

Assessment and Potential of Geothermal Energy in Romania: A Path to Sustainable Heating Solutions

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Abstract

The paper explores the underutilized potential of geothermal energy in Romania, focusing on both shallow and deep geothermal systems as sustainable alternatives for heating applications. Romania's unique geological features, particularly the Pannonian Depression, offer significant geothermal resources, yet these remain largely untapped in many regions. This study presents an analysis of the country's geothermal reservoirs, highlighting their spatial distribution, thermophysical properties, and technical potential. In-depth data on aquifer characteristics, including temperatures, depths, and capacities, supports a comprehensive assessment of the energy output achievable from these natural systems. Current applications of geothermal resources are reviewed, including successful projects in Oradea and Timiș County, which demonstrate the viability of geothermal systems for residential and commercial heating. Furthermore, this study discusses Romania's regulatory landscape and incentive frameworks aligned with European Union standards, identifying key barriers and opportunities for growth. With a robust foundation of technical and spatial data, this paper underscores the strategic role geothermal energy can play in Romania's transition to a low-carbon economy, supporting both environmental sustainability and energy resilience. The results demonstrate how geomatics-based resource mapping and spatial analysis support evidence-based planning of geothermal energy systems at regional and national scales.

Keywords: geothermal energy; renewable energy; geothermal potential; sustainable heating; heat pumps

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1. Introduction to Geothermal Potential

Romania possesses significant geothermal potential, particularly in the western regions of the country [1–3]. This potential arises from its unique geological characteristics, with the Pannonian Depression playing a fundamental role. This region, encompassing parts of the Banat, the western mountains, and sections of Transylvania, exhibits abundant geothermal resources owing to its high thermal flux values, which are notably higher than those observed in other parts of Romania. Such geological formations provide a fertile ground for the exploration and exploitation of geothermal energy, aligning with Romania's goals for sustainable energy development [4]. Similar geothermal development goals have been outlined in regional strategies, highlighting cross-border similarities in potential and ambition [5].

Geothermal resources in Romania have been utilized since ancient times, with evidence dating back to the Roman Empire [1]. Over the past century, these resources have been harnessed for therapeutic purposes, highlighting their longstanding role in regional socio-economic activities. Systematic geothermal exploration began in earnest during the late 20th century, leading to the identification of aquifer layers with diverse thermophysical properties across various geological formations in the western plains [2,3,6]. These layers contain waters at temperatures ranging from 30 °C to 90 °C, categorizing them as low-enthalpy resources, suitable for a variety of applications such as domestic hot water supply, district heating, greenhouse heating, and recreational facilities [7–9].

Significant geothermal aquifer systems, such as the Pannonian aquifer and Oradea reservoir, underline the scale and diversity of Romania's geothermal assets [4]. For example, the Pannonian aquifer spans an area of approximately 2500 km², with depths reaching between 800 and 2400 m and temperatures varying from 50 °C to 85 °C. The Oradea reservoir, on the other hand, claims higher temperatures, between 70 °C and 105 °C, making it suitable for both direct-use applications and potential integration with advanced energy systems like heat pumps [10].

Despite these promising resources, current geothermal exploitation in Romania remains underdeveloped [11–13]. Only about 30% of the identified geothermal potential is actively utilized, primarily in regions like Oradea and Timis County. Projects in these areas have demonstrated the feasibility of geothermal energy systems, including district heating initiatives and heating for greenhouses and industrial processes. Noteworthy among these is the “Nufărul 1” neighborhood project in Oradea, which supplies geothermal energy to over 6000 apartments.

The exploration of geothermal energy is not merely a technical endeavor; it represents a critical component of Romania's broader energy strategy. By integrating geothermal resources into its energy portfolio, Romania has the opportunity to enhance energy security, reduce greenhouse gas emissions, and meet its commitments to the European Union's renewable energy targets [4,14]. As such, the development of geothermal energy must be prioritized, with a focus on innovative technologies, robust policy frameworks, and collaborative research to unlock the full potential of this sustainable resource.

Through this article, we aim to provide a comprehensive overview of the current state and future prospects of geothermal energy in Romania, emphasizing its technical, economic, and environmental relevance [15]. By doing so, we hope to contribute to a deeper understanding of the strategic importance of geothermal energy in achieving a resilient and sustainable energy system for Romania.

From a geomatics perspective, this study emphasizes the role of hydrogeological mapping, spatial analysis of geothermal aquifers, and geoscientific data integration in supporting renewable energy planning and territorial decision-making. By linking geothermal resource characteristics to their geographic distribution and regional development contexts, the paper highlights how geomatics methodologies can inform sustainable heating strategies at local, regional, and national scales.

2. Materials and Methods

This study is based on a narrative review and spatial analysis of geothermal resource data for Romania, compiled within the framework of the Danube GeoHeCo project (Project code: DRP0200244), co-financed by the European Union through the Interreg Danube Transnational Program. The primary geothermal reservoir data, including aquifer depths, temperatures, areal extents, recharge rates, total dissolved solids (TDS), and gas content, were extracted from the Romania Country Status Report produced under the Danube GeoHeCo project [16], which consolidates data from foundational Romanian geothermal surveys [1,8,17–19].

