity is improved by increasing the apparent thickness.

The next stage of research was the TRT. This test should be understood as a measurement method used for the evaluation of factual thermal properties of a rock mass in the tested area. The test is carried out in in-situ, on borehole heat exchangers for a test well. Thanks to it, it is possible to determine a proper amount of vertical borehole exchangers and their placement according to the set temperature conditions of work of a system. A TRT of BHEs measures changes of temperature of a fluid during its circulation in a close circuit in the event of supplying or collecting thermal energy of a steady heating power [8, 10–12].

The TRT is performed on a previously drilled and cased borehole. The borehole is considered to be cased by a system of exchanger pipes located in the borehole, with the space between the borehole wall and the exchanger pipes injected, if possible, with a special sealing grout.

The thermal conductivity of rocks at the location and the thermal resistance of the exchanger can be determined using mathematical methods of interpreting TRT results. In order to determine these correctly, it is necessary to perform an adequate duration test. The recommended duration of TRT varies greatly depending on the literature [13–15]. Minimum duration of the TRT given in most studies is approximately 50 hours. However, in Poland, tests lasting approximately 100 hours are most commonly performed [14]. These tests were also performed for this duration. Methods for interpreting TRT results are described in [1, 8].

3. Results and discussion

The first part of the analysis involving the interpretation of literature data is presented below. In order to calculate the actual length of the inclined BHE, the relationship presented in Table 4 was used. The increase in the length of the inclined borehole depending on the angle for 1 m of the drilled layer is presented in Table 5.

The change in the length of the exchanger is presented below, and thus the increase in the power exchanged between the working medium and the rock mass, assuming the same borehole depth (TVD – True Vertical Depth). The weighted average thermal conductivity per thickness should then be calculated for both the vertical and inclined boreholes. Table 6 shows the determination of the length of the vertical and inclined boreholes.

Table 4. Increase in the length of the inclined borehole depending on the drilling angle, assuming the length of the vertical borehole as *H*

Length of the inclined borehole depending on the drilling angle [m]					
10°	**20°**	**30°**	**40°**	**45°**	**50°**
$\frac{H}{0.985}$	$\frac{H}{0.940}$	$\frac{H}{0.866}$	$\frac{H}{0.766}$	$\frac{H}{0.707}$	$\frac{H}{0.643}$

Table 5. Increase in the length of the inclined borehole depending on the angle for 1 m of the drilled layer

Increase in the length of the inclined borehole depending on the angle for 1 m of the drilled layer [m]					
10°	**20°**	**30°**	**40°**	**45°**	**50°**
0.015	0.064	0.155	0.305	0.414	0.556

Table 6. Lithological profile for fields A and B of the Geoenergetics Lab

Determining the length of the vertical and inclined boreholes (10°) [m]					
No.	**Top [m]**	**Bottom [m]**	**Thickness – vertical borehole [m]**	**Thickness – inclined borehole [m]**	**Thermal conductivity [W·m^{-1}·K^{-1}]**
1	0.0	2.2	2.2	2.23	1.600
2	2.2	2.6	0.4	0.41	1.600
3	2.6	4.0	1.4	1.42	1.000
4	4.0	6.0	2.0	2.03	1.200
5	6.0	15.0	9.0	9.13	1.800
6	15.0	30.0	15.0	15.23	2.200
7	30.0	78.0	48.0	48.73	2.100
Total			78.0	79.18	–

When analyzing the above case, it can be seen that the average conductivity values for the profile are the same, and therefore the average unit power exchanged with the rock mass is also constant. Assuming the same borehole depth (TVD), the length measured in the case of an inclined wells for a borehole exchanger changes. The total power exchanged with the rock mass in a vertical hole is 3014.70 W, while in the case of a diagonal hole (drilled to the same depth but at an angle of 10°) it is 3060.31 W. Other cases were also analyzed. For a borehole drilled at an angle of 30°, the total power exchanged with the rock is 3480.82 W. It should therefore be noted that as the angle of the inclined well increases, the total power exchanged with the rock increases.

