Interreg Danube Region

Co-funded by the European Union

Danube GeoHeCo

Report on Criteria Catalogue for optimization of shallow geothermal hybrid systems

Danube GeoHeCo D.1.1.1

Corresponding authors			
Tomislav Kurevija Marija Macenić	University of Zagreb – Faculty of Mining, Geology and Petroleum Engineering (UNIZG – RGNF)	tomislav.kurevija@rgn.unizg.hr marija.macenic@rgn.unizg.hr	Croatia
Country input			
Marcus Hofmann Thomas Kremsner Andrea Prochazka Johannes Schnitzer	Research Burgenland Ltd. (FB)	marcus.hofmann@forschung-burgenland.at, thomas.kremsner@forschung-burgenland.at, andrea.prochazka@forschung-burgenland.at, Johannes.schnitzer@ forschung-burgenland.at,	Austria
Ognjenka Zrilić Nikola Bojić Branko Zlokapa Slaviša Jelisić Medina Garić	LIR Evolution (LIR)	ognjenkaz@lir.ba nikolab@lir.ba brankoz@lir.ba slavisaj@lir.ba medinag@lir.ba	Bosnia and Herzegovina
Tomislav Kurevija Marija Macenić Anja Vrbaški Lucija Fir Matea Stanić Luka Perković	University of Zagreb – Faculty of Mining, Geology and Petroleum Engineering (UNIZG – RGNF)	tomislav.kurevija@rgn.unizg.hr, marija.macenic@rgn.unizg.hr, anja.vrbaski@rgn.unizg.hr, lucija.fir@rgn.unizg.hr, matea.stanic@rgn.unizg.hr, luka.perkovic@rgn.unizg.hr	Croatia
György Márton Judit Schaffer Zoltán Pámer	CROST Regional Development Nonprofit Ltd. (CROST)	marton@crost.hu schaffer@crost.hu pamer@crost.hu	Hungary
Tamás Medgyes	InnoGeo Research and Service Ltd. (InnoGeo)	tmedgyes@yahoo.com	Hungary
Radu A Munteanu Dan Iudean	Technical University of Cluj-Napoca (TUCN)	radu.a.munteanu@ethm.utcluj.ro dan.iudean@ethm.utcluj.ro	Romania
Davor Končalović Dušan Gordić Dubravka Živković Vladimir Vukašinović Mladen Josijević Filip Nastić	Faculty of Engineering in Kragujevac (FEK)	davor.koncalovic@kg.ac.rs dubravka@uni.kg.ac.rs	Serbia
Anna Krivjanska Rudolf Pastor	Slovak Centre of Scientific and Technical Information (CVTI SR)	anna.krivjanska@cvtisr.sk rudolf.pastor@cvtisr.sk	Slovakia

Mitja Janža Simona Adrinek Dušan Rajver	Geological Survey of Slovenia (GeoZS)	mitja.janza@geo-zs.si simona.adrinek@geo-zs.si dusan.rajver@geo-zs.si	Slovenia

LIST OF FIGURES

LIST OF TABLES

Introduction

The Danube GeoHeCo partner countries jointly created a criteria catalogue as an input for the design and technology optimization of the shallow geothermal hybrid heating and cooling systems in the partner countries Austria, Bosnia and Herzegovina, Croatia, Hungary, Romania, Serbia, Slovakia and Slovenia as well as for the European Union, where applicable, in the "Criteria catalogue for optimization of shallow geothermal hybrid systems".

The report will contribute to the development of IT decision support tool in Danube GeoHeCo project Activity 1.2 and its Deliverables 1.2, which will result in testing of the IT decision support tool in Activity 1.3 (and Deliverables 1.3) and selection of the specific pilot sites which will install hybrid shallow geothermal heating and cooling system. Finally, this will result with the implementation of the Activity 1.4, i.e. with the implementation of five pilot investment.

Constructing a criteria catalogue is crucial in the design of the IT tool which will be used for selecting the pilot sites in respective countries/regions as well as selecting the optimal technology for the selected sites as a show of proof-of concept for wider applications.

The first part of this report contains detailed description of the partner country in regard to the current status of the use of shallow geothermal energy (SGE), statistics regarding the number of installed SGE systems as well as waste heat systems where applicable, country energy mix with most relative data including the cost of energy, overview of current regulations and policies regarding the use of the SGE as well as incentives, where they exist. Furthermore, general country geology, hydrogeology and thermogeological conditions are described as well as costs for the SGE installations and environmental regulations and possible restrictions, all of which serves as an input information for the design of the hybrid systems. All of this information from the country reports is important for the future use of the IT tool, mainly for the investors and designers for the first estimate of the transition to the hybrid systems.
The second part of the report contains general information on the selected method for the making of a criteria catalogue, the so-called Analytic hierarchy process (AHP) methos which provides a comprehensive and systematic approach for multi-criteria decision-making, as is the case with the design and optimization of the shallow geothermal hybrid systems. The AHP is a structured group decision making technique for organizing and analysing complex decisions involving multiple criteria. The methodology of AHP allows decision makers (DMs) to model a complex problem in a hierarchical structure, compare the elements of the hierarchy in pairs, and derive priority scales based on their judgments. For the design and optimization of the hybrid SGE systems the AHP method was used to evaluate the most influencing factors in the established hierarchical structure by the invited DMs who are experts in the SGE system design, with overall goal or the focus (hybrid geo system optimization and project design), the criteria, and the sub-criteria as the lowest level. The criteria were considered as categories, subdivided into sub-criteria. The list of relevant criteria for the design and technology optimization consists of 20 criteria, arranged as sub-criteria for the four categories of criteria which were set as: technical and technological; geological, thermogeological and hydrogeological; socioeconomic and environmental, policy and climate criteria.
This report on criteria catalogue gives directions on what criteria should be focused on by the designer to have solid, reliable and efficient hybrid geothermal system.

1 Country status report for Austria

1.1. Introduction to shallow geothermal energy utilization

General

The utilisation of geothermal energy in Austria began during the oil crises of the 1970s. At around the same time, the first geothermally supplied heat pumps (in particular so-called "direct evaporators" - an Austrian speciality) were installed and the energetic use of thermal waters (direct application) was applied. The first geothermal direct application took place in Bad Waltersdorf (Styrian thermal spa region). Until a few years ago, the utilisation of geothermal energy for direct heat and electricity was closely linked to its use in thermal spas. After the end of the "thermal spa boom" in Austria, the past 10 years have seen a reorientation of geothermal energy towards energy utilisation.
Between 2000 and 2010, geothermal probes and the thermal utilisation of groundwater were the most important heat sources for heat pumps. Since 2010, however, air source heat pumps have become the dominant system due to the ease of authorisation and installation, making them the most important source of heat pumps in Austria. By setting the right incentives (efficient and time-saving authorisation procedures, targeted subsidies, etc.), the significance of geothermal heat within the heat pump market could certainly be significantly improved again.
Among the various geothermal technologies, near-surface geothermal energy has the greatest application potential in Austria, as geothermal energy is available everywhere in Austria and the investment can be made by many people. The Austrian Geothermal Energy Association estimates an expansion potential of around 700 times the current scope of application by 2040 if the right incentives are provided for small investors (house builders) as well as large investors (installers and operators of anergy networks). This means that by 2040, 14 TWh of heat could be made available for heating buildings using near-surface geothermal energy.

Vision 2030 for near-surface geothermal energy in Austria

- Expansion of highly efficient geothermal heat pumps for decentralised heat supply of at least 2 TWh in order to save 200 GWh of electricity annually by increasing efficiency
- Expansion of ecologically compatible and efficient cooling and storage applications (geocooling, seasonal heat storage)
- Expansion of geothermal-based solutions for use in decentralised low-temperature heating and cooling networks (anergy networks)
- With the help of efficiently used geothermal probes, more than 50% of Austria's low-temperature heat demand can be covered in a decentralised manner! [1]

Used Systems

Near-surface geothermal utilization in Austria is typically carried out using deep geothermal probes, shallow geothermal collectors and the direct use of groundwater. There are several other alternative designs for flat-plate collectors, such as trench collectors, trench collectors and geothermal baskets. All these systems are used as geothermal systems for heat pumps. There are various processes for

utilizing natural geothermal energy at depths of up to 100 meters. These processes are used for heating, cooling or hot water preparation in various applications.

Ground source Heat pump (GSHP)

The most used technology for shallow geothermal energy is ground source heat pumps. A circulating fluid absorbs heat from the ground by being channelled through pipe coils in the ground. The extracted heat is then transferred into the building via a heat exchanger, where it is used for heating, hot water or even cooling in summer.

Direct utilization systems

Direct utilization systems tap hot water directly from shallow geothermal sources without the need for a heat exchanger. These systems are suitable for applications with a constant demand for hot water, for example in industry, greenhouses or aquaculture.

Borehole systems (BHE)

Probe systems are vertical boreholes up to 100 meters deep that tap into deeper geothermal water. Compared to horizontal ground collectors of geothermal heat pumps, probe systems reach higher temperatures and are therefore suitable for applications with greater heat requirements. Figure 1.1. shows the base of a typical duplex U probe.

Figure 1.1. Probe base of a Duplex U probe [2]

There are also depth probes with a self-circulating heat transfer medium (Figure 1.2.). These are usually heat pipes filled with CO_2. Heat is transferred to the refrigerant via a heat exchanger at the probe head.

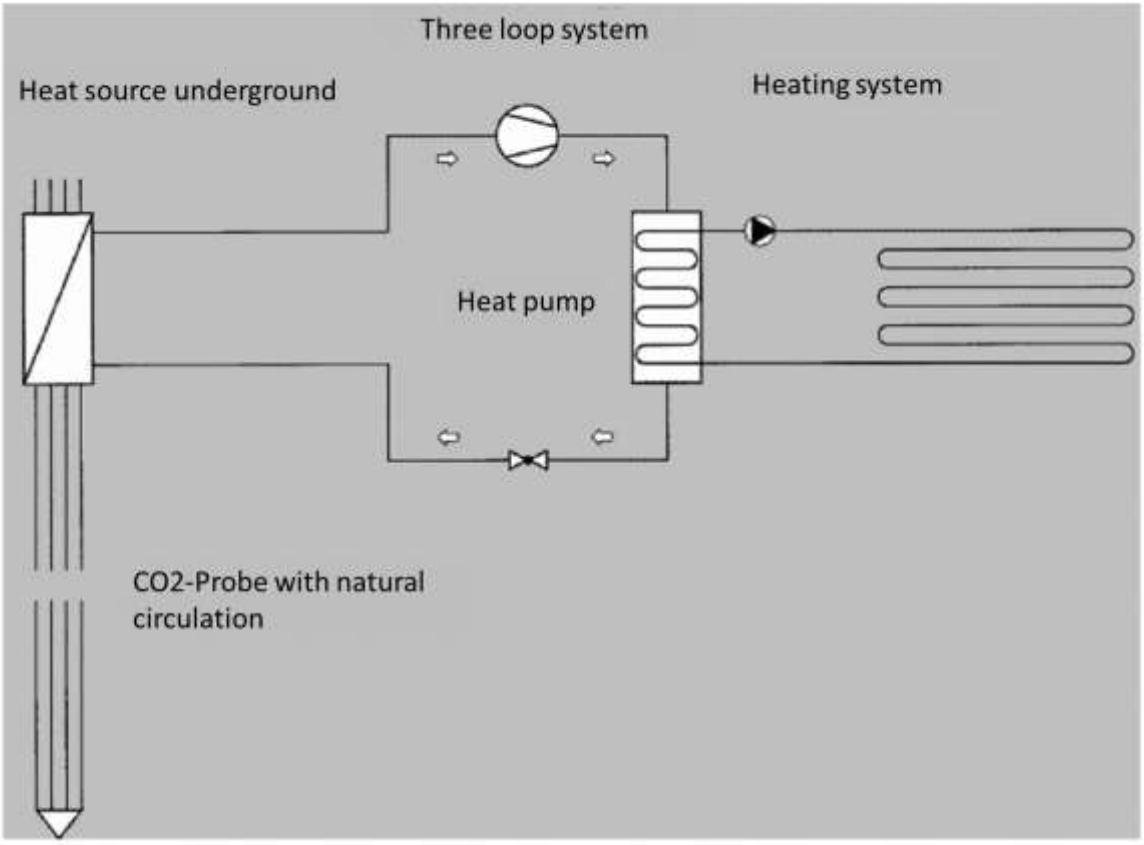


Figure 1.2. Structure of a CO2 depth probe [3]

Hybrid systems

Hybrid systems combine geothermal energy with other renewable or conventional energy sources to optimise energy efficiency and cost-effectiveness. For example, a geothermal heat pump can be combined with a solar thermal system to ensure a more balanced and reliable energy supply throughout the year.

Open Systems

Open systems pump groundwater, channel it for heat exchange and return the cooled water. Due to potential environmental impacts, open systems are less common, but can be efficient and powerful for large applications.

Closed systems

Closed systems, also known as brine circuit systems, use a frost-proof mixture (brine) in a closed pipe system in the ground. The brine absorbs the heat and transfers it to the heat exchanger in the building without touching the groundwater. Figure 1.3. shows a flat-plate collector after the pipes have been laid.

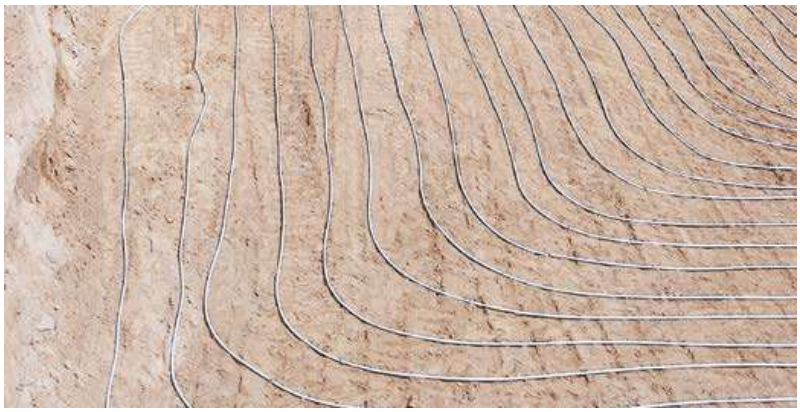


Figure 1.3. Geothermal flat-plate collector [2]

Thermal energy storage systems (TES)

TES systems can be integrated into geothermal systems to store excess thermal energy and release it again when required. This balances energy production and consumption, improves overall efficiency and reduces dependence on the electricity grid.

Geothermal cooling

Ground source heat pumps can also be used for cooling by reversing the heat transfer process. In summer, heat is extracted from the building and transferred to the cooler ground, thereby achieving natural air conditioning.

Use of shallow geothermal energy in Austria

Shallow geothermal energy is becoming increasingly important in Austria due to its environmental friendliness, low CO_2 emissions and cost-effective utilisation. It is particularly suitable for residential buildings, schools, hospitals and commercial properties.

1.2. Country statistics of installed shallow geothermal systems and general energy balances

Market overview of heating systems for each main residence in Austria

There are around four million main residences in Austria. Nationwide, 35 percent of these are still heated directly using fossil fuels: 22 percent heat with natural gas, 13 percent with heating oil. Coal no longer plays a role: only 0,1% of apartments are heated this way. Around half of district heating in Austria is based on renewable energies and is the most widespread form of heating, accounting for 30 percent of all main residences. Direct electricity heating such as night storage heaters, electric underfloor heating or infrared heating are used in six percent of main residences, and heat pumps are already in eleven percent of all main residences. There are also differences in this distribution on the federal state level (Figure 1.4. Big differences between the federal states in Austria [5]). The switch to 100 percent electricity from renewable energies is crucial in order to make these electricity-based forms of heating fit for the future and to bring more efficiency to the space heating sector overall. Wood heating systems are also traditionally widespread in Austria. Pellets, wood chips or logs are used as the primary heating system in 18 percent of main residences. [4]

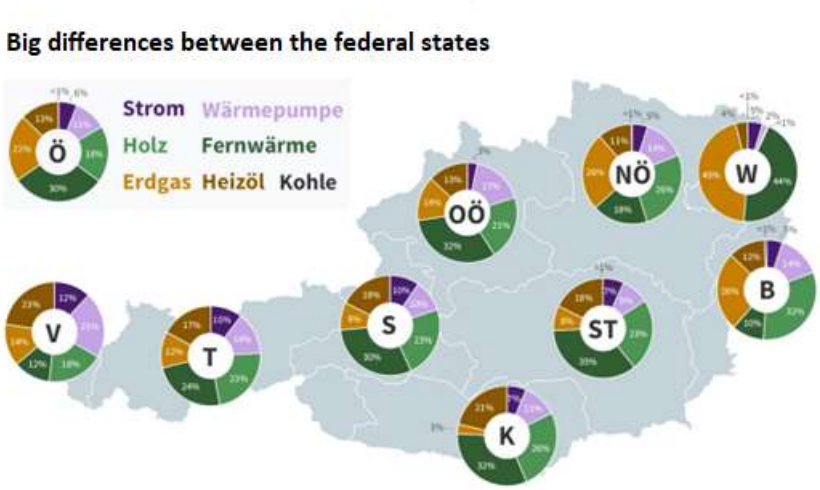


Figure 1.4. Big differences between the federal states in Austria [5]

Market statistics for geothermal energy use in Austria

Installed Systems

With regard to near-surface geothermal energy, there are around 102000 installations in 2024 so far, the installed heat output was around 1600 MW and the heat produced was around 2600 GWh.

With regard to deep geothermal energy, in 2024 there were two electricity generation plants with an installed capacity of 0,2 MW_e, which generated approx. 0,5 GWh_e of electrical energy, and ten heat generation plants (direct-use systems, 9 of which with heat network feed-in) with an installed capacity of 105 MW_{th}, which produced 300 GWh_{th} of heat.

In total, this corresponds to approximately a 4% share of the renewable heating market in Austria (Figure 1.5.) [6].

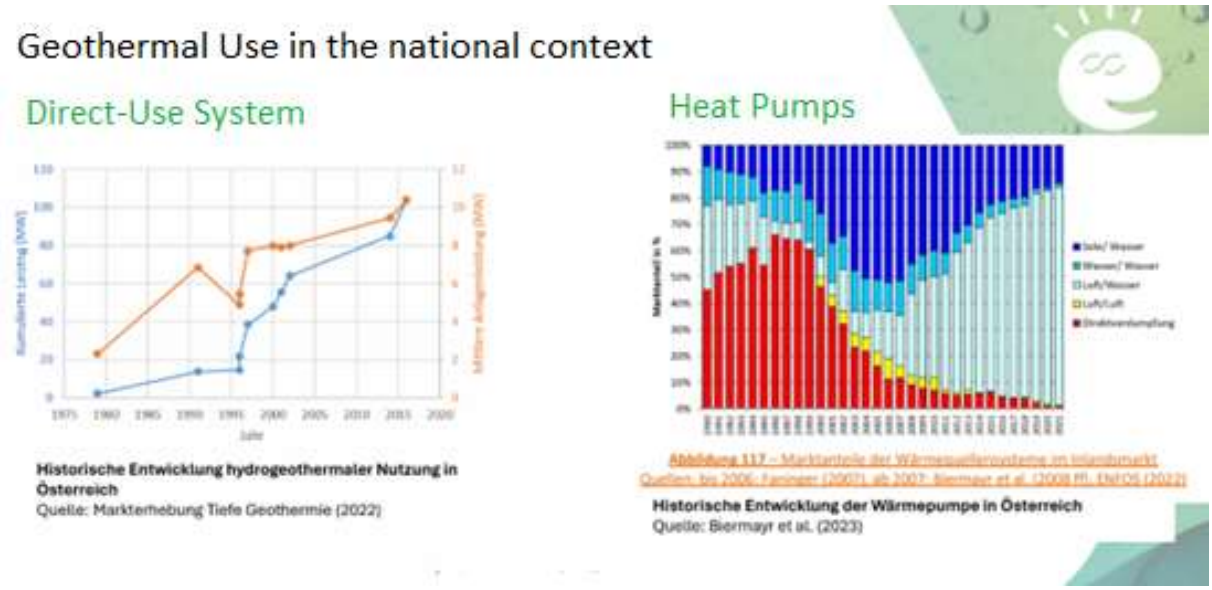


Figure 1.5. Geothermal use in the national context [7]

Geothermal sales – number of heat pumps sold annually

In 2022, 49192 heating heat pumps, 11153 domestic water heat pumps, 1201 ventilation and air heat pumps and 131 industrial heat pumps were sold in Austria [8].
Domestic market 2022: 61677 units (2). In 2022, more heat pumps were sold in Austria than ever before, and sales increased by +62% compared to 2021. The majority (over 50000) are heating heat pumps, making them the top-selling heating system (46% share of the heating market) [9]. An overview of the distribution can be found in Figure 1.6. Table 1.1. shows emission factors for most used energy sources in Austria.