Reservoir selection followed two criteria:

- (i) The reservoir is documented in the Danube GeoHeCo national dataset with at least three characterization parameters (depth, temperature, and areal extent).
- (ii) The reservoir has demonstrated or confirmed potential for direct-use heating applications. On this basis, five reservoirs were selected for detailed analysis: the Pannonian Aquifer, the Oradea Reservoir, the Beiuș Reservoir, the Borș Confined Reservoir, and the Ciumeghiu Reservoir.

Two additional reservoirs identified in the source dataset, Cozia-Călimănești and Otopeni, were noted but excluded from the comparative analysis due to their geographic isolation from the main western geothermal corridor and limited current exploitation data.

Geothermal resources are classified in this study following the enthalpy-based framework established under the EU's Renewable Energy Directive framework—originally Directive 2009/28/EC, subsequently recast as Directive (EU) 2018/2001 and most recently amended by Directive (EU) 2023/2413 (RED III) [20]: shallow geothermal systems operate at depths up to approximately 400 m, while deep geothermal systems exceed this depth. Resources with fluid temperatures in the range of 30–90 °C are classified as low enthalpy, and those between 90 °C and 150 °C as medium enthalpy.

The spatial distribution of geothermal resources was assessed using hydrogeological zonation maps of Romania published by the National Geological Institute of Romania (IGR) at scales of 1:1,000,000 and 1:200,000, as referenced in the Danube GeoHeCo Country Report [16]. The geothermal flux distribution underpinning Figure 1 is based on the iso-flux mapping originally established by Negoită [18] and subsequently validated by Veliciu [19], with the western Pannonian Depression consistently identified as the primary high-flux zone, where surface thermal flows reach values of approximately 85 mW/m², significantly exceeding the European average.

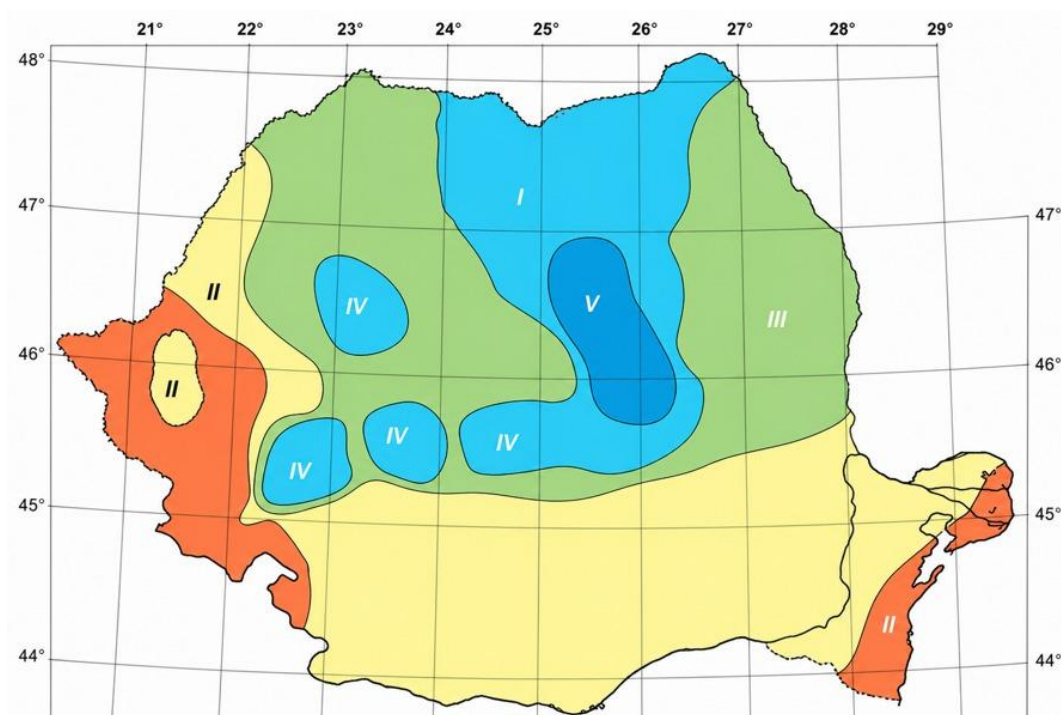


Figure 1. Shallow Geothermal Climatic Zonation of Romania. The map presents two superimposed classification schemes used to assess Romania's shallow geothermal potential, reproduced from a national conference presentation [Error! Reference source not found.]. The underlying five-tier zonation (Zones I–V) classifies the national territory by winter minimum air temperature, shown in a

ignation. This distinction highlights both Romania's currently exploited geothermal infrastructure and the scope for further exploration nationally.

The regulatory and policy incentive comparison presented in Table 1 was compiled from official EU legislative texts [20,24], the European Geothermal Energy Council Market Report 2020 [5], and national Romanian law sources [25–28]. The methodology for calculating the renewable energy contribution from geothermal heat pump systems follows the framework of EU Commission Decision 2013/114/EU, using the seasonal performance factor approach originally defined in Annex VII of Directive 2009/28/EC, a methodology retained in substance under the recast Directive (EU) 2018/2001 [20,29].