The second part of the interpretation analyzes the results obtained during the TRT. The tests were performed using a specialized device shown in Figure 1.

The first stage of installing the device is to correctly connect the tubes of the BHE to the valve module. Using the tubes of the borehole heat exchanger plugged in to the valves, to start the circulation of the working medium. The start of the test is considered to be the point at which a constant heating power is set on the heater. During heating, data such as the supply and return temperature of the working medium, instantaneous flow, and atmospheric (outside) temperature are recorded.

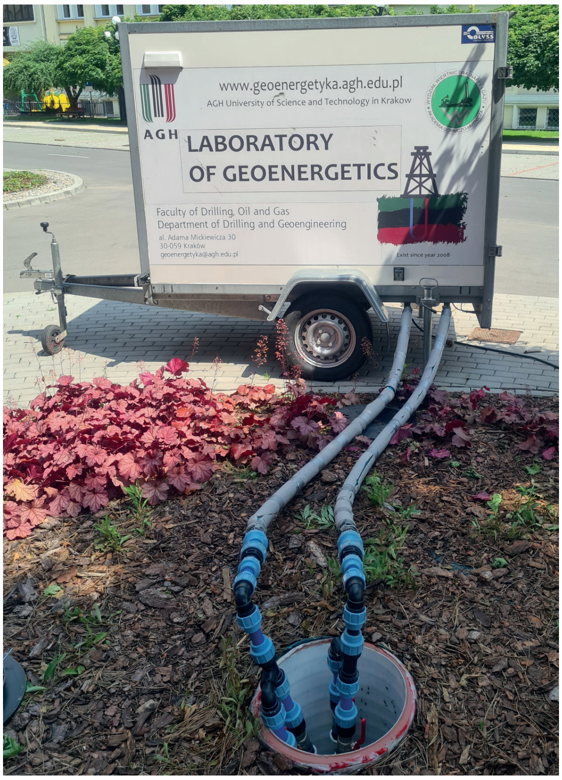

Fig. 1. TRT Equipment (photo Geoenergetics Lab team)

These values are stored in the memory of the computer connected to the device. The data obtained from TRT in the BHEs were interpreted using the classical method [1].

Borehole heat exchangers were tested: vertical and inclined, made at an angle of 10°. After conducting laboratory tests, necessary computer studies, analyses and calculations, the following results were obtained:

- for a vertical borehole heat exchanger, measured and calculated the effective thermal conductivity was 1.47 $W \cdot m^{-1} \cdot K^{-1}$,
- for a inclined borehole heat exchanger, measured and calculated the effective thermal conductivity was 1.69 $W \cdot m^{-1} \cdot K^{-1}$.

When analyzing the above results, it can be seen that real effective thermal conductivity occurs for the inclined borehole. It is recommended to perform a TRT for each new investment for which a field of BHEs is planned. This test should be completed after drilling the first well in order to determine the actual thermal parameters of the rocks, which is necessary for the proper selection of the number of heat exchangers for the investment.

4. Conclusions

Borehole heat exchangers are increasing in popularity because they fit perfectly into the trend of renewable energy sources and can be installed anywhere, regardless of lithology. The development of cities and buildings requires unconventional solutions, such as the installation of borehole heat exchangers in inclined boreholes. This procedure allows for a reduction in the distance between boreholes on the surface without causing heat transfer between nearby boreholes (with depth, the inclined boreholes move further apart). The use of diagonal borehole heat exchangers also allows for maximizing the power exchanged with the rock mass by increasing the length of the borehole in the layer with the highest thermal conductivity. When drilling BHEs, it is recommended to prepare a TRT each time in order to determine the actual parameters of the ground since this allows for the appropriate selection of the size of the BHE installation.