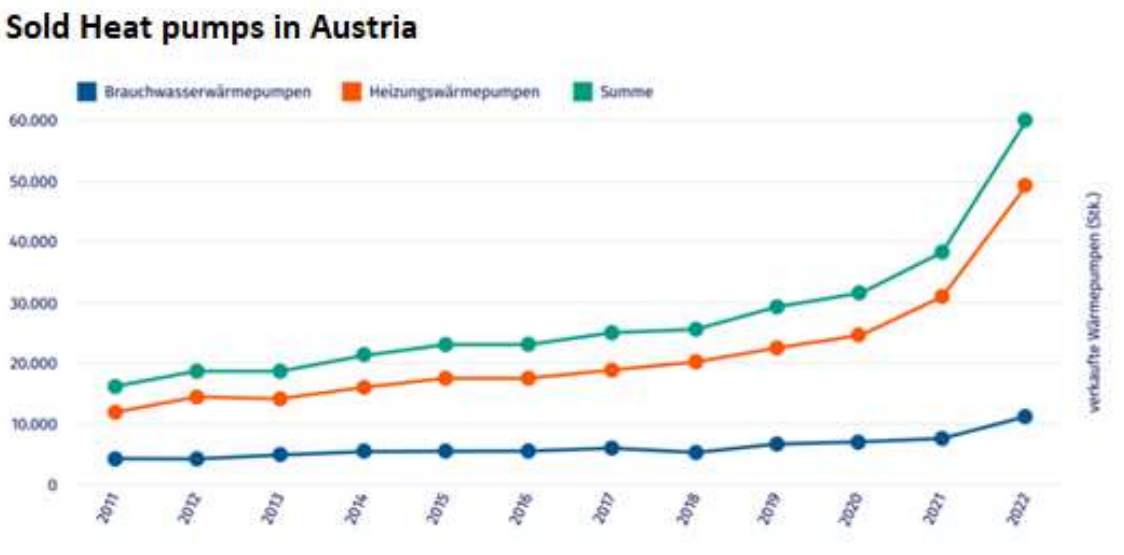


Figure 1.6. Sold Heat pumps in Austria [9]

Table 1.1. Emission factors of individual energy sources in Austria [10]

Energy carrier	Calorific value	Density	CO_2-equivalent-direct emission	CO_2-equivalent-indirect emission	CO_2-equivalent - total emission
	kWh/kg		kg/kWh	kg/kWh	kg/kWh
Power generation Austria	–	–	0,182	0,044	0,226
Extra light heating oil	11,77	0,84 kg/l	0,271	0,074	0,344
Natural gas	13,57	0,75 kg/Nm^3	0,201	0,049	0,249
Wooden pellets**	4,8	650 kg/m^3	0,005	0,021	0,026
Wood**	3,82	–	0,016	0,009	0,024
District heating	–	–	0,126	0,052	0,179

1.3. Overview of current regulations, incentives and general policy related to shallow geothermal

Below are regulations pertaining to shallow geothermal energy utilization.

Renewable Expansion Act

A central energy and climate policy goal of the federal government is to convert our country's electricity supply to 100 percent electricity from renewable energy sources (nationally balanced) by 2030 and to make Austria climate-neutral by 2040, The Renewable Energy Expansion Act (EAG) is intended to create the necessary legal and organizational framework and a long-term, stable investment climate.

The EAG not only addresses the promotion of electricity and gas production from renewable energy sources, but also the organization and functioning of renewable energy communities, certificates of origin for energy from renewable energy sources and their recognition, green certificates for gas from renewable energy sources, a green gas seal and the Creation of an integrated Austrian network infrastructure plan (ÖNIP).

Both operating subsidies in the form of sliding market premiums and investment subsidies are used as funding instruments for the future provision of renewable electricity and gas.

Subsidies based on market premiums are intended for electricity generation from hydropower, wind power, photovoltaic, biomass and biogas systems. The funding period is 20 years (from the start of operation of the respective system). In addition, a successor market premium can be granted for existing biomass and biogas plants until the end of the plant's 30th year of operation.

Investment grants are granted for the new construction and expansion of photovoltaic systems and electricity storage systems as well as for the new construction of wind turbines up to 1 megawatt (MW) in accordance with the respective ranking and the available funding. In order to support the market ramp-up for the production of renewable gases, a service point for renewable gases will be implemented for the first time as part of the EAG. Furthermore, the conversion of existing biogas plants to produce renewable gas to natural gas quality, new plants to produce renewable gas and plants to convert electricity into hydrogen or synthetic gas can be supported through investment grants. [12]

Renewable Heat Act

The Federal Law on the Renewable Heat Supply in New Buildings (Renewable Heat Act (EEC)), Federal Law Gazette I 8/2024, which came into force on February 29, 2024, is intended to allow the installation of heat supply systems based on fossil fuels for space heating and/or hot water preparation is generally prohibited in new buildings (with corresponding transitional provisions for projects under construction).

There are no regulations in the EEC for fossil fuel-operated systems in existing buildings. However, as part of the "Get out of oil and gas" funding campaign, the switch to climate-friendly heating systems in residential buildings is being promoted. All of these grants can already be applied for.
The Renewable Heat Act provides good framework conditions for switching to heat pumps in Austria. The EEC offers transitional periods and long-term funding for the switch. In addition, heat pumps that will be installed up to and including 2024 are not affected by the planned European F-gas regulation.

Relevant technical standards

In Austria, geothermal depth probes are designed according to VDI4640 [12]. A description of the procedure for this standard is summarized in ÖWAV Rules Batt 207 (ÖWAV 207).
The temperature of the groundwater close to the surface and not influenced by anthropogenic effects varies in Austria between 7°C and 12°C at a depth of 7 m below the surface level. The annual temperature fluctuations take place at depths of 10 to 20 m depending on the groundwater dynamics and the soil substrate. In general, the temperature at depth increases by 1°C per 33 m due to the heat inside the earth.
The dimensioning of geothermal probes can be done using the following methods:

- Design based on operating data of existing systems.
- Design according to VDI 4640 – Thermal use of the subsurface
- Design according to SIA 384/6 – geothermal probes.
- Dimensioning of probe fields using numerical modelling

Current federal and state funding

On December 12, 2023, the Environmental Promotion Commission decided on the funding announced by the government, which will come into force on January 1, 2024. The funding is part of a comprehensive program to support the transition to climate-friendly heating systems.
New technology-specific subsidies will apply nationwide from 2024, which vary depending on the type of heating system. For example, the funding for an air-water heat pump is 16,000 euros and for a water-water or brine-water heat pump 23,000 euros. Additional surcharges, such as a drilling bonus or a solar bonus, can further increase these amounts. These federal subsidies, in combination with state subsidies and tax incentives, can cover up to 75% of the total investment costs.

What exactly is being funded?
Eligibility covers various aspects related to the installation of a heat pump, such as the costs of the device itself, planning costs, heat source systems, integration into the heating system, and dismantling and disposal costs for boiler and tank systems that have been taken out of service (Table 1.2.). Here are the most important points regarding heat pumps:

1. Flat rate subsidies and cost caps
2. Federal funding for heat pumps will apply technology-specific flat rate funding from 2024.
3. For air/water heat pumps, the upper cost limit is €25383, while brine/water or water/water heat pumps can be subsidized with up to €37252.
4. There are differentiated flat rate subsidies for different heating systems to take the different investment costs into account. For example, single or two-family homes receive a flat rate of 15,000 euros for a connection to local or district heating, while the installation of a water-water or brine-water heat pump is supported with 23000 euros.

Table 1.2. Overview of federal and state funding

Funding provider	Funding	Sector	Funding agency
Bund	"Get out of oil and gas" single/two-family house/terraced house	Private	Link
Bund	"Clean heating for everyone"	Private	Link
Bund	"Get out of oil and gas" multi-story residential building	Private	Link
Bund	"Get out of oil and gas" new construction, conversion or renewal of HP <100kW	Company/ clubs	Link
Bund	Heat pumps ≥100 kW thermal output	Company/ clubs	Link
Bund	Saving energy in companies	Company/ clubs	Link
Bund	Energy centers for the provision of heat and cold	Company/ clubs	Link
Bund	Optimization measures in climate-friendly district heating networks	Company	Link
Bund	Waste heat extraction	Company	Link
Bund	Innovative local heating networks	Company/ clubs	Link
Burgenland	Replacement of fossil heating	Private	Link
Burgenland	Alternative energy systems heating	Private	Link
Burgenland	Alternative energy systems hot water	Private	Link
Kärnten	Replacement of fossil heating	Private	Link
Niederösterreich	Heat pump as part of housing subsidies for new buildings and renovations	Private	Link
Niederösterreich	Replacement of fossil heating	Private	Link
Oberösterreich	Replacement of fossil heating	Private	Link
Oberösterreich	Heat pumps < 100 kW thermal output	Company	Link
Oberösterreich	Heat pumps ≥100 kW thermal output	Company/ clubs	Link
Oberösterreich	Innovative heating centers and distribution networks	Company	Link
Oberösterreich	Heat pumps for communities	Community	Link

Salzburg	Renewable central heating	Private	Link
Salzburg	Renovation funding: construction or renewal of the building's central heat supply system (housing funding)	Private	Link
Salzburg	Oil boiler out bonus for community buildings of e5 communities	Community	Link
Steiermark	Replacement of fossil heating	All	Link
Tirol	Residential building renovation: CLIMATE-FRIENDLY HEATING SYSTEM + additional funding for heat pumps	Private	Link
Tirol	New construction funding: additional funding for heat pumps	Private	Link
Tirol	Energy saving measures with heat pumps	Company/ clubs	Link
Vorarlberg	Promotion of heat pumps in residential buildings	Private	Link
Vorarlberg	Various community funding	Private	Link
Vorarlberg	Saving energy for SMEs in Vorarlberg	Company/ clubs	Link
Wien	Replacement of fossil heating	Residential construction	Link

Demands to improve the accessibility of geothermal energy in Austria

According to the energy supply company Wien Energie, comprehensive funding and research initiatives are needed to promote the use of geothermal energy in Austria. There is also a need for simplification of administrative procedures and faster authorisation processes. An amendment to the Mineral Resources Act is recommended in order to remove legal obstacles and facilitate investment. According to estimates by Wien Energie, deep geothermal energy in Austria could have a potential of 450 to 700 megawatts, with Vienna alone accounting for up to 60 per cent of this potential. [11]

1.4. General country geology, hydrogeology and thermogeological parameters

Austria has a diverse geological history, characterized by the deposition of various rocks and sediments over hundreds of millions of years. Austria's geological structure is strongly influenced by its location in the Central Alps, which are part of the Alpine mountain system.
The Alps were formed by the collision of tectonic plates, in particular the African and Eurasian plates. This led to the formation of fold mountains in which a variety of rocks can be found, including sedimentary rocks such as limestone, dolomite, marl and sandstone as well as metamorphic rocks such as gneiss and slate. In some areas, igneous rocks such as granite also occur.
In the eastern part of Austria, especially in the Vienna Basin and the Pannonian Plain, sedimentary rocks such as sandstone, clay and limestone dominate, which were deposited during the geological

history of the Neogene and Quaternary periods. Volcanic activity has also influenced some parts of Austria in the past, particularly in the region around Lake Neusiedl.
Overall, Austria's geology offers a rich variety of rocks and geological formations. An overview of the geological structure can be found in the geological map in Figure 1.7**.**

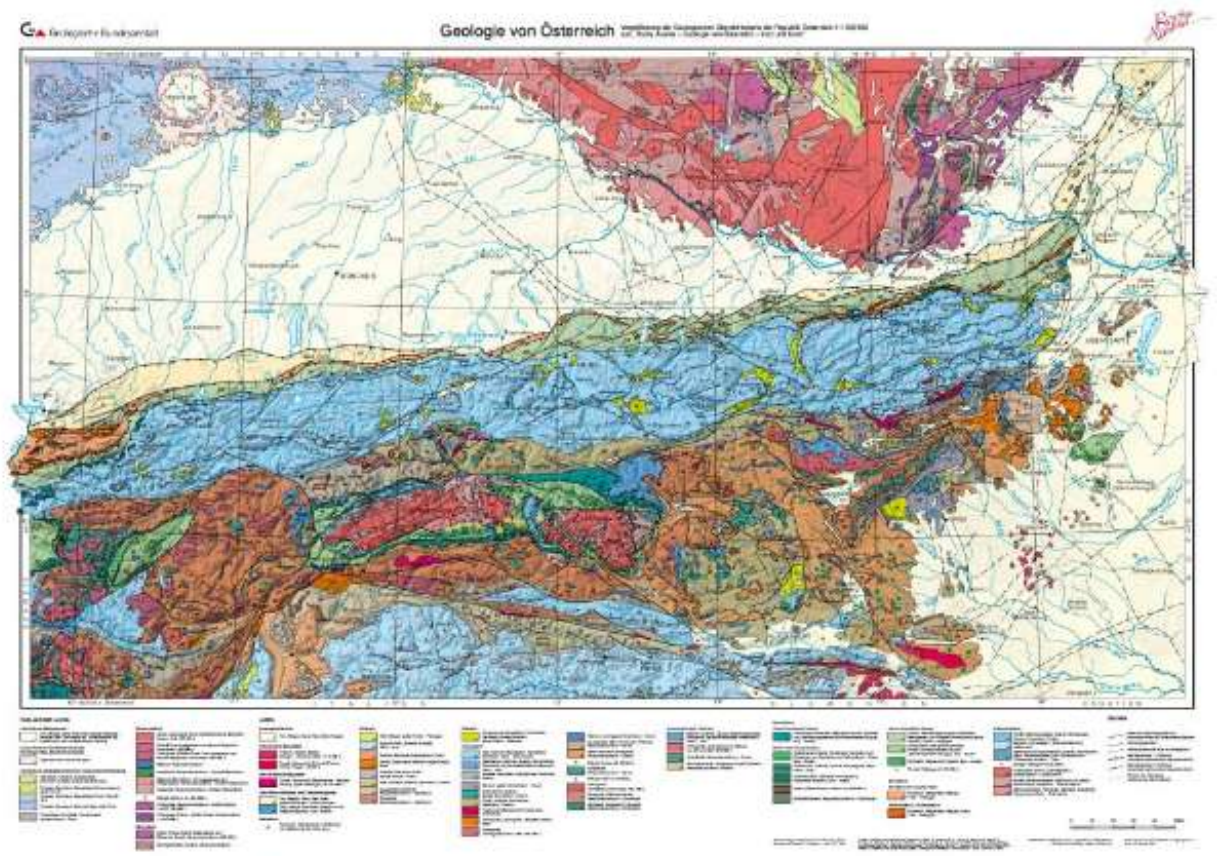


Figure 1.7. Geological map of Austria (Source: Geological Survey of Austria)

Based on the geological subsoil, the possible extraction capacity of the borehole probes can be determined depending on the groundwater occurrence, which can be queried in the water register of the respective location.
The dimensioning according to VDI 4640 [12] is carried out according to specific extraction capacities in W/m for the borehole probe according to the following table (Table 1.3.):

Table 1.3. Extraction capacities of depth probes according to VDI 4640

Substrate	Max. Spec. extraction capacity at 1,800 h/a	Max. Spec. extraction capacity at 2,400 h/a
General guide values:		
Poor substrate (dry sediment (l<1.5 W/mK	25 W/m	20 W/m
Normal rock subsoil and water-saturated gravel (l=1.5-3.0 W/mK)	60 W/m	50 W/m
Solid rock with high conductivity (l>3W/mK)	84 W/m	70 W/m
Individual rocks:		
Gravel Sand dry	<25 W/m	<20 W/m
Gravel, sand water-bearing	65-80 W/m	55-65 W/m
Clay, loam, moist	35-50 W/m	30-40 W/m
Solid limestone	55-70 W/m	45-60 W/m
sandstone	65-80 W/m	55-65 W/m
Acid magmatites (e.g. granite gneiss	65-85 W/m	55-70 W/m
Alkaline magmatites (e.g. basalt)	40-65 W/m	35-55 W/m

If longer operating times are required, the corresponding extraction capacities must be reduced so that the annual extraction work does not exceed the values specified in the table. Flat-plate collectors are assessed and designed according to the nature of the surface and the on-site assessment. The required extraction capacities can be taken from VDI 4640 (Table 1.4.).

Table 1.4. Extraction capacities for flat-plate collectors according to VDI 4640

Substrate	Max. Spec. extraction capacity at 1800 h/a	Max. Spec. extraction capacity at 2400 h/a
Dry, non-cohesive soil	10W/m^2 und 5W/ running metre	8W/m^2 und 4W/ running metre
Cohesive soil, moist t	20-30W/m^2 und 15W/ running metre	16-24W/m^2 und 12W/ running metre
Water-saturated sand / gravel	40W/m^2 und 20W/ running metre	32W/m^2 und 16W/ running metre

The specific extraction rates based on the different layers of the geological subsurface can be used to determine the terrestrial heat flow density [mW/m²]. Figure 1.8. shows an overview for Austria (incl. current thermal water utilization and locations of the 10 CHP plants already mentioned in the market statistics).