Table 1. Comparative Characteristics of Romania's Five Principal Geothermal Reservoirs.

Reservoir	Area	Depth	Temperature	Recharge/Flow Rate	Theoretical/Estimated Heat Output	Current Use	Technical Barriers	Development Priority
Pannonian Aquifer	~2500 km ²	800–2400 m	50–85 °C	N/A	N/A	District heating; greenhouse cultivation	Moderate dissolved gas content; large depth range complicates uniform exploitation strategy	High: largest areal extent and broadest application range
Oradea Reservoir	75 km ²	2200–3200 m	70–105 °C	140 L/s aggregate, 12 production wells [30]; cross-checks against 12 L/s/well [31]	≈17–35 MWth (calculated) *; 34.1 MWt theoretical [31]; ≈13.5 MW average delivered (from 427 TJ/yr) [30]	Large-scale residential & commercial district heating (e.g., Nufărul 1, >6000 apartments); ≈35% of national geothermal heat output [30]	No dissolved gas (mineralization 0.9–1.2 g/L, Ca-SO ₄ -HCO ₃ type)—low scaling risk [30]; high drilling depth increases capital cost	High: proven large-scale deployment; supports sustainable extraction; best-characterized reservoir in dataset
Beiuș Reservoir	47 km ²	1870–2370 m	83–84 °C [30]	45 L/s (single production well, installed 1999) [30]	≈8 MWth (calculated) *	100% of urban heating for the city of Beiuș (sole example nationally); 21 MWth installed capacity, 100% geothermal share [31]	Single-point dependency on one reservoir/well for entire city; resilience risk not discussed in source	Medium–High proof of concept value for full-scale urban geothermal heating

Borș Con- fined Res- ervoir	12 km ²	2500– 2800 m [30–32]	>120–130 °C [30,31]	10 L/s per well × 4 wells [31]; aggregate not directly re- ported	≈8 MWt in- stalled [30]; 8.79 MWt theoretical [31] close agreement	Industrial pre-heating potential (medium– high en- thalpy); ≈34,890 MWh/yr energy sav- ings re- ported [30]	High gas con- tent (70% CO ₂ , 30% CH ₄) and high minerali- zation (13 g/L) cause scal- ing/corrosion [30]; no mitiga- tion strategy specified	Medium high- est tempera- ture in dataset, but gas con- tent raises op- erating cost and complex- ity
Ciameghiu Reservoir	Not Available	~2200 m (avg.) [30]	105 °C [30]	Not reported (1 of 4 operational wells) [30]	5 MWt (1 of 4 wells; re- ported di- rectly, not de- rived) [30]	Formerly used for greenhouse heating; currently not in oper- ation [30]	High minerali- zation, me- thane-domi- nated dissolved gas [30]; only 1 of 4 drilled wells ever brought into service	Low–Medium smallest active capacity; reac- tivating idle wells is a low- cost near-term option

* Estimated heat output methodology: $Q = \dot{m} \times C_p \times \Delta T$, where $\dot{m}$ is mass flow rate (kg/s, derived from reported volumetric flow rate × brine density ≈ 0.99 kg/L), $C_p = 4.18$ kJ/(kg·°C), and ΔT is the assumed temperature drop between extraction and reinjection (40–45 °C reinjection assumed, a standard direct-use district-heating threshold). Calculated values are shown only for Oradea and Beiuș, the two reservoirs for which a verified flow rate is available [30]. For Oradea, the calculated range (≈17–35 MWth) is independently corroborated by the theoretical capacity reported by Gavriluț et al. [31] (34.1 MWt) and is consistent with the average power implied by the reported annual delivered energy of 427 TJ/yr [30] (≈13.5 MW average, reflecting a realistic load factor below theoretical peak capacity). This cross-validation supports the reliability of the calculation method. Heat output is not extended to reservoirs without a reported flow rate (Pannonian aquifer at aggregate scale, Borș, Ciameghiu beyond its directly reported 5 MWt), to avoid stacking an unsupported flow-rate assumption on top of the calculation.

3. Current Utilization and Projects

Romania's geothermal energy sector, while underutilized, has demonstrated significant progress through various localized applications. These range from district heating projects to innovative initiatives supported by European funding. This section highlights the key areas of current geothermal utilization, along with exemplary projects that underline the potential for scaling geothermal energy use across the country (Figure 1).

3.1. Geothermal Energy Applications in Romania

The western part of Romania has been at the forefront of geothermal energy utilization, leveraging its rich aquifers for diverse applications. Geothermal waters with temperatures ranging between 30 °C and 90 °C have primarily been used for heating, therapeutic purposes, and domestic hot water supply.

Notable examples include the following:

- Oradea: A city recognized as a leader in geothermal energy utilization, Oradea has developed a robust geothermal infrastructure. Geothermal energy in Oradea supplies heat and hot water to residential complexes, swimming pools, and industrial establishments [30].

- Timis County: Known for its extensive use of geothermal water for laundry operations, district heating, and recreational facilities, this region exemplifies the practical and economic benefits of geothermal energy [31].