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POSSIBILITIES OF USING INCLINED BOREHOLES IN SHALLOW DRILLING

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Abstract: The article presents the possibilities of using inclined boreholes. Three cases were considered: backfill boreholes, hydrogeological boreholes, and borehole heat exchangers. The advantages and disadvantages of these solutions are described. In the case of an inclined backfill borehole, the time required for backfill material injection is minimized. In the case of an inclined hydrogeological borehole, the active filter area is increased, improving efficiency. In the case of inclined borehole heat exchangers, the unit power exchange with the rock mass is increased by increasing the length of the borehole in the layer with the best thermal conductivity.

Keywords: inclined boreholes, injection boreholes, hydrogeological boreholes, borehole heat exchangers, Geothermal Radial Drilling

1. Introduction

Drilling boreholes are made for various engineering purposes, ranging from exploratory drilling, through production drilling, to drilling for geotechnical, geoengineering, and construction applications, as well as various types of mining applications. Most frequently, wells are made vertically. Drilling boreholes can be classified according to various factors, including purpose, depth, diameter, etc. Taking into account the final drilling depth, a distinction is made between shallow, deep, and super-deep wells [1]. Of course, there are no clear definitions of numerical values since different authors, also due to the purpose of the boreholes, give different depths in an ambiguous way. The authors of this study propose classifying shallow boreholes as wells with a final depth of up to 200–250 m.

In recent years, there has been significant development in shallow drilling, primarily due to the need to eliminate gaps and collapses caused by mining activities or due to the development of renewable energy sources, which include the provision of geothermal energy using borehole heat exchangers. There has also been increased interest in hydrogeological drilling. Currently, all such drilling is performed as vertical wells. An exception is a special type of borehole heat exchanger made using Geothermal Radial Drilling (GRD) technology. This technique involves drilling several angled boreholes from a single point. The fundamental principles were established by Tracto-Technik in the late 1970s, they were the ones who gave it that name [2, 3].

In 2006, the company introduced an advanced system incorporating intelligent technologies for this type of installation. The process utilizes a specialized drilling machine designed for creating these boreholes. The drilled wells are typically inclined and range from 40 to 60 meters in length. What sets GRD apart from traditional drilling techniques is the requirement to build a launch chamber, usually 1 to 2 meters deep. Drilling is typically carried out at angles between 30 and 65 degrees [4, 5]. Such an installation is located in research field C of the Geoenergetics Laboratory (Faculty Drilling, Oil and Gas, AGH University of Krakow). In addition, some of the first borehole heat exchangers in the form of inclined boreholes were drilled from research fields in the Geoenergetics Lab [6].

Currently, directional drilling is most commonly used in deep drilling and trenchless techniques. Directional holes are described by additional data not usually found in vertical boreholes. Measured Depth – this is the depth of a given point in the hole measured along the length of the drill string. True Vertical Depth – this is the depth of a given point in the hole measured vertically to the reference level. Dog Leg Severity – this is the increase in the curvature of the hole per unit of distance. Of course, only the basic concepts are given here. There are many trajectories for directional wells in deep drilling. The main ones are J-type and S-type. You can read more about horizontal directional drilling and deep directional drilling trajectory in [7–11].

Due to their complexity and the necessary lengths of the wells, they are not directly applicable in shallow drilling. Horizontal directional drilling also belongs to the category of directional drilling. This modern technology (classified as a trenchless technology) involves performing horizontal directional drilling. Horizontal directional drilling enables various types of installations (water pipes, gas pipes, power lines) to be carried out using the trenchless method wherever it is impossible to dig an open trench for pipes or cables. Therefore, it is very important to transfer the experience gained there to shallow drilling.