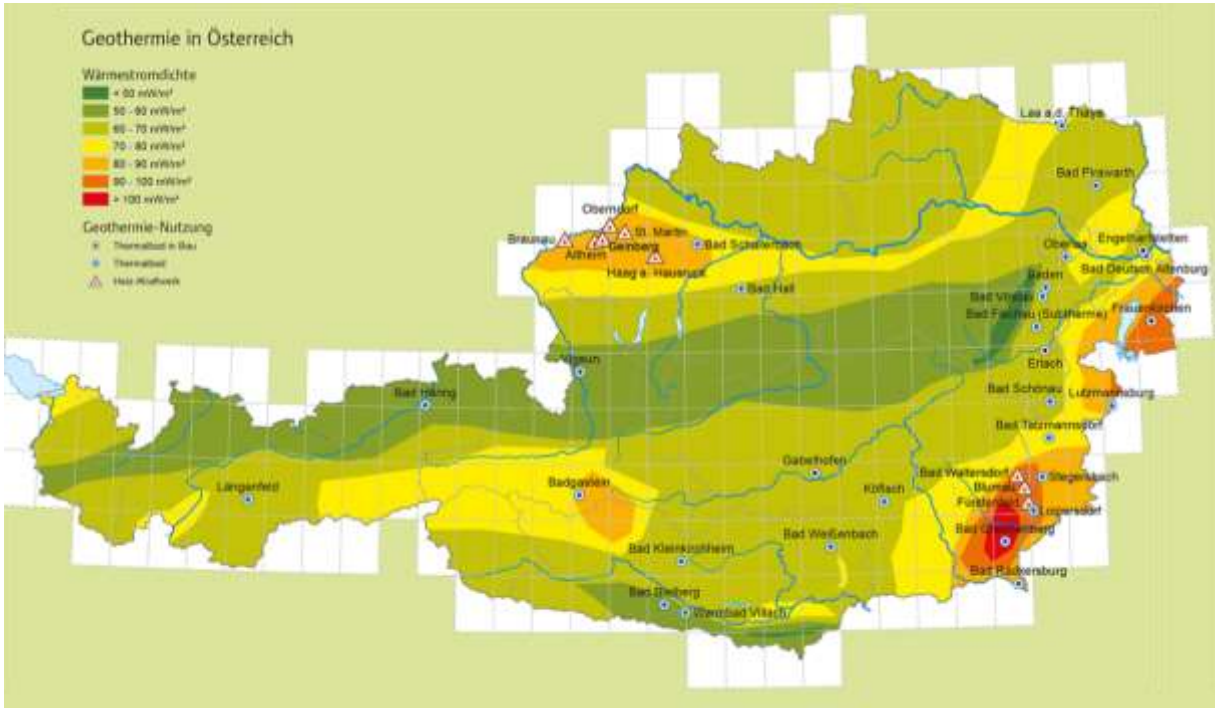


Figure 1.8. Geothermal potentials, terrestrial heat flow in Austria [7]

In Austria, several geothermal projects have already been realized or are currently under development. Upper Austria is regarded as a pioneer with seven geothermal district heating networks, while most of the other heating plants are located in Styria, for example in Bad Waltersdorf, Blumau and Fürstenfeld. Vienna is also currently working on a major deep geothermal project.

Waste heat potentials in Austria

As part of the European Energy Efficiency Directive (2012/27/EU), all member states had to draw up a "*Comprehensive assessment of the potential for the use of high-efficiency cogeneration and efficient district heating and cooling*" in their respective countries. The Vienna University of Technology and ecofys were commissioned by the Federal Ministry of Science, Research and Economy to carry out this assessment for Austria.
Firstly, the current heating and cooling demand of all consumption sectors (households, services and industry) was localized regionally, and scenarios of future development were determined. This heating and cooling demand was then compared with a possible supply of heating and cooling from CHP plants (combined heat and power), industrial waste heat and renewable energy sources. From this, technical potential was initially determined by applying technological restrictions. The economic potential was then estimated using a comprehensive cost-benefit analysis of the various technically feasible options. The technical waste heat potentials calculated within this study by sector are shown in Figure 1.9. The technical potential is to be understood as potential waste heat, the actual utilization possibilities of which depend on the individual technical, economic and regulatory framework conditions.

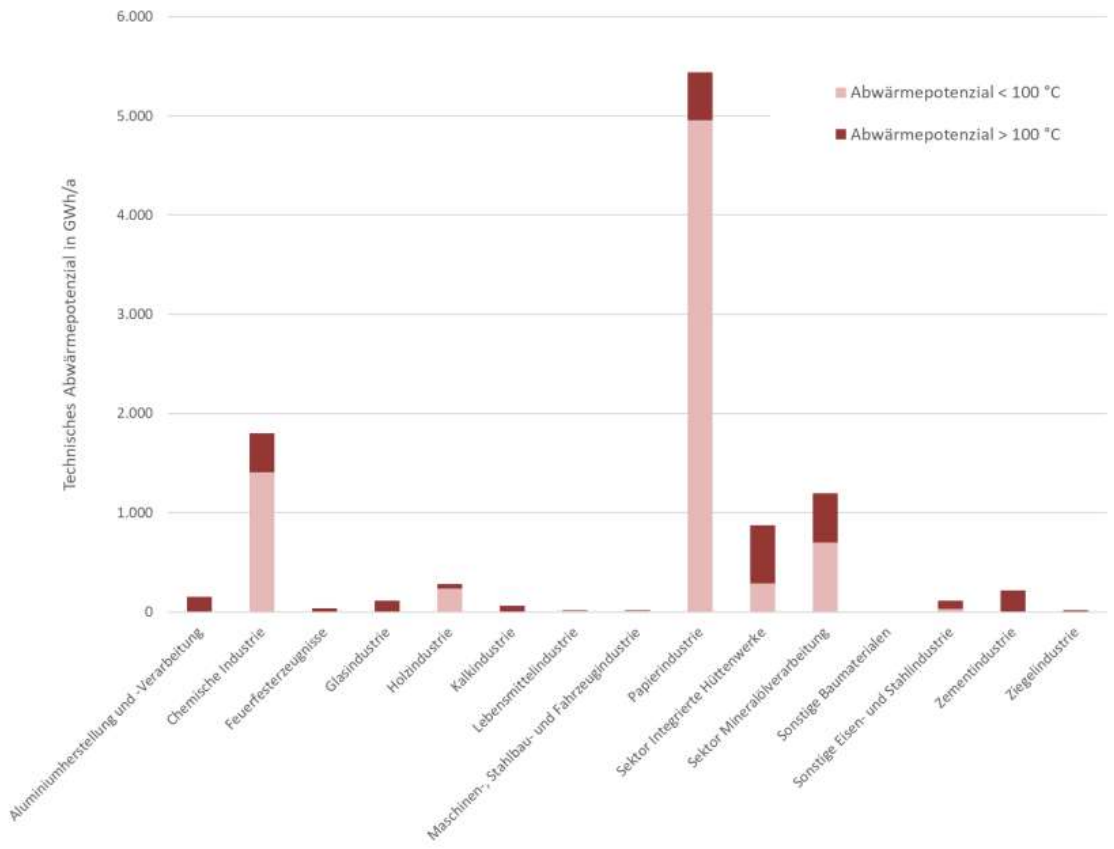


Figure 1.9. Technical waste heat potential by sector and temperature level (source: own calculations, based on the data of [13])

1.5. Current energy cost comparison for residential and non-residential sector with estimated capital cost of drilling and equipment for shallow geothermal

Energy prices

The following energy prices, in Tables 1.5. – 1.12., were gathered from the independent electricity and gas regulatory authority for all consumers in Austria, the e-control [14].

Table 1.5. Electricity prices for residential customers in Austria for March 2024

Residential customers (Status: March 2024)					
Range	Cent/kWh	2022		2023	
		1st half of the year	2nd half of the year	1st half of the year	2nd half of the year
Average	Energy Price	9,041	13,314	19,398	21,922

	Network Price	6,585	7,056	7,743	7,985
	Taxes and expenses	6,873	6,843	6,130	6,576
	Total Price	**22,499**	**27,213**	**33,272**	**36,482**
Residential customers < 1000 kWh/a	Energy Price	12,327	17,844	25,473	26,758
	Network Price	12,382	14,693	15,138	15,725
	Taxes and expenses	12,009	10,359	9,523	9,804
	Total Price	**36,718**	**42,896**	**50,134**	**52,287**
Residential customers 1000 - 2500 kWh/a	Energy Price	10,046	14,788	21,210	23,591
	Network Price	7,866	8,546	9,211	9,497
	Taxes and expenses	8,454	7,492	7,185	7,573
	Total Price	**26,366**	**30,826**	**37,605**	**40,661**
Residential customers 2500 - 5000 kWh/a	Energy Price	9,159	13,590	19,422	22,012
	Network Price	6,660	7,084	7,718	7,890
	Taxes and expenses	6,923	6,280	6,135	6,564
	Total Price	**22,741**	**26,954**	**33,275**	**36,466**
Residential customers 5000 - 15000 kWh/a	Energy Price	8,584	12,599	18,399	20,783
	Network Price	5,777	6,103	6,813	6,888
	Taxes and expenses	5,988	5,449	5,545	5,936
	Total Price	**20,348**	**24,151**	**30,757**	**33,606**
Residential customers above 15.000 kWh/a	Energy Price	8,192	11,796	17,896	20,071
	Network Price	5,159	5,431	6,165	6,287
	Taxes and expenses	5,585	5,048	5,380	5,737
	Total Price	**18,935**	**22,274**	**29,441**	**32,095**

Table 1.6. Electricity prices for residential in Austria by yearly average prices

Cent/kWh		Residential customers
2016	1. Half of the year	6,300
	2. Half of the year	6,234
2017	1. Half of the year	6,031
	2. Half of the year	6,021
2018	1. Half of the year	6,044
	2. Half of the year	6,201
2019	1. Half of the year	6,542
	2. Half of the year	6,948
2020	1. Half of the year	7,162
	2. Half of the year	7,256
2021	1. Half of the year	7,191

	2. Half of the year	7,445
2022	1. Half of the year	9,041
	2. Half of the year	13,314

Table 1.7. Electricity prices for commercial customers in Austria for March 2024

Commercial customer (Status: March 2024)					
Größenklassen	Cent/kWh	2022		2023	
		1. Half of the year	2. Half of the year	1. Half of the year	2. Half of the year
Average	Energy Price	12,500	16,054	19,137	18,369
	Network Price	3,065	3,119	3,768	3,558
	Taxes and expenses	5,485	5,014	5,006	4,809
	Total Price	**21,051**	**24,188**	**27,911**	**26,735**
Commercial customer < 20 MWh/a	Energy Price	9,749	14,163	20,213	22,177
	Network Price	6,304	6,862	7,616	7,839
	Taxes and expenses	6,819	6,521	6,326	6,595
	Total Price	**22,873**	**27,547**	**34,155**	**36,610**
Commercial customer 20 MWh/a uo to 500 MWh/a	Energy Price	9,429	12,828	20,330	20,660
	Network Price	5,005	5,116	5,984	5,799
	Taxes and expenses	5,490	4,765	5,886	5,851
	Total Price	**19,924**	**22,710**	**32,201**	**32,311**
Commercial customer 500 MWh/a up to 2.000 MWh/a	Energy Price	10,680	13,351	20,806	20,104
	Network Price	3,710	3,755	4,555	4,207
	Taxes and expenses	5,066	4,262	5,588	5,324
	Total Price	**19,457**	**21,367**	**30,949**	**29,636**
Commercial customer 2.000 MWh/a up to 4.000 MWh/a	Energy Price	12,819	15,344	20,409	19,201
	Network Price	3,040	3,091	3,731	3,497
	Taxes and expenses	5,257	4,422	5,351	4,985
	Total Price	**21,117**	**22,857**	**29,492**	**27,682**
Commercial customer 4.000 MWh/a up to 20,000 MWh/a	**Energy Price June 2023** – Commercial Customer Price	13,125	16,127	18,962	18,342
	Network Price	2,656	2,774	3,319	3,132
	Taxes and expenses	5,053	4,351	4,912	4,743
	Total Price	**20,834**	**23,252**	**27,193**	**26,217**
Commercial customer 20,000 MWh/a	Energy Price	13,645	16,963	19,800	18,220
	Network Price	2,030	2,187	2,472	2,500

up to 70,000 MWh/a	Taxes and expenses	4,986	4,195	4,858	4,555
	Total Price	**20,661**	**23,344**	**27,129**	**25,275**
Commercial customer 70,000 MWh/a up to 150,000 MWh/a	Energy Price	14,531	18,192	15,950	15,521
	Network Price	1,605	1,637	1,976	1,826
	Taxes and expenses	5,012	4,306	3,558	3,385
	Total Price	**21,148**	**24,135**	**21,484**	**20,732**
Commercial customer above 150,000 MWh/a	Energy Price	14,268	19,145	17,935	15,742
	Network Price	1,242	1,286	1,475	1,393
	Taxes and expenses	4,796	4,700	3,981	3,537
	Total Price	**20,306**	**25,131**	**23,391**	**20,672**

Table 1.8. Electricity prices for commercial customers in Austria by yearly average prices

Cent/kWh		Commercial customer
2016	1. Half of the year	4,011
	2. Half of the year	4,088
2017	1. Half of the year	3,930
	2. Half of the year	3,812
2018	1. Half of the year	3,887
	2. Half of the year	4,240
2019	1. Half of the year	4,675
	2. Half of the year	4,664
2020	1. Half of the year	4,923
	2. Half of the year	5,024
2021	1. Half of the year	5,440
	2. Half of the year	7,170
2022	1. Half of the year	12,500
	2. Half of the year	16,054

Table 1.9. Gas prices for residential in Austria for March 2024

Residential customers (Status: March 2024)					
Range	Cent/kWh	2022		2023	
		1. Half of the year	2. Half of the year	1. Half of the year	2. Half of the year
Average	Energy Price	4,210	8,048	10,855	9,693
	Network Price	1,737	1,909	1,960	2,144
	Taxes and expenses	2,030	2,787	3,637	3,410

	Total Price	**7,977**	**12,745**	**16,452**	**15,247**
Residential customers 5.600 kWh/a	Energy Price	5,068	9,558	12,637	10,413
	Network Price	3,168	3,627	3,437	3,922
	Taxes and expenses	2,712	3,823	4,619	4,246
	Total Price	**10,948**	**17,008**	**20,693**	**18,581**
Residential customers 5.600 kWh/a up to 55.600 kWh/a	Energy Price	3,986	7,908	10,678	9,418
	Network Price	1,711	1,827	1,916	2,047
	Taxes and expenses	1,966	2,710	3,568	3,308
	Total Price	**7,664**	**12,445**	**16,162**	**14,773**
Residential customers above 55.600 kWh/a	Energy Price	4,263	7,506	10,233	9,531
	Network Price	1,299	1,348	1,428	1,498
	Taxes and expenses	1,959	2,626	3,396	3,250
	Total Price	**7,521**	**11,480**	**15,056**	**14,278**

Table 1.10. Gas prices for residential customers in Austria by yearly average prices

Cent/kWh		Residential customers
2017	1. Half of the year	3,092
	2. Half of the year	3,122
2018	1. Half of the year	3,054
	2. Half of the year	3,218
2019	1. Half of the year	3,164
	2. Half of the year	3,240
2020	1. Half of the year	3,186
	2. Half of the year	3,182
2021	1. Half of the year	3,055
	2. Half of the year	3,432
2022	1. Half of the year	4,210
	2. Half of the year	8,048

Table 1.11. Gas prices for commercial customers in Austria for March 2024

Commercial customers (Status: March 2024)					
Range	Cent/kWh	2022		2023	
		1. Half of the year	2. Half of the year	1. Half of the year	2. Half of the year
Average	Energy Price	7,006	10,487	6,324	5,237
	Network Price	0,329	0,391	0,431	0,521

	Taxes and expenses	1,504	1,840	1,354	1,295
	Total Price	**8,839**	**12,717**	**8,109**	**7,053**
Residential customers 278 MWh/a	Energy Price	3,871	5,867	8,107	8,779
	Network Price	1,392	1,512	1,584	1,712
	Taxes and expenses	1,828	2,205	2,919	3,166
	Total Price	**7,091**	**9,584**	**12,610**	**13,656**
Residential customers 278 MWh/a up to 400 MWh/a	Energy Price	3,846	5,391	8,001	8,264
	Network Price	1,121	1,235	1,303	1,366
	Taxes and expenses	1,768	2,037	2,877	2,926
	Total Price	**6,735**	**8,663**	**12,181**	**12,556**
Residential customers 400 MWh/a up to 2.778 MWh/a	Energy Price	4,178	5,743	8,241	7,534
	Network Price	0,860	0,985	0,954	1,112
	Taxes and expenses	1,758	1,983	2,766	2,684
	Total Price	**6,796**	**8,711**	**11,961**	**11,330**
Residential customers 2.778 MWh/a up to 5.595 MWh/a	Energy Price	4,211	6,030	7,055	5,977
	Network Price	0,794	0,883	0,926	0,971
	Taxes and expenses	1,696	1,944	2,455	2,257
	Total Price	**6,701**	**8,857**	**10,436**	**9,205**
Residential customers 5.595 MWh/a up to 27.778 MWh/a	Energy Price	5,518	7,950	6,291	5,251
	Network Price	0,549	0,575	0,633	0,660
	Taxes and expenses	1,862	2,186	2,152	1,963
	Total Price	**7,929**	**10,711**	**9,076**	**7,874**
Residential customers 27.778 MWh/a up to 277.778 MWh/a	Energy Price	5,641	8,333	5,081	3,991
	Network Price	0,302	0,318	0,358	0,376
	Taxes and expenses	1,696	1,966	1,620	1,400
	Total Price	**7,639**	**10,618**	**7,058**	**5,767**
Residential customers 277.778 MWh/a up to 1.111.111 MWh/a	Energy Price	6,192	9,241	4,384	3,612
	Network Price	0,192	0,242	0,280	0,331
	Taxes and expenses	1,577	1,836	0,958	0,874
	Total Price	**7,961**	**11,319**	**5,622**	**4,817**
Residential customers above 1.111.111 MWh/a	Energy Price	8,816	13,588	6,950	5,568
	Network Price	0,160	0,201	0,233	0,362
	Taxes and expenses	1,285	1,661	0,921	0,891
	Total Price	**10,261**	**15,450**	**8,104**	**6,822**

Table 1.12. Gas prices for commercial customers in Austria by yearly average prices

Cent/kWh		Residential customers
2017	1. Half of the year	1,952
	2. Half of the year	1,952
2018	1. Half of the year	2,071
	2. Half of the year	2,336
2019	1. Half of the year	2,000
	2. Half of the year	1,671
2020	1. Half of the year	1,490
	2. Half of the year	1,559
2021	1. Half of the year	1,983
	2. Half of the year	4,862
2022	1. Half of the year	7,006
	2. Half of the year	10,485

The Table 1.13. shows the energy prices for biogenic energy sources published by the Austrian Biomass Association [14, 15].