In addition to these prominent regions, geothermal energy is also used in smaller-scale applications across Romania, including greenhouse heating, agricultural drying, and recreational spa facilities.

3.2. Significant Projects and Investments

3.2.1. Nufărul 1 Neighborhood, Oradea

One of Romania's most ambitious geothermal projects is the heating system for the Nufărul 1 Neighborhood in Oradea. Supported by over 18 million euros in European funding, this project integrates geothermal water into a district heating system that serves over 6000 apartments, public institutions, and commercial spaces [33]. The system has significantly reduced energy costs for residents while contributing to environmental sustainability by cutting carbon emissions [30].

3.2.2. Beiuș: A Geothermal Heating Pioneer

Beiuș is the only city in Romania where urban heating is entirely powered by geothermal energy [30]. This centralized system not only provides heat but also acts as a model for other regions aspiring to transition to renewable energy sources.

3.2.3. The GEOTHERMICA Project

Funded under the Horizon 2020 program, the GEOTHERMICA ERA-NET Cofund project (Horizon 2020, Grant Agreement No. 731117, 2017–2022) aimed to accelerate the deployment of geothermal energy through transnational research collaboration and joint innovation calls across sixteen European countries [5]. The initiative emphasizes the integration of geothermal systems with heat pumps and other renewable energy sources, showcasing Romania's commitment to technological advancements. The outcomes of this project, including improved cost-efficiency and energy accessibility, hold promise for scaling geothermal applications across the country.

3.2.4. Emerging Trends and Opportunities

Romania is witnessing a shift towards modernized geothermal applications. With ongoing European and national investments, several new projects are under development. These include:

- Hybrid systems combining geothermal and solar energy for enhanced efficiency [16];
- Pilot projects aimed at using geothermal resources for electricity generation, a potential game-changer for Romania's energy sector [5].

To facilitate these advancements, Romania must focus on expanding infrastructure, improving resource mapping, and fostering public–private partnerships [16]. By aligning with European Union directives, the country has a strong foundation to further integrate geothermal energy into its broader energy portfolio.

While the reservoir-scale aquifers discussed above (Pannonian, Oradea, Beiuș, Borș, Ciumeghiu) represent Romania's deep and confined hydrothermal resources, shallow geothermal potential accessible nationwide via ground-source heat pumps independent of deep reservoir geology follows a distinct, climate-driven zonation. Figure 1 presents this complementary shallow geothermal classification, governed primarily by ground temperature rather than aquifer productivity.

4. Technical Potential and Aquifer Data

Romania's geothermal energy potential is underpinned by an array of aquifer systems, each defined by unique thermophysical properties. These geothermal resources, as seen in Figure 2, concentrated predominantly in the western part of the country, present a wealth of opportunities for renewable energy integration. This section examines the technical attributes of these resources, their utilization potential, and the challenges they face.

4.1. Key Geothermal Aquifers in Romania

The western region of Romania, particularly the Pannonian Depression, hosts most of the country's geothermal aquifers [22]. These reservoirs vary in depth, temperature, and recharge rates, catering to a wide range of applications:

Pannonian Aquifer:

- Area: ~2500 km²;
- Depth: 800–2400 m;
- Temperature: 50–85 °C;
- Features: This aquifer exhibits moderate dissolved gas content and high thermal conductivity, making it well-suited for direct-use applications such as district heating and greenhouse cultivation.

Oradea Reservoir:

- Area: 75 km²;
- Depth: 2200–3200 m;
- Temperature: 70–105 °C;
- Recharge Rate: 310 L/s;
- Applications: Ideal for large-scale heating systems, including residential and commercial complexes in Oradea [10]. Its recharge capacity supports sustainable extraction without significant resource depletion.

Beiuș Reservoir:

- Area: 47 km²;
- Depth: 1870–2370 m;
- Temperature: 84 °C;
- Significance: Powers the only Romanian city, Beiuș, where urban heating is exclusively geothermal [30]. It serves as a model for centralized renewable energy use [34].

Bors Confined Reservoir:

- Area: 12 km²;
- Depth: ~2500 m;
- Temperature: >120 °C;
- Challenges: The reservoir's high gas content (70% CO₂, 30% CH₄) necessitates advanced scaling mitigation technologies, which increase operational complexity [35].

Ciumeghiu Reservoir:

- Thermal Capacity: 5 MWth;
- Applications: Supports localized greenhouse heating and potential hybrid applications, such as solar-geothermal integration [34].

4.2. Thermal Energy Capacity and Applications

The thermal energy capacities of Romania's geothermal aquifers range from low-enthalpy to medium-enthalpy resources (temperatures of 30 °C to 120 °C). These resources are particularly well-suited for (Figure 3):

- **District Heating:** In cities like Oradea and Beiuș, geothermal energy powers large-scale heating systems with minimal carbon emissions, consistent with broader trends in modern district heating technology [36,37].
- **Agricultural Applications:** Greenhouses and agricultural drying facilities benefit from consistent and cost-effective heating, as demonstrated in Ciumeghiu and Timis County [5,27].
- **Industrial Processes:** Medium-enthalpy aquifers, such as Bors, hold potential for more energy-intensive applications, including pre-heating in manufacturing processes [30].