2. Results

The realization of the above-described examples of vertical wells in the form of inclined wells can bring many benefits. An inclined injection well (backfill well) is recommended for chambers or gaps intended for stabilizing that are located under heavily urbanized areas. It is also recommended to make diagonal backfill boreholes in order to provide greater apparent thickness of the chamber or cavity in relation to a vertical hole. This results in an increase in the length of the perforated section of the pipe used to inject the backfill material. A similar solution is proposed for groundwater access. Compared to a vertical borehole, this technological solution will increase the surface area of the well's filtration zone cylinder, thus increasing the surface area of water inflow to the well (the so-called apparent thickness). Similarly, in the case of borehole heat exchangers installed in a borehole to obtain low-temperature heat, the use of an inclined borehole design can bring economic benefits by making a longer part of the borehole in a layer with the highest possible thermal conductivity, which will increase the amount of heat exchanged between the rock mass and the heat carrier circulating in the exchanger pipes.

The increase in the length of the inclined borehole (Fig. 1) will be the same for each case described in this paper and will depend on the angle at which the inclined well is made.

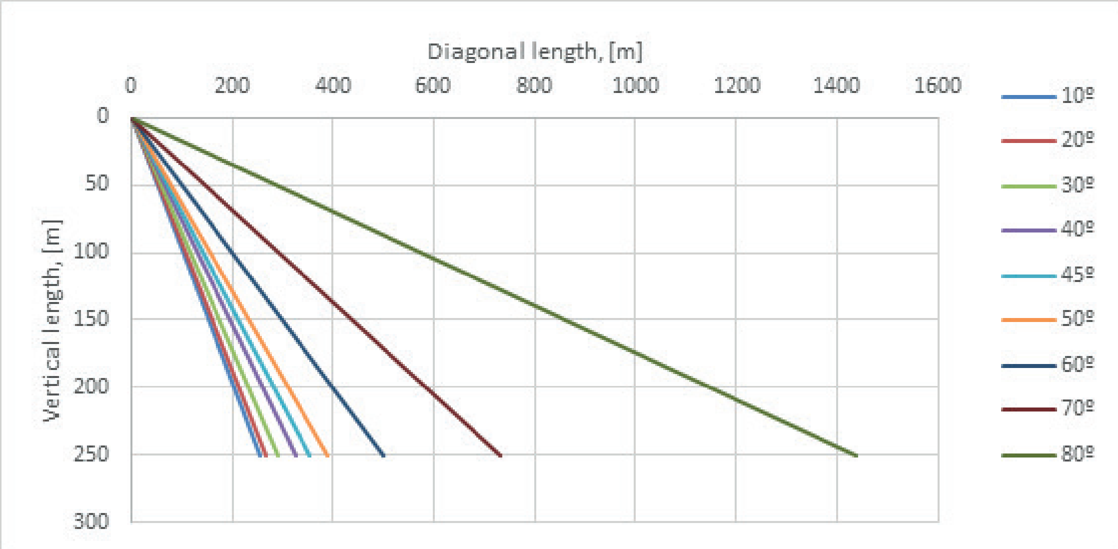

Fig. 1. Comparison of the length of a vertical borehole and an inclined borehole drilled at a defined angle

2.1. Injection boreholes (backfill boreholes)

Backfill boreholes are specially designed technical boreholes used to transport backfill material (usually a mixture of sand, ash, hydraulic grout, or brine) from the surface to voids created by mining operations. Their main purpose is to fill underground excavations and stabilize the rock mass, which minimizes the risk of subsidence and surface deformation and improves the safety of infrastructure facilities located in post-mining areas. In areas designated for construction, the presence of voids resulting from previous mineral extraction activities often requires remedial actions to ensure ground stability. The intensification of geological resource exploitation has contributed to the reactivation of subsidence and collapse phenomena. To address these challenges, drilling techniques are increasingly employed for the backfilling of underground cavities and discontinuities in the rock mass. Through the use of specially designed boreholes, backfilling materials can be efficiently transported from the surface directly to the targeted voids or post-mining chambers. The design parameters of these boreholes are typically determined based on the lithological profile of the subsurface and established drilling standards. Literature reports indicate that steel casing pipes with diameters ranging from 12 inches to 18 inches are most commonly used for this purpose. However, variations exist – for instance, some boreholes, such as the TP-25 well in the Wieliczka Salt Mine, utilize initial casing diameters exceeding 20 inches, whereas final segments may be reduced significantly, down to 6 5/8 inches for effective backfill transport [12, 13].