Table 1.13. Energy prices for biogenic energy sources [14,15]

	Electricity	Oil extra light	Natural gas	Pellets	Firewood/hard	Forest chips
Apr.24	34,14	12,14	17,02	6,09	7,26	4,08
Mär.24	34,18	12,12	17,19	6,55	7,26	4,1
Feb.24	34,44	12,64	17,83	6,91	7,31	4,14
Jän.24	34,66	12	18,09	7,32	7,31	4,09
Dez.23	35	12,35	18,11	7,86	7,39	4,08
Nov.23	35	12,35	18,11	7,86	7,39	4,08
Okt.23	34,91	13,3	18,13	8,08	7,39	4,02
Sep.23	35,45	13,39	18,23	8,39	7,39	3,85
Aug.23	35,36	12,61	18,13	8,49	7,43	4,27
Jul.23	33,31	11,09	18	8,41	7,43	4,27
Jun.23	34,41	10,87	17,37	7,78	7,45	4,25
Mai.23	35,58	11,36	17,22	6,69	7,46	4,64
Apr.23	35,58	11,36	17,22	6,69	7,46	4,64
Mär.23	34	11,78	16,49	7,47	7,46	4,68
Feb.23	36,59	12,38	16,95	8,9	7,42	4,67
Jän.23	36,44	13,35	16,85	10,51	7,42	4,42
Dez.22	25,54	13,48	12,75	11,11	7,22	4,53
Nov.22	25,54	14,65	12,75	12,36	7,2	4,53

Okt.22	25,54	17,14	12,12	12,93	7,09	4,53
Sep.22	25,54	15,77	11,72	11,61	6,8	4,43
Aug.22	22,96	15,25	9,01	10,98	5,96	4,33
Jul.22	22,96	16,05	9,01	8,99	5,96	4,33
Jun.22	22,28	15,82	8,8	7,49	5,53	3,7
Mai.22	22,8	13,65	9,46	6,85	5,34	3,7
Apr.22	22,14	13,93	9,1	6,59	5,17	3,65
Mär.22	21,53	15,83	8,93	6,25	4,65	3,27
Jän.22	22,9	9,09	8,32	6,13	4,18	3,16
Dez.21	23,09	8,4	8,04	5,41	4,08	3,16
Nov.21	22,95	8,93	8,04	5,08	4,07	3,16
Sep.21	22,95	7,62	8,03	4,68	4,06	3,16
Jul.21	22,76	7,57	8,06	4,54	4,06	3,16
Jun.21	22,76	7,39	8,05	4,51	4,06	3,16
Mai.21	22,76	7,11	8,05	4,46	4,06	3,16
Apr.21	22,76	6,86	8,05	4,73	4,05	2,38
Mär.21	22,76	6,88	8,1	4,73	4,05	3,16
Feb.21	22,76	6,79	8,1	4,75	4,05	3,16
Jän.21	22,74	6,26	8,1	4,72	4,04	3,19

Average costs of near-surface geothermal energy

Drilling is one of the most significant cost factors in geothermal projects. The average drilling costs are 1000-2000 euros per meter and increase significantly with increasing depth. For deep geothermal energy projects with boreholes between 1000 and 3000 meters, the investment costs can amount to up to 10 million euros. Added to this are the expenses for industrial heat pumps, which can be considerable depending on the project. For example, heat pumps with an output of 5 MW can cost 15-20 million euros in large projects.
For earth probe (BHE) drilling up to a depth of 100 meters, the average costs vary between 50 and 100 euros per meter of drilling, depending on the depth and condition of the ground. The costs for heat pumps are also variable. For small household geothermal heat pump (5-20 kW) costs are around 10000-15000 euros, while an 80 kW geothermal heat pump costs are around 40000 euros. According to a study by Meyers et al. [16] the costs for heat pumps with an output of over 100 kW are usually between 300 €/kWP and 1000 €/kWP, with the average being around 400 €/kWP. A heat pump with an output of 500 kW can cost up to 500000 euros [17].

1.6. Environmental regulations and restrictions related to shallow geothermal development

General

The distinction between “surface” and “deep” geothermal energy can be made based on various aspects. On the one hand, the distinction can be made based on the depth: In Austria, water law alone is responsible for depths of 300 m; for greater drilling depths, the Mineral Raw Materials Act also applies. This limit is legal, not technical. Other distinctions are based on the technology: near-surface geothermal energy is usually used to heat or air-condition buildings in combination with a heat pump. Deep geothermal energy, on the other hand, can also be used directly for balneology (for thermal baths) or for feeding into district heating networks due to the higher temperatures that occur. A gap opens up in between, which is closed with the term “medium-depth geothermal energy”.
There is currently no internationally valid definition for the terms deep and medium-deep geothermal energy, as the terms have often been established based on regional conditions - both in terms of the legal situation and the geological conditions. In Austria, deep or medium-depth geothermal energy refers to the use of thermal energy from layers of the earth at depths of 300 m or more below the earth's surface. This results from the fact that drilling deeper than 300 m in Austria is subject to the Mineral Raw Materials Act. The Mineral Raw Materials Act regulates drilling, but not geothermal use. Depending on the type of use, commercial, building and energy law permits are required at regional and national level.

Near-surface geothermal energy

The legal basis for the use of geothermal energy in Austria is the Water Rights Act (WRG 1959). This legal text sets the framework; the federal states are responsible for enforcement. In all cases, thermal groundwater use requires approval in accordance with the approval procedure (§103 WRG 1959). Geothermal probes generally do not require a permit; approval in the notification procedure (§114 WRG 1959) is only necessary under certain conditions. These prerequisites are the presence of artesian groundwater bodies or water protection areas. These zones can be seen in Austria in the so called “water book”.

Process of the official procedure

The notification procedure has a maximum processing time of 3 months and once the deadline has expired, the planned project is considered approved (Figure 1.10.). The responsible authority can also give written consent before the deadline expires, so construction can begin. The authority can also convert the notification into an approval process which is communicated in writing.

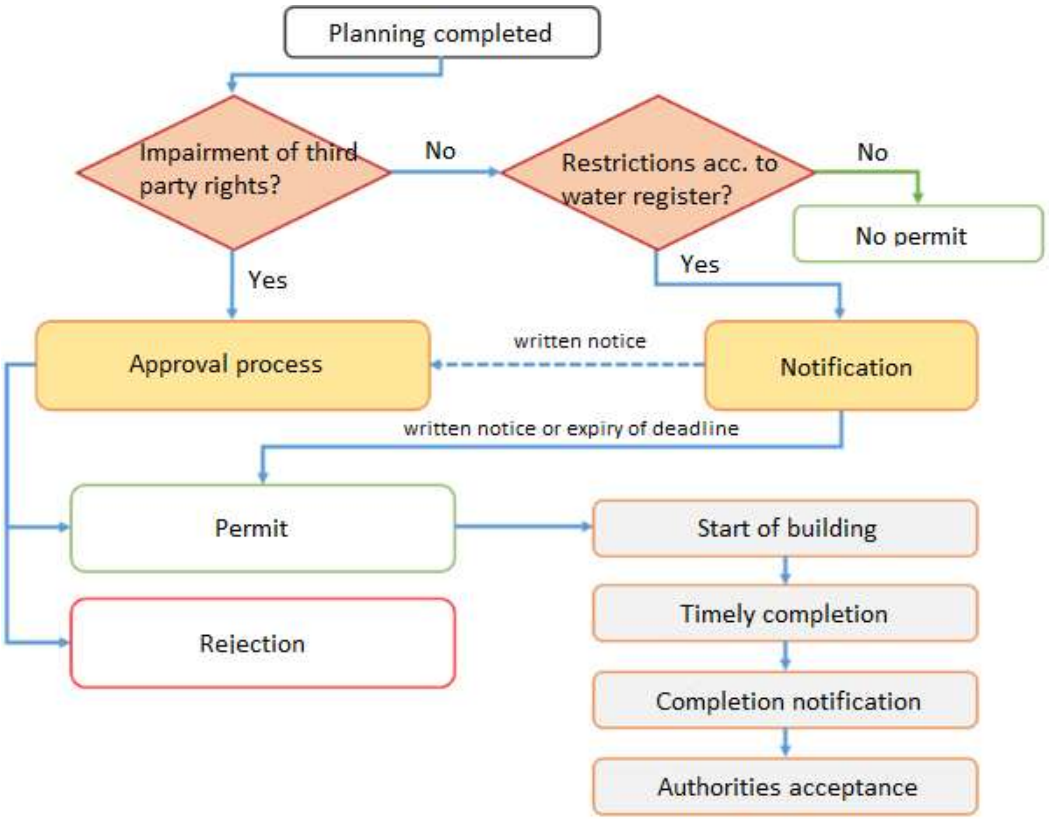


Figure 1.10. Illustration of the official procedure [17]

Legal basis for thermal groundwater use

These are systems in which groundwater is extracted and, after its thermal use, is changed (heated or cooled) and reintroduced into the ground. The following approval requirements apply:

- Section 10 WRG 1959 for the extraction of groundwater
- Section 32 paragraph 2 lit.b WRG 1959 for infiltration (reinjection)

Both cases require approval and are dealt with in a joint water law approval procedure. The prerequisite for approval is in particular that the planned project (removal and return) neither harms public interests (Section 105 WRG 1959) nor violates third-party rights (Section 12 WRG 1959). The water law procedure must examine whether the environmental objectives for surface water and groundwater (§§ 30a and 30c WRG 1959) are achieved.

All extraction tests and pumping tests that may be required require approval in accordance with Section 56 WRG 1959 if an impairment of public interests or a violation of existing rights (Section 12 WRG 1959) cannot be ruled out. All other systems to which these points do not apply do not require a permit

2 Country status report for Bosnia and Herzegovina

2.1. Introduction to shallow geothermal energy utilization

Historically, Bosnia and Herzegovina has utilized thermal springs and shallow geothermal resources for bathing and therapeutic purposes, dating back centuries. These natural hot springs were revered for their healing properties and were often incorporated into spa towns and wellness centres (Figure 2.1)

Figure 2.1. Geothermal spas in Bosnia and Herzegovina [18]

Potential of geothermal energy is not explored sufficiently in Bosnia and Herzegovina, although based on currently available data it could be said that Bosnia and Herzegovina has a certain geothermal energy potential, as regarding its presence and temperature value.

Geothermal energy is currently not used for district heating or production of electricity within the country. Geothermal energy in Bosnia and Herzegovina is related to artesian basins in its northern part from the Una to the Drina rivers, and in the central parts of Bosnia and Herzegovina with water temperatures of 20 - 96°C (Figure 2.2.). Temperatures at so far known and investigated locations in Domaljevac, Šamac (96°C), Kakanj (54°C), Sarajevo-Ilidža (58°C), Gračanica (39°C) and others are too low for the production of electricity, and this is the reason why geothermal energy from those sites is used only for exploitation in spas (balneology and heating facilities) and greenhouse production. There are no locations with temperature above 100°C, but it is assumed that higher temperatures can be found in some locations in northern part of Republika Srpska entity in greater depths.

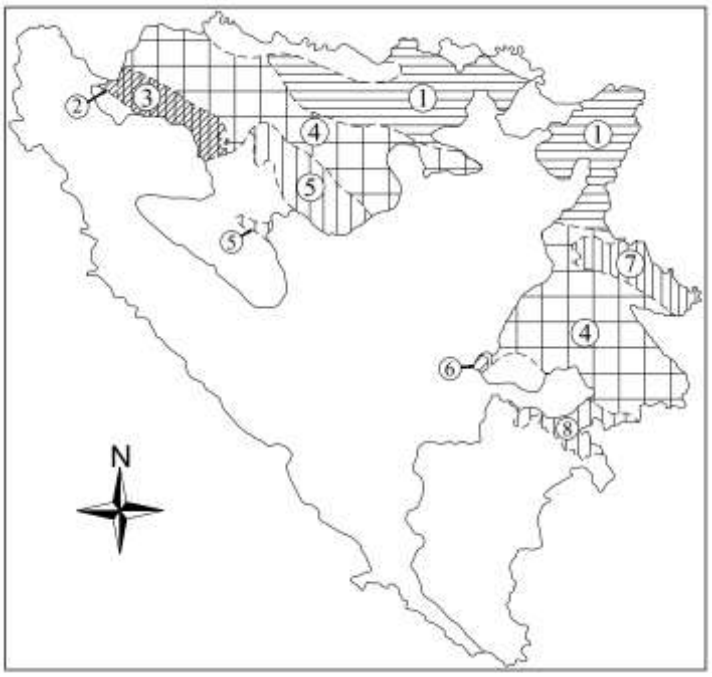


Figure 2.2. Geothermal regions in Republika Srpska - 1. North Bosnia, 2. Bihać-Kladuša, 3. Una-Sana, 4. Central part of Bosnia, 5. Banjaluka-Sarajevo,6. Central Bosnia region, 7. Eastern part of Bosnia, 8. Southeast part of Bosnia (based on map N. Miošić 1986) [19]

Geothermal gradients unevenly cover the Republika Srpska and have lower values than the average in Europe, which amount to 30 °C/km. Areas of the outer Dinarides have lower values, while areas of the inner Dinarides are characterized by a wider range from 21 – 50 °C/km. The highest values of the geothermal gradient are in the area of Semberija and Posavina, which range from 45 – 50 °C/km. The size of the heat flow, considering the thickness of the Earth's crust of 27 km on the territory of Republika Srpska, ranges from 65 - 100 mW/m^2, north of the line Novi Grad - Banja Luka - Doboj – Zvornik cities. [20]

2.2. Country statistics of installed shallow geothermal systems and general energy balances

All shallow geothermal (SG) systems in Bosnia and Herzegovina are financed in private arrangements and there are not any statistical data on number or capacity of those systems. Since regulation does not require any specific approval or documentation for installation of SG system (close loop) on private objects, responding data is not collected by any institution or organisation. Based on observation and estimation it could be concluded that SG systems are installed in a few hundred objects all over Bosnia and Herzegovina and used for heating of existing geothermal spas, but it is not utilized for district heating and overall share of geothermal in heat consumption is negligible.
Gross electricity production in Bosnia and Herzegovina was 1384 GWh in February 2024 (Table 2.1.). In total gross electricity production hydro power plants participated with the share of 38,4%, thermal power plants with 57,7% and solar and wind power plants with 3,9%.

Table 2.1. Electricity supply, BiH, February 2024 [21]

2022	2023		2023	2024		*Supply*
XII	I	II	XII	I	II	
1 519	1 528	1 292	1 514	1 573	1 384	*Gross production*
587	641	613	709	585	531	*Hydro power plants*
901	844	640	771	929	799	*Thermal power plants*
31	43	39	34	59	54	*Wind and Solar*
1 416	1 438	1 225	1 425	1 478	1 300	*Net production*
572	637	609	705	582	528	*Hydro power plants*
813	758	577	686	837	718	*Thermal power plants*
31	43	39	34	59	54	*Wind and Solar*
416	344	354	369	329	323	*Import*
716	684	564	717	670	633	*Export*
1 116	1 098	1 015	1 077	1 136	990	*Available for final consumption*

Due to the large share of thermal power plants in production, the network emission factor for carbon dioxide amounted to about 820 kg/MWh in 2018 (in 2013, it was about 720 kg/MWh) [22].

2.3. Overview of current regulations, incentives and general policy related to shallow geothermal

Bosnia and Herzegovina consists of two entities (Republika Srpska and Federation of BiH) and District of Brčko. The regulatory framework is very complex, and the energy legislation is under jurisdiction of entity Governments and their corresponding Ministries of energy. This includes legislation related to renewable energy, including geothermal energy. Energy legislation of both entities is mostly in conformity with each other, while the EU Accession process of BiH is contributing to gradual transposition of EU energy acquis into national law.

The Law on Geological exploration of Republika Srpska, enacted in 2022, regulates the types of geological research, the conditions and the method of carrying out geological research exploration of mineral and other geological resources, as well as geological exploration for the purpose of production documents of spatial planning, design, construction of buildings, rehabilitation and recultivation of terrain, development and revision of geological research programs and projects, expert examination, research area, development and revision of studies on reserves and studies on performed research, cadastre of research areas, Geological information system, Fund of professional documentation, Bank of exploratory well cores and other issues related to the field of geological research. In case of open-loop systems which utilise underground waters, regulatory approval is conditional following conducting of exploratory study to define existence, quantity, quality and other characteristics of underground water and aquifers, in accordance with the Law on waters of Republika Srpska.

Law on geothermal research of Republika Srpska states:

Article 9 (3) Detailed hydrogeological research is carried out for:

1) using hydro-geothermal and petro-geothermal resources, that is, to use the thermal energy of rocks.

Article 11 (4) Detailed geological research is also carried out for the purposes of using hydro-geothermal or petro-geothermal resources, that is, using the internal heat of the earth's crust.

Based on above stated legislation, any kind of research or use of geothermal energy would require preparation of the Research project and obtaining official approval regardless on type of research of matter of geothermal energy use. However, in practice existent shallow geothermal closed-loop systems have been implemented without any official approval and precise interpretation of Law is in dispute at least regarding this type of systems.

Despite a significant potential for utilization of geothermal energy in Republika Srpska, there has not been a detailed study and the potential is mainly used for balneological purposes and in spas. The Energy Strategy of Republika Srpska 2035, foresees that geothermal energy will be used for household heating with an expected target of 0,5%. In order to achieve this target detailed research and commercialisation of geothermal energy is required. The Law on Renewable Energy Sources of Republika Srpska, enacted in 2022 recognizes geothermal energy as one of renewable energy sources and foresees that the Government of RS can introduce subsidies for purchase of equipment for heating and cooling using geothermal energy. Up to now, a subsidy scheme has been implemented at the start of 2024 by the Fund for Environmental Protection and Energy Efficiency of Republika Srpska, whereby it was possible to apply for a subsidy for purchase and installation of geothermal heat pump systems. However, the subsidy amount was fairly small (up to 2500 EUR per user), so in practice shallow geothermal heat pump systems were not feasible for application within this programme. This subsidy scheme has been financed by the European Union for mitigation of negative effects of the energy crisis and support to energy transition.

2.4. General country geology, hydrogeology and thermogeological parameters

General country geology

Bosnia and Herzegovina as the state within Alpine orogene belongs to Dinaride geotectonic unit and has a very complex geological structure (Figure 2.3.). Geological map on Figure 2.4. shows the geology of the pre-Quaternary. The geological units and tectonic lines as faults and thrust are bounded by red coloured lines. The identification number (IN) provides the link between geological unit on the map and the description in the database is provided in Table 2.2.

Figure 2.3. Geological map of Bosnia and Herzegovina

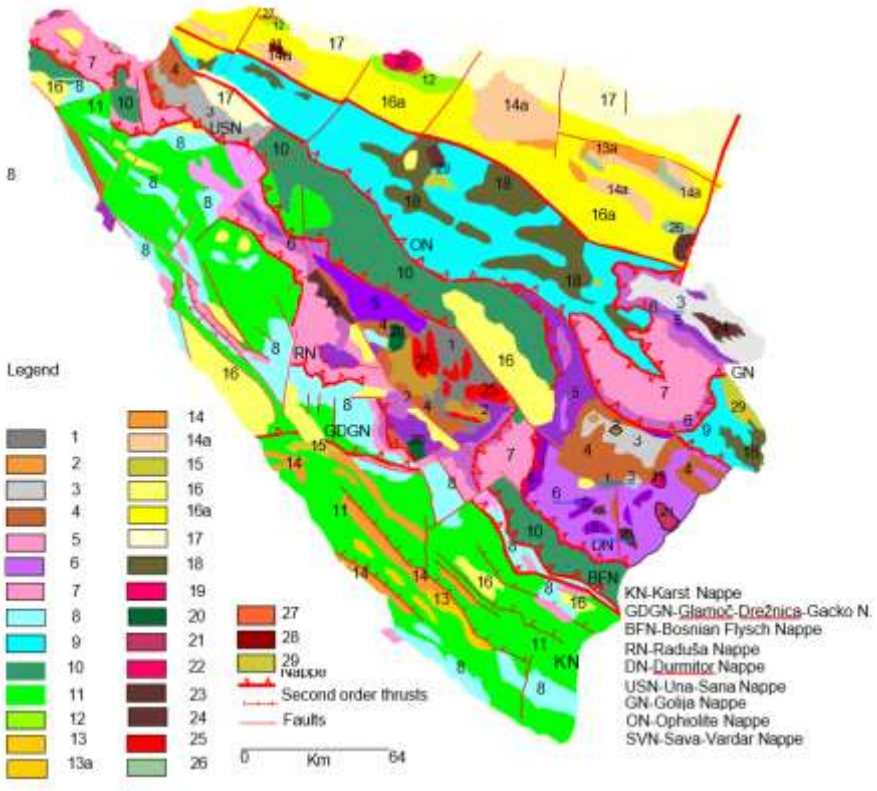


Figure 2.4. Pre-Quaternary geological map of Bosnia and Herzegovina [23]

Table 2.2. Legend for Pre-Quaternary geological map of Bosnia and Herzegovina

1	2	3	4	5	6
(IN) number	**Age**	**Petrography Category and rocks type**	**Orogen**	**Genesis**	**Region**
1	O, S	Metamorphic: Greenschist (shale, quartzite, marbl)	Alpine	Deep sea floor to escarpment	Mid-Bosnian Schist Mountains
2	D	Metamorphic: Limestone, dolomite, marble	Alpine	Marine platfor m	Mid-Bosnian Schist Mountains
3	C	Metamorphic: Greenschist: (Siltstone, sandstone, claystone, chert)	Alpine	Turbidite	Una-Sana, Southeast Bosnia and East Bosnia
4	P_3	Sedimentary: gypsum, ahydrite, sandstone, siltstone, limestone	Alpine	Epicontinental marine	Dinarides
5	T_1	Sedimentary: Sandstone, siltstone, claystone, limestone		Epicontinental Marine and fluvial system	Dinarides
6	T_2	Sedimentary: Limestone, marlstone, tuffite chert		Continental rift	Dinarides