Main Uses of Geothermal Energy in Romania (End of 2018)

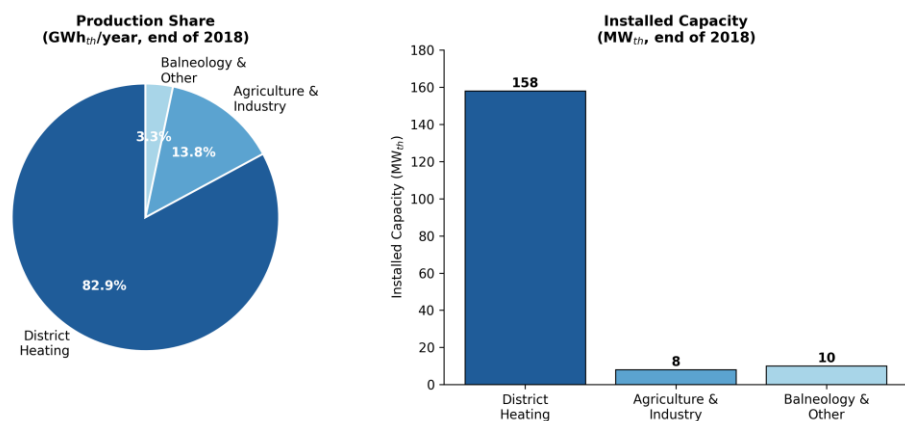


Figure 3. Main uses of geothermal energy in Romania, end of 2018—installed capacity (MW_{th}) and annual production share (GWh_{th}/yr) by application category: district heating, agriculture and industry, and balneology and other uses [31].

4.3. Challenges in Geothermal Utilization

Despite the promising potential, several challenges hinder the full exploitation of Romania's geothermal resources:

- **Scaling and Corrosion:** High dissolved solids and gases in some aquifers, such as those in the Bors Reservoir, lead to scaling and corrosion, necessitating advanced treatment systems [18,38].
- **Infrastructure Gaps:** Many geothermal systems lack modernized drilling and heat exchange technologies, limiting their scalability [5,39].
- **Policy and Financial Barriers:** While European Union directives provide a supportive framework, national implementation lags in terms of incentives and streamlined regulatory processes [40].

4.4. Future Directions for Development

To address these challenges and capitalize on the available potential, Romania must adopt a multi-faceted approach:

- **Enhanced Resource Mapping:** Deploy advanced geological and geophysical surveys to identify and quantify untapped geothermal resources [36]. The application of 3D seismic imaging and subsurface modeling, as practiced in Iceland and New Zealand, can greatly improve Romania's resource characterization and risk assessment [16].
- **Integration with Hybrid Systems:** Combine geothermal energy with solar or wind systems to maximize energy efficiency and minimize operational costs [41,42]. In addition to hybrid solar-geothermal systems, leveraging advancements in binary cycle

power plants and enhanced geothermal systems (EGSs) could unlock deeper reservoirs and expand Romania's geothermal frontier [43,44].

- **Incentive-Based Policies:** Introduce robust financial mechanisms to attract private investments and encourage public-sector involvement in geothermal energy projects [5].

5. Geothermal Resource Management

Effective management of geothermal resources is critical to ensuring their sustainable utilization while maximizing economic and environmental benefits [45,46]. In Romania, geothermal energy management operates within a framework of national policies and European Union directives [20,47]. This section explores the regulatory, operational, and strategic aspects of geothermal resource management in Romania, highlighting challenges and opportunities for improvement.

5.1. Regulatory Framework

Romania adheres to a robust regulatory framework that aligns with European Union standards for renewable energy [20].

The following key directives and laws govern geothermal energy use in the country, alongside occupational health and safety standards applicable to drilling operations [48]:

- **Directive (EU) 2023/2413 (RED III)**, amending Directive (EU) 2018/2001: Sets a binding EU-wide target of at least 42.5% renewable energy share by 2030, building on the original framework established by Directive 2009/28/EC (2009) and its 2018 recast [20].
- **Directive (EU) 2023/1791 (recast Energy Efficiency Directive)**: Establishes the “energy efficiency first” principle as a binding legal obligation and sets a target of reducing EU final energy consumption by at least 11.7% by 2030 relative to 2020 projections, replacing the original Directive 2012/27/EU, which was formally revoked as of 12 October 2025 [24].
- **National Energy Strategy (2020–2030)**: Identifies geothermal energy as a priority resource for district heating and energy-efficient urban planning [5].

At the national level, the Romanian government has implemented tax incentives and subsidies to encourage the development of geothermal systems. For instance, the “Casa Verde Classic” program provides financial support for individuals and institutions to install geothermal heating systems, covering up to 8000 RON per project [27].