Backfill boreholes made as inclined wells will significantly reduce the time needed to pump backfill material. In special cases of highly urbanized surface development, they will allow backfilling to be carried out from an area not located directly above the chamber being backfilled. In addition, the advantage of using backfill materials is that they reduce rock mass deformation caused by deposit exploitation, thereby protecting the surface and the levels and deposits above. Occasionally, some backfill boreholes serve as water inflow routes to the mine, and in order to limit this adverse effect, all such holes should be sealed after fulfilling their technological purpose. To achieve insulation around the holes, additional sealing of the rock mass should be designed using the hole injection method carried out from the surface. To achieve isolation around the holes, additional sealing of the rock mass should be designed using the hole injection method carried out from the surface [12].

2.2. Hydrogeological boreholes

Hydrogeological boreholes, designed to access aquifers, are mainly constructed as vertical structures. Initially, hydrogeological boreholes were constructed using the percussion method, which involved drilling a borehole with a smaller diameter and then widening it to the required final diameter. The circular method was used next. These holes require human strength, so it is only possible to drill in this way in very soft and soft rocks. At the same time, manual drilling of holes is characterized by low technical and economic drilling indicators. In the first half of the 20th century, this method was replaced by rotary drilling, performed as large-diameter boreholes, i.e., boreholes with a diameter of more than 0.5 m [14]. The increased profitability of rotary technology compared to the percussion method was achieved thanks to significant advances in drilling using reverse circulation drilling mud. Hydrogeological boreholes are mainly drilled using clay drilling mud, often natural. The development of drilling technology and techniques has made it possible to access groundwater using boreholes drilled using the rotary method with normal mud circulation. This is mainly due to the possibility of reducing the final diameter determined by the well equipment (submersible pump, outer diameter of the filter column, etc.). An important aspect of hydrogeological drilling is therefore a thorough lithological survey. This allows for the elimination of possible "missed boreholes" which, after the column with the filter has been inserted, do not guarantee good well performance. As stated earlier, the efficiency is determined on the basis of a test pumping. The radius of the depression cone is determined, which extends from the axis of the hydrogeological borehole to a distance where no drop in the water table in the borehole is observed during water extraction. In the process of rotary drilling with mud, depending on the rate of penetration, the type of drill bit, flow character and the type of mud, the operation of the mud pumps, and the mud cleaning system from cuttings, the pressure of the mud on the bottom and the wall of the borehole can vary significantly of the drilling fluid to the bottom and walls of the borehole. The pressure in the borehole reaches different values in different phases of drilling operations. In addition, poorly selected drilling fluid for drilling through aquifers or improperly chemically treated may lead to the sedimentation of solid particles from it, and under the influence of the pressure difference between the mud column in the hole and the reservoir water, these particles may be pressed into the pores and cracks of the rock, clogging them [14].

Inclined boreholes significantly improve the technical and technological indicators as well as the economics of the work described in the study. Accessing aquifers through an inclined bore will increase the active surface area of the filter, thereby increasing the water inflow to the filter column. The increase in water inflow to the completed well will directly affect the dynamic water table of the well, which will settle at a higher level. Each inclined well made to access groundwater will be characterized by an increased length of the active filter surface. It is recommended to select the casing and drill bit diameters in accordance with API standards, depending on the geological conditions encountered. The dimensions of the filters are determined primarily on the basis of the designed capacity of the well and the geological and hydraulic conditions of the aquifer. The length of the filter should be as long as possible, as it directly affects the flow of water from the aquifer into the production column.