7	T_3	Sedimentary: Limestone, dolomite, marlstone		Marine carbonate platform	Dinarides
8	J (Lower to Late)	Sedimentary: Limestone, dolomite, marlstone,		Marine carbonate platform	External Dinarides
9	J2-3	Mixed: Sandstone, siltstone, chert, diabase, gabro,			Dinaride Ophiolite melange
10	J,K_1 K_2	Sedimentary: Sandstone, marlstone, siltstone, conglomerate, chert		Pasive Continental margin	Flisch Bosniaque
11	K_2	Sedimentary: Limestone, marlstone, dolomite		Marine carbonate platform	External Dinarides
12	K2	Metamorphic: Sandstone, marlstone, siltstone, phylite		Active Continental margin	Sava- Vardar Zone
13	Pc	Sedimentary: Limestone, marlstone,		Marine carbonate platform	External Dinarides
13a	Pc	Sedimentary: Limestone, sandstone		Active Continental margin	Sava-Vardar zone
14	E	Sedimentary: Limestone, marlstone, sandstone, siltstone		Marine carbonate platform	External Dinarides
14a	E	Sedimentary: Sandstone, siltstone		Active continental margin	Sava-Vardar zone
15	E,Ol	Sedimentary: Conglomerate, sandstone, claystone		Marine molasse	External Dinarides (Promina conglomerates)
16	M (Lower to Late)	Sedimentary: Claystone, marlstone, sandstone, limestone		Continental molasse	Neogene intramontain basin Dinarides
16a	M	Sedimentary: Sandstone, siltstone, shale, evaporites, dolomites, limestone		Shallow marine	South Panonian basin (Tuzla basin)
17	Pl	Sedimentary: Claystone, marlstone, sandstone, silt		Continental molasse	Neogene intramontain basin Dinarides
18	J2-3	Mixed: Peridotite, dunite, harzburgite, lherzolite, amphibolite, serpentinite		Mid ocean ridge - Ophiolite complex	Dinaric Ophiolite Zone
19	T2	Plutonic: Alkaly syenite		Active continental margin	Čajniče area (East Bosnia)
20	T2	Plutonic: Gabro group,		Active continental margin	Vrbas fault (Gabro Jablanice)

21	T2	Plutonic: granodiorite group		Active continental margin	East Bosnia (Čelebići)
22	E	Plutonic: Granite group		Magmatic arc	Vardar zone (Motajica and Prosara Mts.)
23	T2	Volcanic: Basalt group		Magmatic arc	Vrbas fault
24	M	Volcanic: Trachyte group, dacite, andesite		Magmatic arc	Vardar zone (Srebrenica area)
25	S,D	Volcanic: Rhyolite group		Continental rift	Mid-Bosnian Schist Mts.
26	K2	Limestones and siliciklastics		Active continental margin	Vardar zone
27	E	Orto and Paragneiss		Magmatic arc	Vardar zone
28	J2,3	Mafic and ultramafic		Ophiolite zone	N-Kozara (Vardar zone)
29	K1	Conglomerate, sandstone, siltstone, marly limestone		Fluvial system and shallow marine	Pogari formation (Overstep sequences in Ophiolite zone)

Significant elements suggesting geothermal potential indications are: crustal and lineament faults, deep old regional and repeatedly reactivated faults, existence of large overthrusts, thinning of the epidermal part of the earth crust and less distance from surface to the Mohorovičić discontinuity in the Pannonian basin to 25 km and increasing to the south to circa 45 km. All these factors condition creating of numerous hydrogeothermal convective systems which are proved by the existence of thermal and thermomineral springs and wells. The most important aquifers are Triassic carbonate marine sediments with the highest thermoenergetic potential in all regions. Collectors are characterized by vertical and horizontal discontinuity. Depth and thickness of collectors and their hydrogeological and geothermal parameters are mainly in the phase of prognoses, especially for deep hydrogeothermal systems. [24]

Individual space heating with heat exchangers is performed in 5 localities (Ilidža Terme, Ilidža Termalna rivijera, Slatex-Slatina, Slatina and Drove). In Kulaši Prnjavor spa water after balneological use is heated by coal burning and serves for heating closed space of this spa. This type of heating is used for 6 month a year. Total geothermal energy used for individual space heating is 114, 08 TJ/yr. The GHPs are used in an open loop water - water system at 3 localities of thermal spas only (Fojnica FB-2, Višegrad, Gata), where water temperature is low for raising the thermal water temperature for space heating. The geothermal energy used for GHPs amounts to about 13,31 TJ/yr. Three GHPs were used in Laktaši spa, which are now out of work because of technical difficulties. Closed loop geothermal or ground source heat pumps are proposed for some individual objects from good promotion of producers of equipment and open loop systems with groundwater sources of inlet temperature of 13°C are planning especially for greenhouses (Klokun – Herzegovina). [24]

There are projects for energy renovation that considered GSHP as the heating source, but there is small number of these installations. Reasons are small number of qualified installers and small number of suppliers of adequate equipment. The promotion and awareness rising for GSHP installations are on a low level. The examples of energy renovation with heat pumps installations are:

- Kindergarten “Srna” in Banja Luka
- Residential building in Gradiška (heat pump capacity 106,8 kW)
- Hotel in Prijedor (heat pump capacity 52,3 kW)
- Public building in Srbac (heat pump capacity 18 kW

Thermal response test

Thermal response test (TRT) was conducted in Srbac [25] during installation of the heat pump in the public building on June 2014 on one BHE of 100 m (Figure 2.5.). The findings were following:

- The effective static temperature along the length of the borehole is 15,7°C, measured by circulation with a flow of 0,50 l/s. The lithological composition is predominantly clayey sand well saturated with water, while a surface layer has alluvial deposits.
- Average heat power was 4,74 kW (or 47,4 W/m) and total of 106,4 kWh of thermal energy stored in the rock mass was measured.
- The measured thermal conductivity on the BHE is 2,05 W/m°C (coefficient of determination R2=0,9973 when determining the slope of the line in logarithmic time) which indicates an excellent environment for the exploitation of geothermal energy
- After 24 hours of testing, the temperatures reached were input/output = 28,4/26,3°C (achieved steady heat energy transfer at 47 W/m) which indicates that it is possible to store more power per borehole at peak loads in the cooling cycle, while remaining in the operating conditions of the heat pump (in peak periods an additional 0,4 kW can be stored for each further degree of temperature rise to a steady state). However, it should be emphasized that in this case the COP of the pump significantly decreases and there is no advantage over air pumps in energy savings. For a classic system of condenser temperatures of 35°C (EN14511) possible storage would be 74 W/m.
- According to the plotted inverse curve in the heating cycle with 47,4 W/m, temperatures reached values of input/output= 5,1/3,0°C after 24 hours of continuous use at maximum power during heating (achieved steady state). The maximum yield for the BHE under the standardized condition EN 14511 of 0,0/-2,0 °C at peak consumption in the heating cycle is determined in the size of 67,7 W/m.

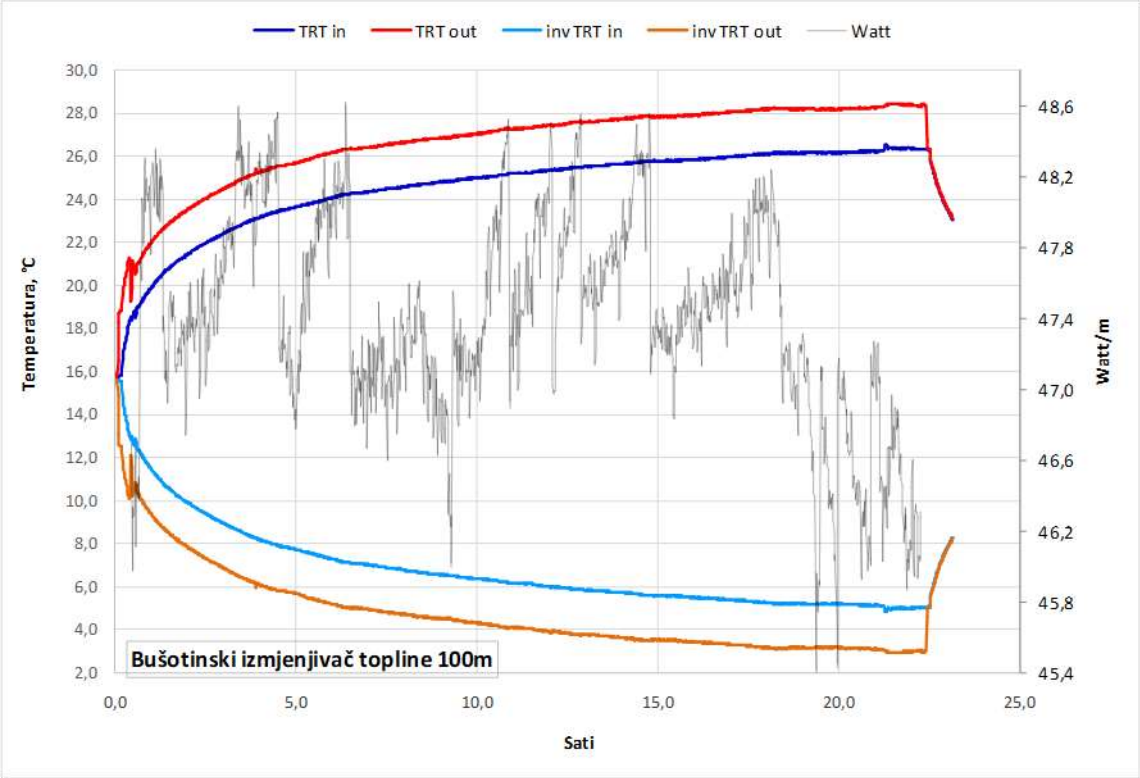


Figure 2.5. Changes in temperature and thermal power per m at the BHE in Srbac

The general conclusion of the TRT analysis was that there is a very good yield of thermal energy from the BHE and that 4,7 kW of thermal power per borehole for the regime 5,0/3,0°C (COP ~2,8 @ 55°C outlet) can be easily achieved. Power of 6,7 kW can be achieved if the yield takes place in the regime 0/-2.0°C, but with an even lower COP of 2,4@55°C outlet. The recommendation was to use a lower distribution temperature for system efficiency.

Hydrogeological data

Bosnia and Herzegovina could be separated in four hydrological structures with appositely similar hydrogeological characteristics (Figure 2.6.):

- Northern Bosnian hydrological structure – the terrain is built mainly of quaternary and tertiary formations, but smaller part has been built of Paleozoic and Mesozoic formations. Alluvial formations in rivers Sava, Una, Vrbas, Bosna, and Drina present rocks with intergranular porosity and scale of coefficient of filtration from k = 1x 10^{-3} m/s to k = 1x10^{-7} m/s.
- Prijedor - Banja Luka – Kladanj – Višegrad hydrological structure - includes Palaeozoic and central ophitic zone. Contact of the north and south border of this structure causes all phenomena of thermal, thermo mineral and mineral waters. Appearance of these waters is in connection with deep fault zones such as “Busovačka” and “Sprečanska”. Inside the hydrogeological structure there are regions where significant accumulation of cold water are formed. These parts of terrain are solely built of limestone and dolomites.
- Middle Bosnian hydrological structure - Overlapping geotectonic unit of Paleozoic slates and Mesozoic limestone. The terrain is a complex fabric with different lithologic elements. Significant phenomena of thermal and thermo mineral waters are characteristic for the north

border of the structure. The most extended aquifers of cold water in north-west part of Bosnia and Herzegovina.

- West and East Herzegovina hydrological structure - part of holokarst terrain which could be separate entity with complete karst evolution. Rock masses are significant collectors of ground waters which are pouring out on limestone and clastic contacts. These formations locally presented hydrogeological barriers, so there are wells on one side of the field and sink holes on the other side. [26]

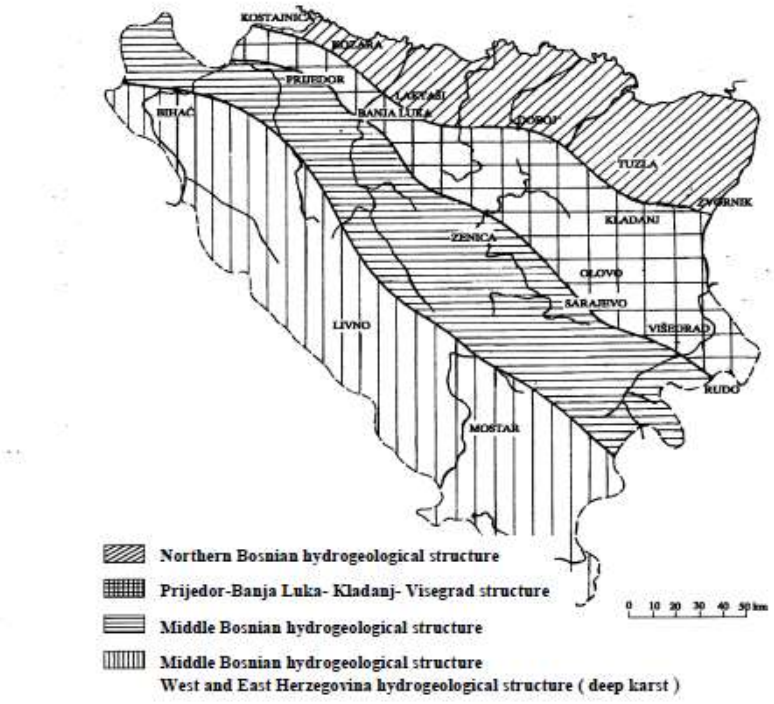


Figure 2.6. Hydrological structure of BiH

2.5. Current energy cost comparison for residential and non-residential sector with estimated capital cost of drilling and equipment for shallow geothermal

Price of electricity in Bosnia and Herzegovina as well as Republika Srpska entity is determent by the government on recommendation of the public company distributers (Table 2.3.). Currently it is government policy to provide relatively low price of electricity for households that is below cost of production and distribution and in that way subsidies households budgets. Republika Srpska does not have any gas pipeline and there is no available district heating on natural gas or LPG. District heating in cities Banja Luka, Prijedor and Gradiška are based on biomass.

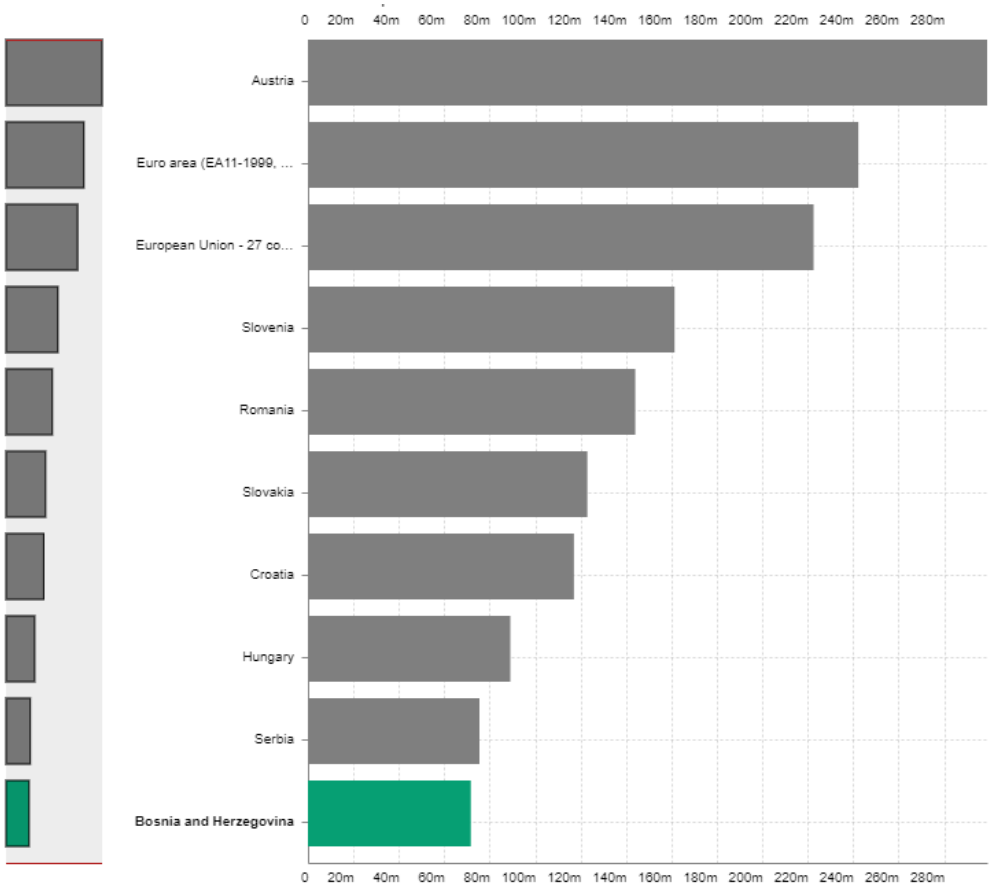
Table 2.3. Prices of electricity for public supply [27]

Buyer	Level of consumption (kWh)	Tariff	Measuring place	Calculated Power	Active energy	Overladed reactive energy
			EUR/ month	EUR/kW/ month	EUR/kWh	EUR/ kVArh
Household with a single-tariff meter	Up to 500 kWh	Medium tariff	1,483565	1,894416	0,06341	-
	501 – 1500 kWh	Medium tariff	1,483565	1,894416	0,085544	-
	1501 kWh and more	Medium tariff	1,483565	1,894416	0,151288	-
Households with a two-tariff meter	Up to 500 kWh	High tariff	1,483565	1,894416	0,079622	-
	Up to 500 kWh	Low tariff		-	0,04008	-
	501 – 1500 kWh	High tariff	1,483565	1,894416	0,106302	-
	501 – 1500 kWh	Low tariff		-	0,05342	-
	1501 kWh and more	High tariff	1,483565	1,894416	0,185505	-
	1501 kWh and more	Low tariff		-	0,093022	-
Small consumers – other consumption on 0,4 kV		High tariff	1,483565	10,91401	0,066521	0,037986
		Low tariff		-	0,0335	-
		Medium tariff	1,483565	3,908355	0,087758	0,031526
		High tariff	1,483565	3,908355	0,107558	0,037986
		Low tariff		-	0,054138	-
		Medium tariff	1,483565	3,908355	0,068914	0,031526
		High tariff	1,483565	3,908355	0,084886	0,037986
		Low tariff		-	0,042652	-

Low daily tariff rates are applied from 22:00 to 06:00 for “winter time”, or from 23:00 to 07:00 for “summer time” and on weekends continuously from Friday at 22:00 (23:00) until Monday at 06:00 (07:00) hours. Calculated power for households is 3,3 kW while for other consumers on 0,4 kV grid is 5 kW.

Based on the Licence for trade and supply of electricity, public company “Elektroprivreda Republika Srpska” as a supplier has the right to freely negotiate terms, including prices of supply with the consumers according to market principles. Market supply of electricity includes end consumers at voltage levels of 110, 35 and 10 kV, as well as consumers with annual consumption of more than 35.000 kWh per measuring point from 0,4 kV voltage level categories. [28]

Based on Eurostat data, average price of electricity in the second semester of 2023 in Bosnia and Herzegovina for households was **0,0717 EUR** (Figure 2.7.) and for non-households was **0,0898 EUR** (Figure 2.8.).