5.2. Challenges in Resource Management

Despite a supportive policy environment, several challenges hinder the efficient management of geothermal resources in Romania:

- **Fragmented Policy Implementation:** While national strategies identify geothermal energy as a priority, inconsistent enforcement and bureaucratic hurdles delay project execution.
- **Data Gaps in Resource Mapping:** Comprehensive and updated resource mapping remains a significant gap, leading to suboptimal exploration and utilization of geothermal aquifers.
- **Limited Financial Resources:** While programs like “Casa Verde” exist, funding is often insufficient to cover the high upfront costs associated with geothermal drilling and system installation [40]. A study by the Joint Research Centre (JRC) highlights the importance of harmonized financial instruments to de-risk geothermal projects across the EU [49]. (Table 2).

Table 2. Comparison of geothermal energy incentives in Romania and other European Union member states, highlighting subsidy levels and policy measures.

Country	Incentive Programs	Type of Incentives	Key Features
Germany	Renewable Energy Sources Act (EEG)	Feed-in Tariffs (FiTs)	Guaranteed prices for geothermal electricity [20]
	Market Incentive Program	Grants and Low-interest Loans	Financial support for heating systems and deep geothermal projects
France	Heat Fund (Fonds Chaleur)	Subsidies	Covers up to 60% of investment costs for renewable heat projects [20]
	Reduced VAT Rate	Tax Incentives	Reduced VAT on renewable energy equipment
Italy	Conto Energia Termico	Grants	Financial support covering a portion of investment costs [5]
	Ecobonus	Tax Deductions	Tax deductions up to 65% for energy efficiency improvements
Netherlands	SDE++ Scheme	Operating Subsidies	Subsidies for unprofitable components of projects [27]
	Geothermal Guarantee Scheme	Risk Mitigation	Covers costs if geothermal exploration is unsuccessful
Romania	Casa Verde Program	Grants/Subsidies	Up to 8000 RON (~€1600) for geothermal heat pump installations [26]
	Reduced VAT Rate	Tax Incentives	VAT reduced from 19% to 5% on renewable installations
Hungary	Renewable Energy Support Scheme (METÁR)	Feed-in Tariffs	Guaranteed purchase prices for renewable electricity [5]
		Investment Grants	Grants covering up to 50% of investment costs
Poland	Operational Program Infrastructure and Environment	EU Co-financing	EU funds for renewable projects, including geothermal [5]
	Tax Reliefs	Tax Incentives	Accelerated depreciation and tax relief for investments
Croatia	Feed-in Tariffs	FiTs	Long-term contracts with guaranteed prices for geothermal electricity [5]
	EU Cohesion Funds	EU Co-financing	Funding for sustainable energy projects

6. Best Practices and Innovations

Romania can benefit from adopting international best practices in geothermal resource management (Figure 4). Key strategies include:

- Integrated Resource Mapping and Monitoring:
- Examples from Iceland and Italy show that advanced geological survey integration with real-time thermal monitoring enhances geothermal planning and sustainability [5];
- Investing in advanced geological surveys and real-time monitoring systems to improve resource mapping accuracy and sustainability assessments [16];
- Collaboration with research institutions and international organizations to leverage global expertise. International networks like the European Geothermal Energy Coun-

cil (EGEC) and IEA Geothermal have proven effective in disseminating technical guidelines and fostering innovation in member states [5].