2.3. Borehole heat exchangers

Low-temperature energy can be used for heating and heating-cooling purposes by using a heat pump system with borehole heat exchangers. This is one of the most popular methods of extracting heat from the rock mass. The rock mass is a good heat reservoir. The heat can come from solar or geothermal energy, or it can also be anthropogenic heat. Correct drilling of the borehole is very important for the precise operation of geothermal heat pump systems with borehole heat exchangers. A very important element of this process is the selection of the appropriate drilling method. Borehole heat exchangers are most often made using one of two methods [15–17]: the rotary method or the percussion-rotary method. The drilling of a borehole and the installation of heat exchanger pipes in it consists of a series of steps, the correct execution of which guarantees the achievement of the intended goal. Boreholes are most frequently drilled using the rotary method with normal mud circulation. In many cases, cutting drills are used to drill rocks, and native or bentonite clay mud is used to remove drill cuttings from the bottom of the well to the surface. The individual stages of drilling a borehole consist of assembling the drilling rig, preparing the mud system and drilling mud, installing the initial casing string, drilling rock, crane operations with the drill string, and the cementing process [6].

The correct design and construction of installations based on borehole heat exchangers requires a complex approach involving a number of key stages. First, it is necessary to assess the thermal potential of the rock mass, which allows the energy efficiency of the planned installation to be determined. Next, an analysis of the techniques and technologies used for drilling holes and their adaptation to the function of heat exchangers in various geological conditions is carried out, which allows the drilling method to be adapted to local geological conditions. Another important stage is the selection of the appropriate design of borehole heat exchangers, including the composition of sealing grouts, which guarantee adequate sealing of the borehole exchanger and prevent water migration between different aquifers. To predict the behavior of the installation during operation, modeling of borehole heat exchangers is performed, and on this basis, the parameters of their operation technology are optimized to increase the energy efficiency and durability of the entire system. Borehole heat exchangers installed in inclined wells will be characterized by increased apparent thickness in layers with the highest possible thermal conductivity. This will have a positive effect on the total power exchanged with the rock mass. The efficiency of the entire heating or heating-cooling system based on borehole heat exchangers will therefore increase.

3. Conclusions

- Backfill boreholes can be drilled as vertical and inclined wells from the surface or from underground mine levels. Inclined backfill wells may be drilled in the following cases: a) when vertical drilling is not possible, b) when drilling from underground mine levels is necessary, c) in order to reduce the time needed to inject the backfill materials.
- Hydrogeological boreholes (exploratory, production, research, absorption, observation, dewatering) can be drilled as vertical and inclined boreholes. Inclined hydrogeological wells can be drilled: a) when vertical drilling is not possible, b) when dewatering from underground mine levels is necessary, and c) to improve performance parameters (water flow). Cases a and b are independent of the investor's decision. In case c, the decision to drill inclined will enable a higher flow of the production well.
- Drilling inclined through an aquifer increases the surface area of groundwater inflow into the borehole. Using a longer filter (active part) increases the rate of flow at the same depression, measured vertically. Drilling a hydrogeological borehole in an inclined borehole is more difficult than in a vertical borehole. The difficulty and possibility of complications increase with the increase in the angle between the borehole axis and the vertical direction.
- Borehole heat exchangers (single U-tubes, multi-U-tubes, centric, etc.) can be drilled as vertical and inclined wells. Inclined drilling of borehole heat exchangers can be performed in the following cases: a) when vertical drilling is not possible, b) when there is not enough space on the surface for the required number of vertical heat exchangers, c) when heat storage is available under infrastructure facilities, d) when drilling from inside buildings, e) to improve functional parameters (heating capacity).
- The use of inclined wells will lead to benefits in each of the cases described and will have a positive impact on the efficiency of hydrogeological drilling, the amount of energy exchanged with the rock mass in the case of borehole heat exchangers, and the time required to inject backfill material into the chamber or gap left by mining operations.

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