Source of data: Eurostat (online data code: nrg_pc_204)
Last update:25/04/2024 09:10

eurostat

This graph has been created automatically by ESTAT/EC software according to external user specifications for which ESTAT/EC is not responsible.
General disclaimer of the EC website: https://ec.europa.eu/info/legal-notice_en.html

Figure 2.7. Average electricity prices for households in 2023-S2 [29]

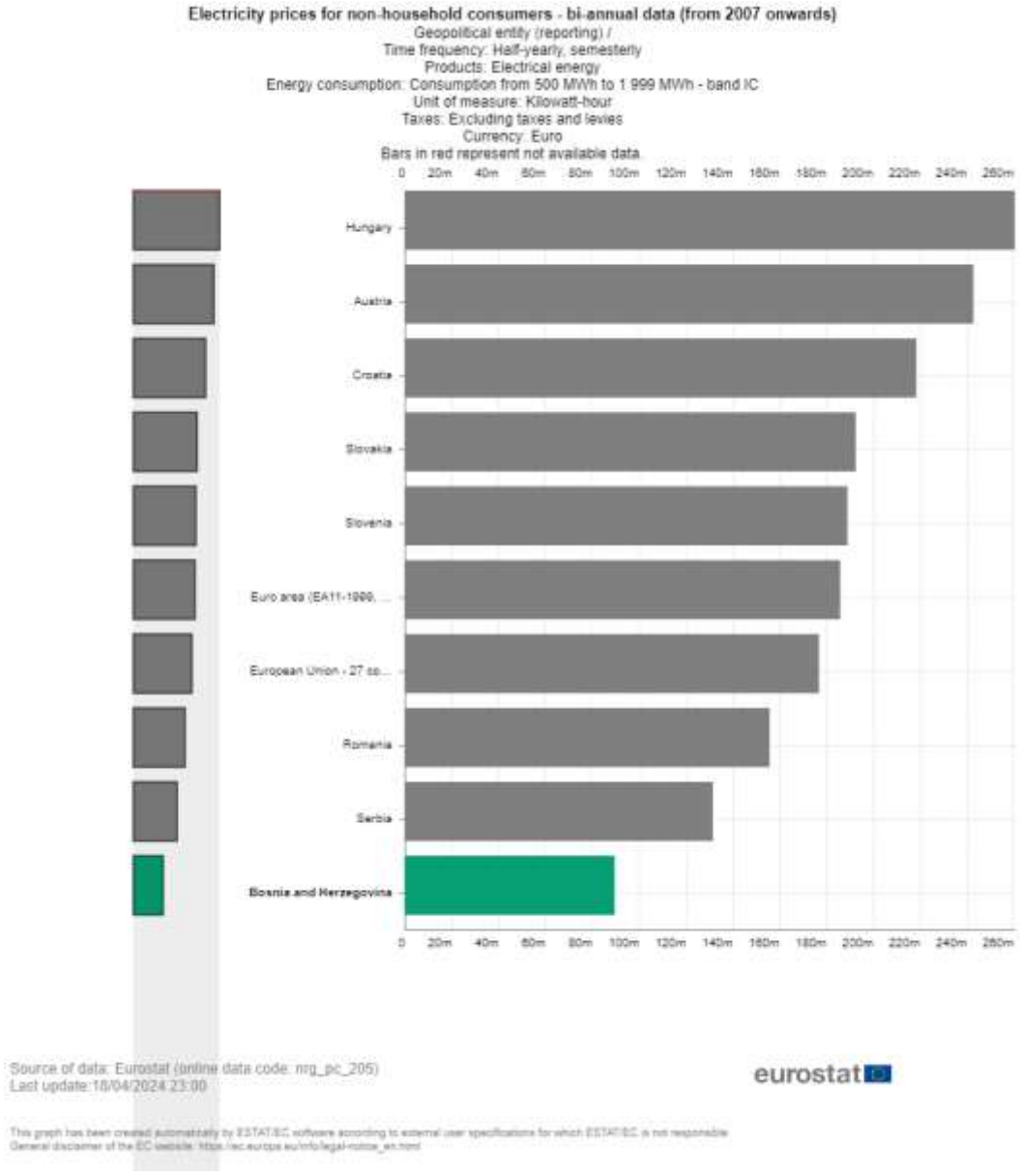


Figure 2.8. Average electricity prices for non-households in 2023-S2 [30]

Estimated capital cost of drilling and equipment for shallow geothermal

For earth probe drilling up to a depth of 100 meters, the average costs vary between 60 EUR and 100 EUR per meter of drilling, depending on the depth and condition of the ground. Just drilling costs are between 50-80 EUR, and probe is around 10-20 EUR.
The costs for heat pumps are also variable depending on supplier and manufacture. Based on capacity prices are listed in the Table 2.4.

Table 2.4. Price of heat pumps in BiH

Capacity	Price in EUR (including VAT)
8 kW	3600 - 4200
20 kW	6500 - 7800
80 KW	16700 - 21000
150 kW	27000 - 30000
210 kW	36000 - 42000

2.6. Environmental regulations and restrictions related to shallow geothermal development

The main environmental regulation for the territory of Republika Srpska is the Environmental Strategy of Republika Srpska 2022 – 2032, prepared by the Stockholm Environment Institute and it includes overarching goals and plans of specific actions which should contribute to achieving these goals. The document is essential to support relevant institutions in their efforts to achieve sustainability in the next decade, as well as to secure improvement of health and welfare of citizens. The efforts particularly focus on public policy-making. These policies are expected to: mitigate and reduce the impact of and increase resilience to climate change, better align actions in the Republika Srpska with the EU regulations and relevant international agreements, and ensure more sustainable public services, but they should also upgrade the environmental protection framework and facilitate the transposition of the EU acquis. The content of the Environmental Strategy covers a broad range of environmental topics, which coincide with the seven thematic areas of the EU acquis and the above set of strategic activities, and these are: water management; waste management; biodiversity and nature conservation; air quality, climate change and energy; chemical safety and noise, sustainable resource management (including agriculture, forestry, fishery, and mining activities); and environmental management (as a horizontal policy). Even though the Strategy does not specifically address shallow geothermal energy, within the strategic goal 4. Mitigation and adaptation to climate change and improvement of air quality and the priority 4.6 Increase the share of renewable energy sources along with a reform of the incentive scheme, the Strategy foresees measures to create and enabling environment for renewable energy sources and increase the share of renewable energy sources in electricity generation and transport, which can broadly cover SGE.
The related environmental regulation on the territory of Bosnia and Herzegovina is the Strategy of Adaptation to Climate Changes and Low-carbon Development of B&H 2020-2030, prepared within the project "Preparation of the Fourth National Report on Climate Change and the Third Biennial Report on Greenhouse Gas Emissions in Bosnia and Herzegovina" implemented by UNDP in partnership with the Ministry of Spatial Planning, Construction and Ecology of Republika Srpska, as the UNFCCC contact institution for Bosnia and Herzegovina. The Strategy focuses on six priority sectors identified during consultations: agriculture, water resources/water management, forestry and forest resources, biodiversity and sensitive ecosystems, tourism, health of the population. The Strategy approaches the

climate change adaptation process in a coordinated manner and focuses on the implementation of practical adaptation measures with the aim of increasing the resilience of Bosnia and Herzegovina to current climate variability and long-term climate change, while ensuring development opportunities. In terms of low-carbon development, the Strategy aims to interrupt the trend of increasing greenhouse gas emissions, significantly reducing emissions to 2030, with simultaneous growth of the economy through measures and programs that will result in reducing greenhouse gas emissions for 50% by 2050 compared to 2014. The Strategy predicts use of geothermal energy within measures for mitigation of climate changes and low-carbon development such as introduction of RES in existing district heating systems; construction of new district heating systems based on renewables / including central preparation of consumable hot water. Estimation is that implementation of such measures will contribute to potential reduction of 70,0 Gg CO_2 by 2030 and 224,4 Gg CO_2 by 2050, Estimated costs of realization of mentioned measures by 2030 are 100 Mil EUR.

3 Country status report for Croatia

3.1. Introduction to shallow geothermal energy utilization

The Republic of Croatia has a short history of using shallow geothermal energy, when compared to other European countries, regardless of good geothermal potential. The first one to determine overall geothermal potential was Jelić [37], in his doctoral thesis where evaluation of thermic characterization was given for Sava and Drava sub-basins. By analysing data obtained for over 100 deep boreholes, drilled as a survey, oil, gas or geothermal wells, correlations for determining geothermal properties of rock around 2000 meters were obtained, for each of the sub-basins. By determining how rock density changes with depth, and with known values for the heat capacity of the rock, one can also obtain thermal diffusivity, a very important geothermal parameter. Jelić and Lukačević [38] later also published the results of extensive research on geophysical exploration and testing on rock samples to determine thermal conductivity for the area of Zagreb. Further exploration of the subject led to the publishing of maps of geothermal gradient and heat flow for entire Croatia in 1997 [39].
According to Kurevija [40], there was no significant use of shallow geothermal energy via heat pumps by 2008 in Croatia. In the same paper, techno-economic analysis of using such a system for heating and cooling was presented for a building in Zagreb with a review of cost-effectiveness for specified area, which showed potential in utilizing ground source heat pumps.
Ruševljan, Soldo and Ćurko (2009) stated that proper design of shallow geothermal systems is usually based on complex mathematical simulations that have to be performed not only for peak building loads, but also for building loads that are calculated throughout the whole year. For this reason, the building loads have to be analyzed in more detail than for sizing of a conventional system. Designers of heat pump systems coupled to the BHE should also take into account the long-term temperature changes in the ground surrounding the borehole, which would influence the overall efficiency of the system during its life cycle.
One of the first science researches on standard double-loop borehole heat exchanger was carried by Soldo, V. and Ruševljan [41] at the Faculty of Mechanical Engineering and Naval Architecture in Zagreb. For a research purpose, first borehole of 100m was drilled and 2U heat exchanger was inserted, along with the thermocouples for each 10m of depth. Also, during this research first prototype of Thermal Response Test (TRT) equipment was constructed by same authors. Data showed that temperature at 100m in city of Zagreb is 15,2°C and that average temperature during test circulation is 13,5°C.
First commercial testing with TRT equipment was conducted during soil investigation works prior to construction of IKEA store in Zagreb. Based on this investigation [42] first data about thermal conductivity in city of Zagreb, which was 1,7 W/m°C was given. These results, as well as the one obtained from test borehole at their Faculty, were published in numerous domestical and international conferences, promoting development of shallow geothermal research in Croatia [42, 43].
Based on research of Jelić [37], Jelić and Lukačević [38] and Jelić and Kevrić [39], Kurevija [44] concluded that mean thermal ground conductivity up to 100 m will vary between 1,5 and 1,8 °W/m °C for a northern part of Croatia. In this research, a techno-economic evaluation of shallow geothermal potential in Croatia was carried out. Analysis showed that areas of significant potential are continental parts (mainly Pannonian Basin) and Adriatic coastline, with Dinarides regions showing lesser potential for implementing ground source heat pump systems.
Beside thermal conductivity and geothermal gradient, the undisturbed ground temperature is an important element when assessing shallow geothermal resource. Undisturbed ground temperature is defined as a ground temperature at a depth where there is no influence of climatic changes and solar

radiation on ground temperature. Undisturbed ground temperature can be determined while performing a Thermal Response Test (TRT) and is an important parameter when sizing the heat exchanger system (i.e. determining its length). A Thermal Response Test is a method for determining ground thermal properties. The method consists of circulating heated fluid through the heat exchanger with a pump, thus rejecting the heat in the ground via TRT equipment. During the heat rejection period of minimum of 48hr, temperature response of the circulating fluid, at the inlet and outlet of the exchanger, is logged. Heat rejection rates are set with turning the heaters on and off. Based on heat rejection rate heat extraction rate can be determined since they are mirror values. From collected data of temperature response, thermal conductivity and resistance can be determined.

When seasonal ground temperature deviations are monitored, Kurevija and Vulin [45] determined three main regions of Croatia, based on analysis of ground temperatures obtained from various regional meteorological stations. Analysis showed that in northern Croatia mean undisturbed temperature of 13,1 °C can be found at the depth of 10,5 m. For the region of Lika and Gorski Kotar it was found that undisturbed ground temperature of 11,9 °C occurs at the depth of 11,4 m. In the third region, Adriatic, due to large climate diversities, the mean value of undisturbed temperature at specific depth could not be uniformly determined. However, data is available for four cities which represent a larger city area. For Rijeka, undisturbed ground temperature is 14,1 °C (at 6,6 m), for Zadar it is 17,0 °C (11,1 m), for Split 14,7 °C (at 14,8 m) and for Dubrovnik 17,4 °C (at 12,3 m).

When it comes to the sizing of a heat exchanger system, Kurevija, Vulin and Krapec [46] showed the influence of different geometric arrays, the spacing of adjacent boreholes and thermal interference on determining required borehole length. The analysis showed discrepancies in calculated borehole length when using two methods describing heat transfer – simple line source and cylindrical source. The discrepancies were smaller in cases of larger spacing between boreholes in given borehole array.

Kurevija, Vulin and Macenić [47] analyzed the influence of geothermal gradient on sizing borehole heat exchanger for the area of Zagreb, since the ground temperature will depend on geothermal gradient after the depth of undisturbed ground temperature. It was found that in the regions where geothermal gradients are higher than average, they can have a significant impact on sizing the length of borehole heat exchangers.

As part of the IPA project, titled “Research and the promotion of the use of shallow geothermal potential in Croatia (Grant no. IPA2007/HR/16IPO/001-040506), 8 borehole heat exchangers were installed in the area of Pannonian basin and Dinarides. The project is also referred to as GeoThermalMapping. The purpose was to assess the potential for use of ground source heat pumps in representative geological formation in Croatia. The project was carried out by Faculty of Mechanical Engineering and Naval Architecture, in cooperation with Croatian Geological Survey.

In order to determine undisturbed ground temperature, an improved method of TRT was applied for measuring [48]. The method is called distributed thermal response test (DTRT), and it measures the temperature of the circulating working fluid by optic fiber cable inside the BHEs. By applying DTRT vertical distribution of thermal conductivity and borehole thermal resistance are determined along the length of BHE. Results obtained by DTRT were compared with those of TRT and direct measurements of sediments for a 100 m double-U pipe heat exchanger in Osijek. The results showed good agreement between DRTR and TRT measured values. However, there were some discrepancies when compared to direct measurement of thermal properties. It was concluded that for large-scale heat pump and for the location use of thermal response test is recommended.

Boban et al. [49] showed that use of fiber-optic cable for distributed temperature sensing allows determination of vertical distribution of thermal properties as main output data. DTRT consists of three phases. In the first phase temperature is measured with no fluid circulation. Next 48 hours fluid is circulated with imposed constant heat flux and in last phase thermal recovery of the ground is

observed. While the second phase allows determination of thermal properties, the last phase gives indication about heat transport in ground layers. Thermal properties for one location are presented, together with influence of the groundwater flow on the conventional thermal response test and the effective values of the thermal properties obtained.

Later, Soldo, Boban and Borović [50] published results of measurement on all 8 locations with DTRT. On 8 different sites, double-U pipe heat exchangers were installed, with a depth of 100 or 130 m. The results of measuring temperature response showed that in the Pannonian Basin, characterized by various sediments, thermal conductivity is in the range of 1,62 to 2,1 W/m °C. Dinarides locations showed larger variability in results, in the range of 2,01 to 3,19 W/m °C, and is characterized dominantly with carbonate rocks. Based on the results, it was concluded that the coastline, as part of the Dinarides region, shows potential for utilizing shallow geothermal energy. BHEs located in the mountain region of the Dinarides showed lower values of undisturbed ground temperature. These findings are in accordance with results of Kurevija and Vulin [45].

Beside GeoThermalMapping, there were few other projects in Croatia that deal with utilizing and monitoring of shallow geothermal energy. One of them was LEGEND (Low Enthalpy Geothermal Energy) which covered countries of Adriatic area [51]. As a partner, two regional energetic agencies were involved – IRENA (Istrian Regional Energy Agency) and DUNEA (Regional Development Agency of Dubrovnik Neretva County). The project lasted from 2012 to 2015. Through IRENA two public buildings in Labin, Istria were set with vertical borehole heat exchangers with corresponding heat pumps. DUNEA was involved in the project by installing heat baskets in one public building in Opuzen, Dubrovnik Neretva County. Remote monitoring system was installed at every location. The entire project showed a favorable potential of using shallow geothermal energy for the Adriatic area [51], which is in accordance with previous research of Adriatic coastline in Croatia.

Another EU funded project that dealt with the investigation of shallow geothermal potential is MUSE - Managing Urban Shallow geothermal Energy [52]. The project is focused on investigating shallow resources in European urban areas. Croatian Geological Survey was representative partner for Croatia, and the project ended in 2021.

Beside thermogeological parameters of the ground (i.e. undisturbed ground temperature, thermal conductivity, and thermal diffusivity) and geometry parameters of the heat exchangers, grout properties are also important parameters when designing ground source heat pump systems. The research to determine influence of various grouts was conducted in the area of Zagreb with, then novel, steady-state thermal response step testing (SS-TRST) [53]. The results showed that in a mediocre thermal conductivity environment there is no techno-economic benefit of using thermally enhanced grout. The novel method of SS-TRST consists of performing extended TRT, with a series of fall-off tests, carried out with lowering heat power of the heater, until steady-state is achieved for each of the fall-off steps. The analysis was done for three consecutive fall-off tests for a real project of installed heat exchangers in the area of Zagreb. The results showed good agreement between obtained values from fall-off tests and values obtained by extending the line from the response of the first step by using line source linear trend equation. This showed that usually long performing TRT could be shortened by using a series of fall-off tests.