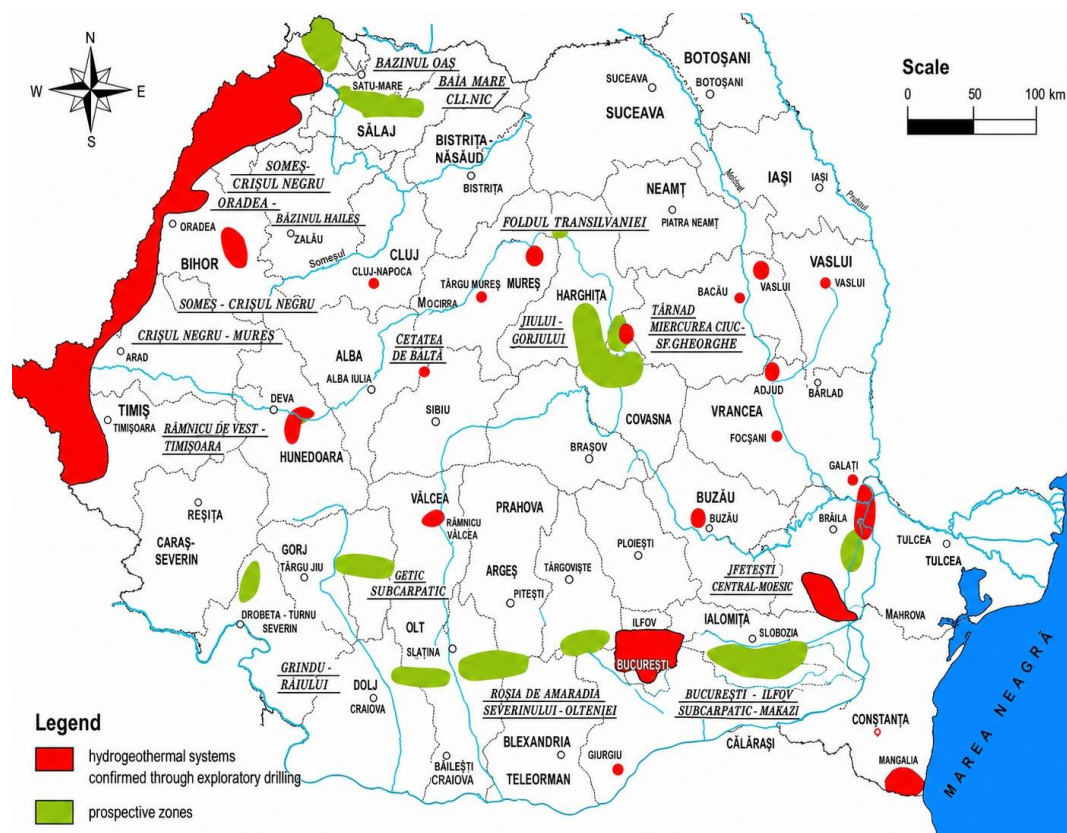


Figure 4. Geographical distribution of researched geothermal systems and prospective zones in Romania. Red-marked areas indicate hydro-geothermal systems confirmed through exploratory drilling, including the large western Pannonian corridor (Borș, Oradea, Banatul de Vest) and numerous localized sites such as Mociu, Ibănești, Cetatea de Balta, Secuieni, Adjud, Tușnad, Arbănași, Hârșova, and Mangalia. Green-marked areas indicate prospective zones with identified geothermal potential not yet confirmed by drilling, including Bazinul Oaș, Toplița–Lunca Bradului, Miercurea Ciuc–Sâncrăieni, Godeanu, Târgu Jiu–Târgu Cărbunești, Slatina–Hârșești, Bolintin Vale–Crevedia Mare, and București Fundulea–Slobozia–Amara. The map includes a north arrow and a 100 km scale bar, modified after Negoită (1970) [18], Bandrabur et al. [1], Cadere (1985) [10], and CoHuț and Bendea (2000) [41].

- Public–Private Partnerships (PPPs):
- Encourage private investment through favorable policies, risk-sharing mechanisms, and streamlined approval processes [40].

Examples from other EU nations, such as Iceland’s geothermal sector, highlight the importance of PPPs in accelerating resource development. PPP models adopted in countries such as Germany and Denmark have accelerated geothermal deployment by reducing financial risk and promoting investor confidence [34].

- Technology Upgrades:
- Adopt cutting-edge technologies such as automated drilling systems and hybrid geothermal solutions to reduce operational costs and enhance efficiency [11];
- Integrate geothermal energy with other renewable systems (e.g., solar thermal or biomass) for hybrid applications [50].

Future Policy Directions

To address existing challenges and capitalize on geothermal resources, Romania's policy framework must evolve in the following ways:

- **Strengthening Incentives:** Expand financial support programs to include subsidies for research and development (R&D) and pilot projects [5];
- **Decentralized Energy Planning:** Empower local governments to develop and manage geothermal projects, tailored to regional needs and capabilities [8,28];
- **Legislative Updates:** Introduce updated legal frameworks to streamline project approvals, regulate sustainable extraction rates, and minimize environmental impact [4].

7. Prospects for Geothermal Energy Development in Romania

Romania's geothermal energy sector, while demonstrating considerable potential, remains largely underutilized. As the country strives to meet its commitments under the European Union's renewable energy targets for 2030 and beyond, the development of geothermal energy presents a transformative opportunity. This section explores the future directions, technological advancements, and strategic initiatives that could unlock Romania's geothermal potential.

7.1. Exploration of Untapped Resources

Romania's geothermal resources are predominantly concentrated in the western regions, yet many areas remain underexplored. The implementation of advanced resource mapping techniques, such as 3D seismic imaging and thermal conductivity analysis, is crucial for identifying and quantifying untapped aquifers. Particular attention should be directed to regions such as the southern Carpathians and the eastern plains, where geothermal potential is suspected but lacks detailed geological surveys.

Increased collaboration with European research institutions and industry leaders could further enhance exploration efforts. Programs such as Horizon Europe provide funding for such initiatives, fostering innovation in geothermal resource assessment and development.

7.2. Integration with Advanced Technologies

The future of geothermal energy in Romania lies in its integration with cutting-edge technologies. Hybrid renewable systems, combining geothermal energy with solar or wind, can maximize energy efficiency and provide a stable energy supply [41]. Enhanced geothermal systems (EGSs), which involve creating artificial reservoirs to tap heat from dry rock formations, represent another promising avenue for Romania [43,51]. EGSs have the potential to expand geothermal energy beyond traditional aquifer-based systems, making it feasible in regions currently deemed unsuitable [52].

Additionally, the incorporation of smart grid technologies can optimize the distribution of geothermal energy, enabling real-time adjustments to demand and enhancing overall system efficiency [49,53]. Smart grid integration has already proven effective in several countries [54], offering a blueprint for optimized geothermal distribution and real-time energy management [49].

Furthermore, recent studies emphasize the role of digital technologies and enhanced operational models in scaling geothermal energy. For instance, [55] highlighted how reinforcement learning and predictive analytics can optimize heat flow management in building energy systems powered by geothermal sources. Similarly, [35] evaluated innovative well trajectory designs—such as multi-lateral and sub-horizontal wells—to enhance efficiency in marginal reservoirs, which holds relevance for Romania's deeper aquifers.

7.3. Policy and Strategic Goals

Romania's renewable energy strategy must align with the European Union's Green Deal and Fit for 55 packages, which aim to achieve carbon neutrality by 2050 [20]. To meet these ambitious targets, the government should:

- **Expand Incentive Programs:** Enhance existing schemes like the Casa Verde Program to cover a broader range of geothermal applications, including district heating and industrial uses. Successful incentive models, such as those adopted in France and the Netherlands, show the importance of stable, long-term financing for geothermal infrastructure development [5].
- **Streamline Permitting Processes:** Simplify regulatory procedures to reduce project lead times, encouraging private sector investment.
- **Promote Public Awareness:** Increase outreach campaigns to educate communities on the benefits of geothermal energy and its role in sustainable development. Public education campaigns in countries with robust geothermal sectors have shown that social acceptance improves markedly when communities understand the environmental and economic benefits of such projects [56].

By adopting these measures, Romania can create a robust policy framework that supports the accelerated deployment of geothermal technologies.

7.4. Economic and Environmental Benefits

Investing in geothermal energy offers both economic and environmental advantages:

- **Economic Gains:** Reduced reliance on imported fossil fuels can enhance energy security and stabilize energy prices. Furthermore, the growth of the geothermal sector could create jobs in drilling, equipment manufacturing, and system maintenance.
- **Environmental Impact:** Geothermal energy is a clean and sustainable resource. Utilizing Romania's geothermal potential could contribute significantly to reducing national greenhouse gas emissions, in line with targets established under Romania's National Energy Strategy 2020–2030 [27,28]; international assessments of comparable geothermal facilities confirm substantial emissions reductions relative to conventional heat and power generation [57].

7.5. Regional Collaboration and Research

The European Union encourages cross-border cooperation in renewable energy projects, and Romania stands to benefit from regional partnerships in geothermal energy. Collaborating with neighboring countries like Hungary and Croatia, which have established geothermal industries, can provide valuable insights and shared resources [5]. Joint research projects and technology transfer initiatives can accelerate the adoption of best practices and innovative solutions [16].

Romania's academic institutions also play a pivotal role. By fostering partnerships between universities, research institutes, and industry stakeholders, the country can build a skilled workforce and develop the technological expertise needed to advance its geothermal energy sector [16].

8. Conclusions

Romania's geothermal energy sector, with its substantial untapped potential, offers a transformative opportunity to reshape the country's energy landscape. As the nation moves toward meeting European Union renewable energy and carbon neutrality targets, geothermal energy stands out as a sustainable, reliable, and economically viable resource [58].

The exploration and development of geothermal resources, particularly in underexplored regions like the southern Carpathians and eastern plains, could significantly increase Romania's renewable energy capacity. Advanced techniques such as enhanced geothermal systems (EGSs) and hybrid renewable systems integrating geothermal with solar or wind energy provide pathways to expand geothermal utilization beyond its traditional aquifer-based applications [59,60]. These innovations not only diversify the resource base but also strengthen Romania's energy security by reducing dependency on imported fossil fuels. Reports from the IRENA and EU Innovation Fund suggest that countries investing in next-generation geothermal systems will lead regional decarbonization strategies [5,16].

Policy and strategic alignment are critical to realizing this potential. By streamlining regulatory processes, enhancing financial incentives, and fostering public awareness, Romania can create a favorable environment for geothermal energy investments. Programs such as Casa Verde, coupled with EU structural funding, have already proven effective in spurring localized projects. However, scaling these efforts requires a concerted focus on simplifying bureaucratic procedures and incentivizing large-scale infrastructure development.

Economically, geothermal energy promises long-term stability. Lifecycle analysis conducted in the EU demonstrates that geothermal systems, while capital-intensive upfront, become cost-effective within 5–7 years in urban heating scenarios [5,34]. Its lower lifecycle costs and consistent energy output position it as a cost-effective alternative to conventional energy sources. The sector's growth also has the potential to stimulate local economies through job creation in drilling, system installation, and maintenance. Environmentally, geothermal energy offers a clean alternative, capable of contributing meaningfully to reducing Romania's greenhouse gas emissions in line with national and EU climate commitments [27,28].

Collaboration is another key driver for success. Partnering with neighboring countries like Hungary and Croatia, which have well-established geothermal industries, provides an opportunity to exchange knowledge, resources, and best practices. Additionally, fostering ties between academia, research institutions, and private enterprises within Romania can accelerate technological development and create a skilled workforce to support the sector's growth [16].

In summary, geothermal energy is not just a supplementary resource but a cornerstone for Romania's sustainable energy future. With strategic investments in exploration, technology, policy reform, and international collaboration, Romania has the potential to establish itself as one of the leaders in geothermal energy within Eastern and Central Europe. Harnessing this resource effectively will not only help meet national and EU energy targets but also pave the way for a greener, more resilient energy system that benefits both the economy and the environment [16].

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