In order to determine hydraulic and thermogeological design difference of double-U and coaxial heat exchangers, extended thermal response test was carried out on two different locations in the area of Zagreb [54]. It was stated that there is a growing trend of installing inclined multiple coaxial heat exchangers, with an average depth of 40-50 m for each borehole. Hydraulic nomograms for both designs of BHE were presented, with respect to different glycol mixtures. From the hydraulic and thermodynamic standpoint, it was shown that double-U exchangers consume less electrical energy for circulation pumps and therefore are more favorable. It was concluded that coaxial heat exchangers

are still viable to use in cases where there is a relatively small area for installation around object. Due to lower values of thermal borehole resistance, coaxial pipes of $63^{17}/40^{11}$ setting show an advantage when compared to $63^{11}/32^{11}$ setting. For coaxial heat exchanger to have more similar hydraulic and thermodynamic properties to double-U pipes, working fluid mixture must have a lower content of glycol. Analysis of novel SS-TRST showed that in the same geological setting, heat extraction rate for a coaxial heat exchanger is around 20% less than for a double-U vertical heat exchanger [54].Novel approach in determining the starting period of semi-steady state heat transfer was applied, in order to determine timeframe when temperature change is linear function of the logarithm of time. The approach is similar to derivation curve method used for well testing analysis in petroleum industry.
Further research was conducted on three different coaxial heat exchangers in the area of Zagreb with the application of classic thermal response test and steady-state thermal response step testing [55]. The analysis was done with respect to active and passive cooling. Classic TRT was done to determine thermogeological properties of each location as well as values of thermal borehole resistance. Analysis of SS-TRST was used for determining heat rejection rates for active and passive cooling. It was concluded that data obtained from SS-TRST can be used in proper sizing of the borehole heat exchangers. The analysis showed that coaxial BHEs are not adequate for passive cooling systems.
Borović et al. [56] Investigated possibility of installation of ground-and water-source heat pumps in karst terrains with discussing case studies from Croatia. It was determined that rock thermal conductivities are favorable for ground heat pump utilization and that wells with high enough yield and stabile seawater or groundwater temperatures for water source heat pump utilization can be designed in appropriate structural settings. Advantages and disadvantages of the utilized methodology have been pointed out, as well as methods which should prove useful in the future. Hydrogeological, geotechnical and thermal risks expected during the drilling, installation and operational phases have also been identified. Presented case studies have given the insight into the heat pump installation options and conditions in Croatian part of the Dinarides but can be useful to other researchers and engineers both in the Dinarides and in similar karst regions.
Research on undisturbed ground properties was done by performing TR test with two different heat injection rates and by logging temperature profiles of the borehole wall at different depth of the double-U heat exchanger, in the area of Zagreb [57]. Temperature response on the different radius from the borehole was also logged. The results showed that by using falloff method is useful in evaluating variations of thermal properties with time. The analysis also showed that if higher heat flow rates are used while performing TRT it can minimize the influence of heterogeneous environment as well as groundwater.
Another approach well known in petroleum industry, called the Horner method, was applied in analyzing the results of thermal response test with regard to falloff temperature, logged after the heater is turned off [58]. This is possible due to the same analogy of solving diffusivity equations for radial fluid flow and heat flow. In this case, the time for heat rejection to the ground was set to 96 hours. The recovery time, or falloff period also lasted 96 hours. Two possible flow directions were set for a coaxial heat exchanger in Zagreb, with five different heat rejection rates. Cumulative measuring time was 2000 hours. With obtained results recommendation was made to perform falloff test, whenever it is possible. This is due to the observation that by analyzing falloff thermal test temperature response it is possible to determine thermal conductivity more accurately.

3.2. Country statistics of installed shallow geothermal systems and general energy balances

A quality database with thermo-technical properties of existing systems can be of great use to geothermal and mechanical engineering designers for future installations. Therefore, a list of installed systems was formed considering available literature, as well as through personal contact with drilling companies providing shallow geothermal installation service. Not every installed system is on the map, since not every company was willing to share their information, but vast majority was available. Based on this data, a map was formed in Google Earth™ application, with approximate locations of installed systems in Croatia. Since majority of installations are disclosed private investors, the locations are pinpointed approximately in area. Each pin has a short description of configuration and length of installed heat exchangers. It could be seen that installation of double-U heat exchanger prevails among others. There are only few coaxial systems and one geothermal piles system installed. Considering configuration and construction of the geothermal piles, when observing yield and circulation, they can be considered as shallow double-U heat exchangers. Presented map showed that most of the installations are concentrated in the wider area of Zagreb and in Istria County. The maps and location descriptions for entire Croatia were done in Google Earth Pro™ and results are freely available at ResearchGate™ DOI: 10,13140/RG.2.2.14374.57924. Collected data showed that the overall length of installed closed-loop heat exchangers is 44615 m. Of overall length, 3280 m is length of installed coaxial borehole heat exchangers. Overall length of double-U heat exchangers is 41335 m. By determining mean values of heating/cooling power for each of the system, a simple estimation of installed capacity and heating/cooling energy was done, considering typical efficiency parameters. It is estimated that total heating and cooling energy obtained by using shallow geothermal energy is 4,45 GWh_t while installed capacity for heating and cooling amounts to 4,13 MW_t. PLIGES [59]

Total energy consumption in Croatia in 2022 amounted to 356,2 PJ, which is 2,1 per cent lower than the previous year, when it amounted around 364,0 PJ. At the same time, the real gross domestic product (GDP) growth rate was 6,2 per cent compared to the previous year. Energy intensity in the Republic of Croatia in 2022 amounted to 83,7 kgoe/103 US$ 2010 (according to purchasing power parity), 4,7 per cent lower than the average in the European Union (EU 27). The total primary energy production in the Republic of Croatia in 2022 amounted to 155,0 PJ, of which 43,0 per cent (66,9 PJ) belongs to firewood and biomass, 17,0 per cent (26,3 PJ) is natural gas, 16,4 per cent (25,4 PJ) crude oil, 12,7 per cent (19,7 PJ) hydropower energy, 9,7 per cent (15,0 PJ) belongs to renewable sources, while 1,2 per cent (1,9 PJ) belongs to non-renewable waste (Figure 3.1.). Figure 3.2. shows the trends in the total primary energy supply from 1990 onward. In 2022, Croatia's total primary energy supply decreased by 3,2 per cent compared to 2021. [60]

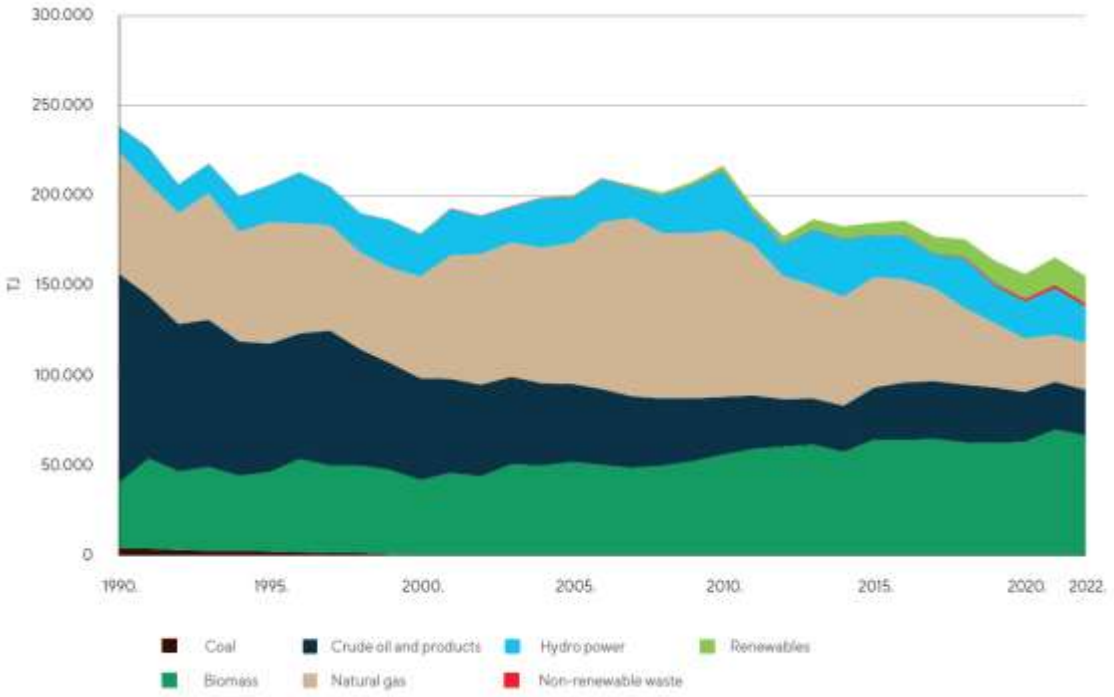


Figure 3.1.Primary energy production in Croatia [60]

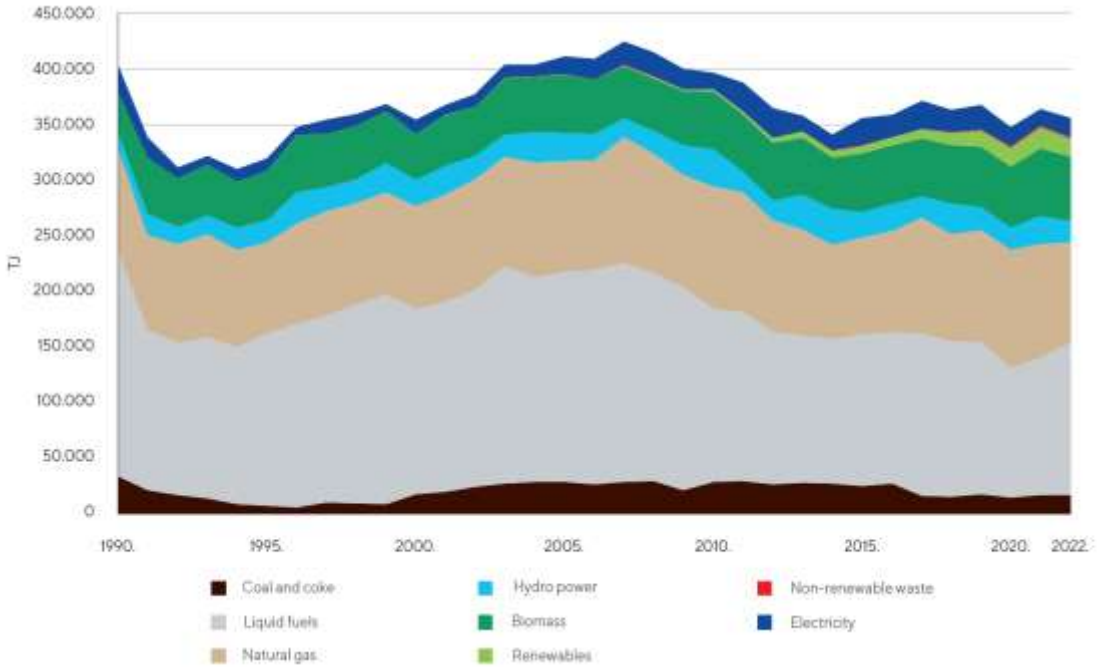


Figure 3.2. Total primary energy supply in Croatia [60]

The share of renewable energy sources in gross final energy consumption in 2022 is estimated at 29,5 per cent. The total electricity production in the Republic of Croatia in 2022 amounted to 14220,5 GWh, with approximately 63,7 per cent (9064,9 GWh) produced from renewable energy sources, including large hydropower plants. Large hydropower plants participated in this percentage with 38,4 per cent (5454,2 GWh), and 25,4 per cent (3610,8 GWh) of electricity was generated from other renewable

sources (wind energy, small hydropower plants, biomass, geothermal energy, biogas, and photovoltaic systems). Domestic electricity production covered 75,2 per cent (14220,5 GWh) of electricity needs, which in 2022 amounted to 18915,3 GWh. Electricity imports in 2022 amounted to 11919,7 GWh, 63,0 per cent of total consumption. Electricity exports amounted to 7224,9 GWh or 50,8 per cent of total domestic electricity production (14220,5 GWh). From 2000 to 2022, there is a visible decline in the energy efficiency improvement index, i.e. there is an improvement in energy efficiency for the entire economy in Croatia of about 20 per cent. Out of all sectors, industry and households make the most significant contribution to this. According to the preliminary results for the year 2022, the CO2 emissions from stationary and mobile energy sources amounted to 15,6 million tons, which is 3,7 per cent more than the emission in the previous year and 21,2 per cent less than the level of emission in the base year 1990, Compared to last year, the increase in CO_2 emissions in 2022 is mainly due to the increase in emissions from energy production and transformation facilities and the transport sector. [60]. Energy flows in Croatia are seen in Figure 3.3. and Figure 3.4

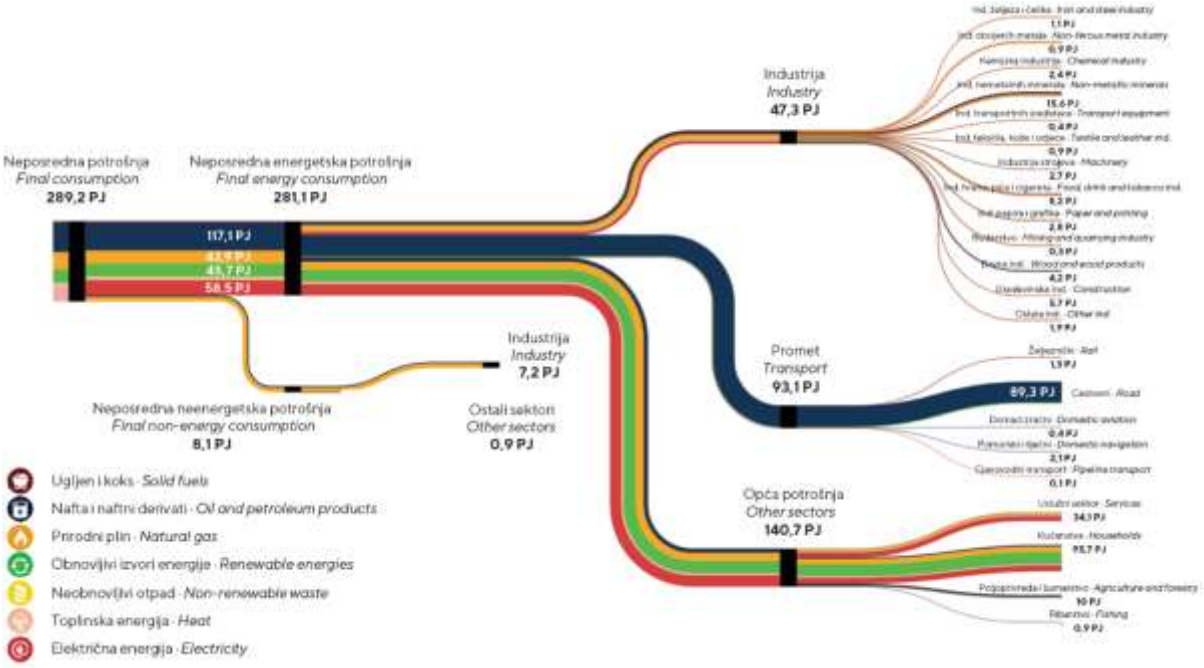


Figure 3.3. Energy flow analysis for Croatia for the Q1/2023; part 1/2 (Eurostat, EIHP)

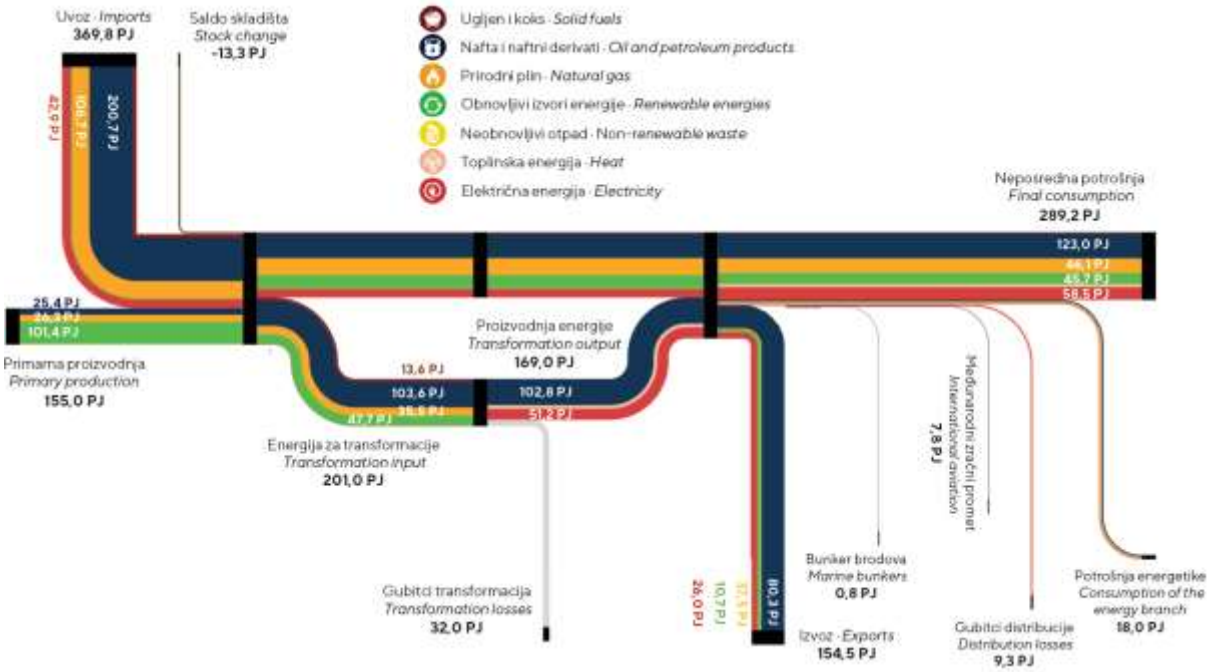


Figure 3.4. Energy flow analysis for Croatia for the Q1/2023; part 2/2 (Eurostat, EIHP)

Regarding the price of energy in Croatia, according to report Energy in Croatia Ministry of Economy and Sustainable Development [60], the average inflation in Croatia, measured by the harmonised index of consumer prices (HIPC), increased strongly, from 2,7 per cent in 2021 to 10,7 per cent in 2022, thus reaching the highest level in the last 28 years. Inflation rose significantly during 2022 globally, including in the euro area countries, i.e., our most important foreign trade partners, which continued the trend that began in mid-2021. The recovery of demand after the economies' reopening stimulated a global increase in energy prices, other raw materials, and intermediate products. The strengthening of inflationary pressures was influenced by the difficulties in the global supply chains that were still present at the time, due to which the supply of certain semi-finished and finished products was limited. At the same time, the demand in the conditions of the pandemic shifted from services to goods, which stimulated an increase in their prices. The already high prices of energy products (primarily crude oil and natural gas) on world markets increased further with the beginning of Russian aggression against Ukraine. In addition, prices of food raw materials that Russia and Ukraine supply to the world market and mineral fertilisers, an essential input component in agricultural production, have also risen. Also, Russia is a significant exporter of iron, steel, and non-ferrous metals. The reduced supply of these raw materials due to sanctions and the ban on the export of certain raw materials from Russia enormously increased metal prices on the world market after the start of the war. The significant increase in consumer price inflation in Croatia in 2022 resulted from the import, as mentioned earlier, inflationary pressures, i.e., the spillover of high raw materials prices and other input costs on the world market to producer and consumer prices. In addition, higher inflation can partly be connected to increased profit margins in circumstances of uncertainty regarding raw material prices and future price trends. Inflationary pressures also came from the domestic labour market, where the demand for workers was strong, and unemployment was declining, which led to relatively strong growth in nominal wages. On the other hand, the intensity of accelerating inflation during 2022 was somewhat mitigated by restrictions on the price level of some energy products and primary food products. Also, the effect of the base period associated with a significant acceleration of inflation from mid-2021 helped to stabilise

the annual growth rate of consumer prices in the second half of last year. Consumer price inflation in Croatia accelerated strongly during the first seven months of 2022 (to 12,7 per cent from 5,2 per cent in December 2021) due to continuous monthly price increases of many products and services from the consumer basket, especially from March to July. Such developments reflected the rise in prices of energy and other raw materials after the start of the war in Ukraine, as well as solid tourist demand. In the second half of the year, price increases were significantly less pronounced and at the previous year's level; therefore, the total annual inflation stabilised around the level of inflation reached in July. All main components of inflation contributed to the acceleration of inflation. Thus, the annual growth rate of food prices increased from 7,3 per cent in December 2021 to 16 per cent in December 2022, which was mainly the result of the spillover of imported cost pressures, i.e. the increase in the prices of energy sources, food raw materials and mineral fertilisers on the world market. Furthermore, the annual rate of growth in the prices of services accelerated from 2,3 per cent in December 2021 to 9,9 per cent in December 2022. The main contributors to this were hospitality and accommodation services, the demand for which rose significantly after the lifting of epidemiological measures, which led to a substantial price increase. The increase in prices in restaurants and cafes was influenced by the rise in input costs (prices of food and beverages and energy) as well as inflationary pressures resulting from the increase in wages (in conditions where there is a lack of qualified labour in the catering industry). Influenced by still-present disruptions in supply chains and spillovers from earlier increases in energy and industrial raw material prices, annual growth in consumer prices of manufactured goods also accelerated significantly (from 2,9 per cent in December 2021 to 11,2 per cent in December 2022). Due to the increase in the annual price growth of both main components (industrial products and services) during 2022, core inflation also accelerated noticeably, to 10,5 per cent in December 2022 from 2,5 per cent in December 2021, which is significantly higher than the long-term average (1,5 per cent). It also shows that the delayed effects of the previous increase in the costs of energy and other raw materials and intermediate goods are present to a considerable extent, which is additionally visible in the movement of producer prices of industrial products for mass consumption, whose annual growth during 2022 has accelerated significantly. The relatively strong growth of nominal wages additionally influenced the retention of core inflation at high levels. In 2023, the average consumer price inflation in Croatia is expected to slow to 7,0 per cent, reflecting a significant reduction in the annual growth of energy and food prices. The significant increase in the annual growth of energy prices from 12,4 per cent in December 2021 to 25,8 per cent in mid-2022 primarily reflected the increase in the price of petroleum products that followed the movement of crude oil prices on the world market. In addition, the administrative prices of natural gas and electricity increased in April due to their significant increase in the European market, further accelerating the annual growth of energy prices. In the remaining part of the year, the annual growth rate of energy prices decreased to 14,7 per cent in December, mainly due to the slowdown in the annual growth rate of oil derivatives prices, which was contributed by the noticeable price reduction of crude oil on the world market and the favourable effects of the base period, while consumer prices of electricity and natural gas were stable. The highest price growth on an annual level was recorded for liquid fuels, at over 30 per cent; for solid fuels, at 29 per cent; for electricity, at 8 per cent; and for gas, at 6 per cent. [60]

3.3. Overview of current regulations, incentives and general policy related to shallow geothermal

In the Republic of Croatia there is no legislative or regulatory office that deal with installation of ground heat exchangers. When it comes to legislature, they are defined as a simple construction

objects/installation and they do not require any form of permit, as stated in Ordinance on Simple and Other Buildings and Works (NN 112/17) [61]. This can be considered as an advantage for the investors. Since there is no unified legislature at a government level, there is no project data monitoring of installed ground heat pump systems. This can pose an inconvenience when it comes to setting up a dimensioning standard and project quality certification.

3.4. General country geology, hydrogeology and thermogeological parameters

The values of geothermal gradient and heat flow showed that Croatia can be divided into two distinct regions: Dinarides with Adriatic coastline and Pannonian Basin. For the region of the Dinarides with Adriatic coastline authors determined that the values of geothermal gradient are in the range of 0,01 up to 0,025 °C/m with a mean value of 0,018 °C/m. The heat flow in this region was determined at 0,029 W/m^2. In the region of the Pannonian Basin geothermal gradient was determined to be in the range of 0,04 to 0,07 °C/m, with mean heat flow of 0,076 W/m. Sava sub-basin shows mean geothermal gradient of 0,048 °C/m and mean heat flow of 0,067 W/m^2. Drava sub-basin showed values somewhat higher than Sava sub-basin, with a mean geothermal gradient of 0,051 °C/m and a mean heat flow of 0,082 W/m^2. Due to low resolution, the map of geothermal gradients was later digitally reproduced, with the same data [47] (Figure 3.5.). There are two distinct geothermal regions, based on geothermal gradient values. The differences in heat flow, and consequently geothermal gradient are most likely to be due to the shallow position of Mohorovičić discontinuity in the Pannonian basin, at around 30 km. In the region of Dinarides, the Mohorovičić discontinuity is at around 50 km depth.
Republic of Croatia can be divided into two main regions, the Pannonian Basin and Dinarides, from geological point of view. Out of these two regions the Pannonian Basin System is recognized with geothermal potential. In general, the Pannonian Basin System is mostly lowland area, bordering with the Carpathian Mountains, Dinarides and Alps, comprising of igneous, metamorphic and sedimentary rocks, spanning from Precambrian to Quaternary age. The Croatian part of the Pannonian Basin System (CPBS) covers the area of around 30000 km^2 and was formed during the Neogene in three main megacycles. The sediments of the 1st megacycle are of Lower Miocene and Middle Miocene age, and lithological very heterogeneous. They are mostly comprised of clastic sedimentary rocks, such as breccia, conglomerate, sandstone, claystone etc., and carbonates such as limestone and calcareous sandstone. The formations of 2nd megacycle are of Upper Miocene age, characterized with alterations of sandstones and marl. The 3rd megacycle formations are of Pliocene-Quaternary age, mostly comprised of beds of clays, sand, gravel and thin layers of lignite. The Neogene sediments are overlying crystalline bedrock or Mesozoic sedimentary rocks and underlying Quaternary deposits [62]. The oil and gas reservoirs are usually located within the sediments of 1st and 2nd megacycle [63]. The CPBS is usually divided into four main sub-basins Mura, Sava, Drava and Slavonija-Srijem, with variable Neogene and Quaternary sediment thickness. In Mura sub-basin sediment thickness reaches maximum of around 5000 m, as well as sediments in Sava sub-basin. Slavonija-Srijem sub-basin has the smallest sediment thickness, of around 4000 m, while in Drava sub-basin it can reach up to 7000 m [62].

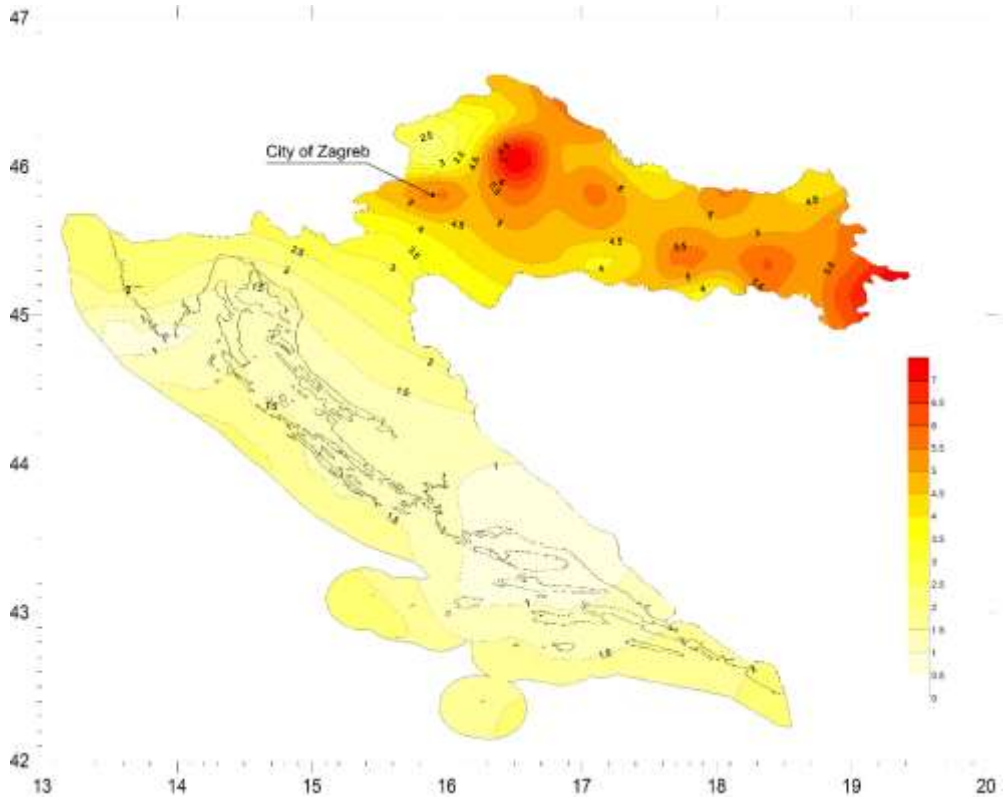


Figure 3.5. Geothermal gradients in the Republic of Croatia [47]

The data on selected 154 wells, located in the CPBS (Figure 3.6.), regarding depth, temperature and location was collected from well logs (BHT data), DST logs, drilling logs and final reports regarding a certain well and used to construct a new geothermal map of Croatia [64]. All of the wells contained data for temperature measurement with maximum thermometer at the bottom of the well. It can be seen form the map of geothermal gradient that the CPBS shows good potential when it comes to harnessing geothermal energy. This is especially evident in the areas where the geothermal gradient exceeds values 0,05 °C/m. [64]

Mapping of geothermal gradient values is recognized as a first step in determining geothermal potential of an area [64]. Such maps indicate areas of higher interest and can dictate potential interest in further research and exploratory work to determine local and economical potential.

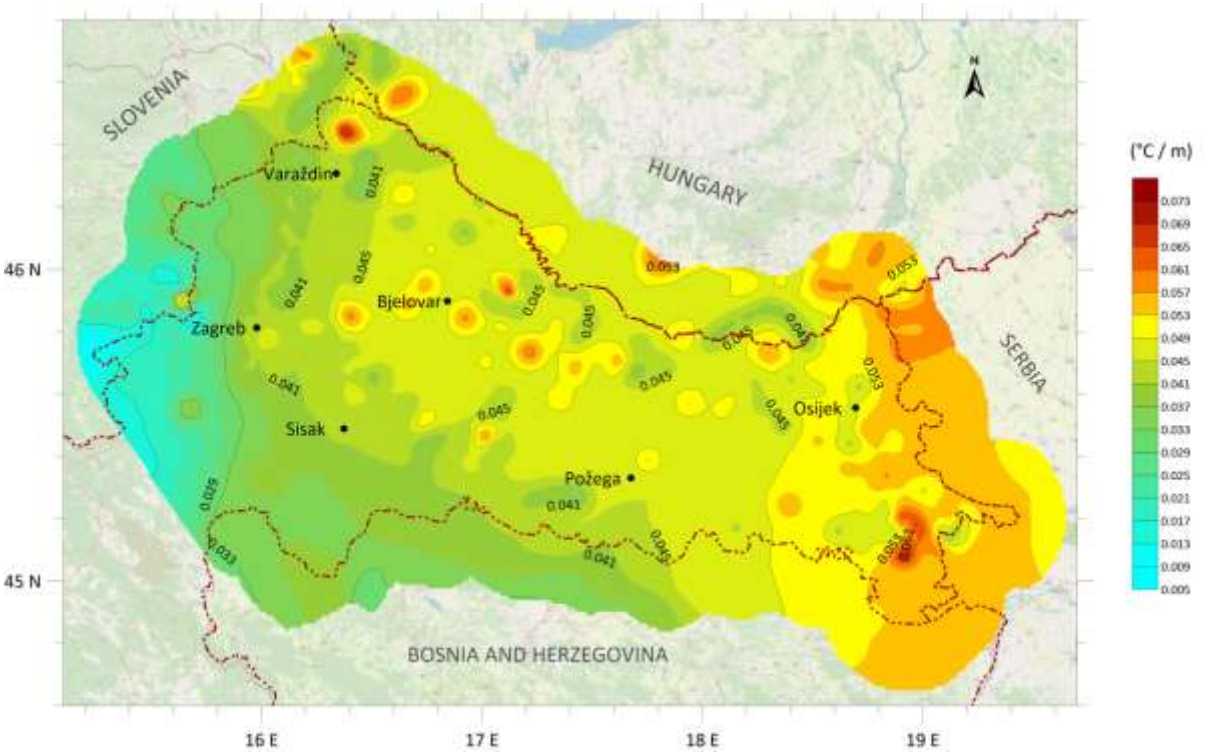


Figure 3.6. Novel constructed map of geothermal gradient for the CPBS [64]

The territory of the Republic of Croatia is predominantly built from sedimentary rocks covering more than 95% of the surface. These rocks can be divided into two main groups according to [62]

a) Clastic rocks – unconsolidated (gravel, sands, mud, and silt), partially consolidated (clays), and consolidated (sandstone, siltstone, shale, breccia, limestone, conglomerate),

b) Carbonates – limestones and dolomites.

Metamorphic rocks (crystalline schist and gneiss) occupy about 3% of the area, while igneous rocks (granite and basalt) can be found on less than 1% of the surface. In the Pannonian Basin, rocks from the Precambrian, Paleozoic, as well as those from the Neogene and Quaternary periods dominate, including clastic, metamorphic, and magmatic rocks. In the karstic region of southern Croatia, carbonate rocks from the Mesozoic and Paleogene periods are dominant. The general geological map (Figure 3.7.) shows two specific lithological areas. In the northern part of Croatia (north of Karlovac), clastic sedimentary rocks are predominant. The term clastic refers to rocks or sediments primarily composed of crushed fragments of older existing rocks or minerals that have been transported a certain distance from their origin. The term applies to indicate the formation of rocks or sediments from sources both within and outside the basin. Common clastics in the Pannonian Basin are sandstone and shale. Most unconsolidated clastic rocks are of Holocene and Pleistocene origin, mainly found around the Sava and Drava river basins and almost the entire eastern Slavonia. In northwestern Croatia, particularly in parts of Banija and western Slavonia, occurrences of Neogene clastics and limestones are frequent. Metamorphic rocks from the Precambrian era are the oldest rocks in Croatia, with outcrops in the Papuk and Psunj mountains and parts of the Moslavina region, where Palaeozoic granites can also be found. South of Karlovac, the lithology changes, with rocks mainly composed of carbonate sedimentary rocks built primarily from carbonate minerals – calcite (calcium carbonate – limestone) and dolomite (calcium-magnesium carbonate – dolomite). The coast and islands are mainly built from Cretaceous carbonates with sporadic occurrences of clastics (flysch), except for the Zadar

region (Paleogene limestones) and the Split archipelago (Paleogene clastics, flysch). In the regions of Lika and Gorski Kotar, Triassic, Jurassic, and Cretaceous carbonate rocks are predominant.

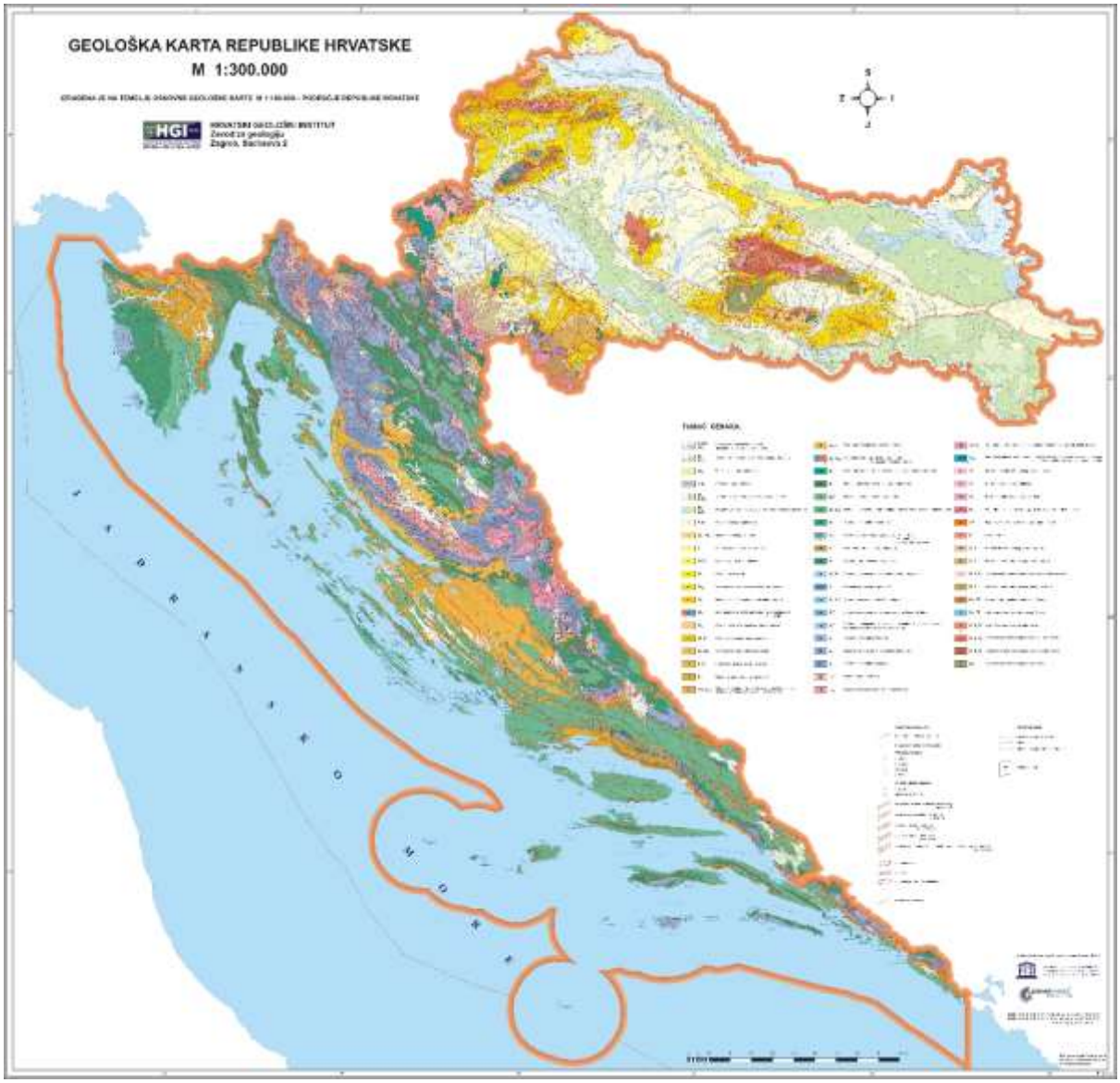


Figure 3.7. Geological map of Croatia 1:300 000[65]

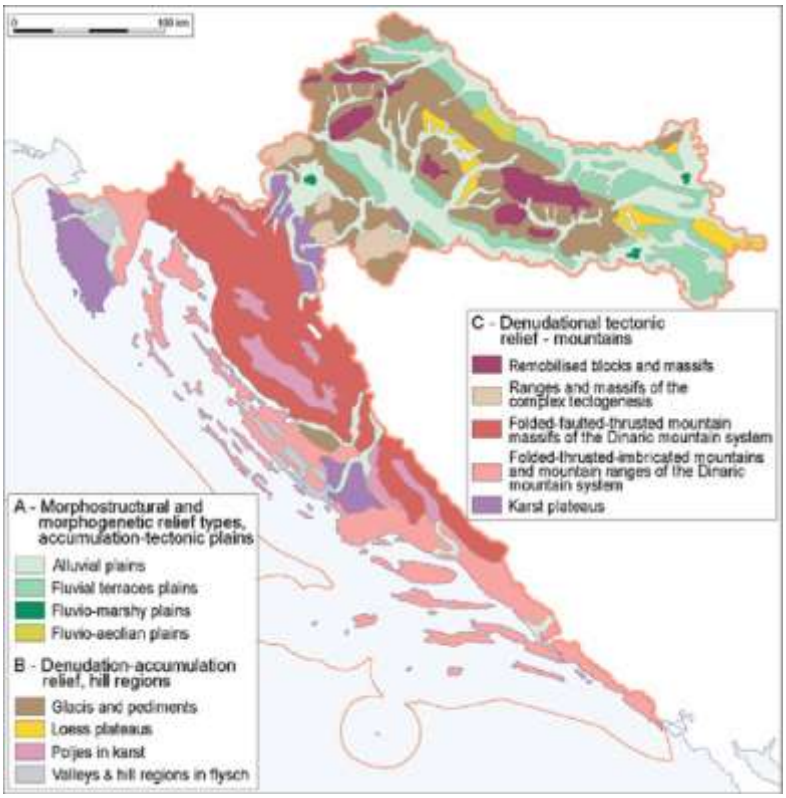


Figure 3.8. Relief categories in Croatia [66]

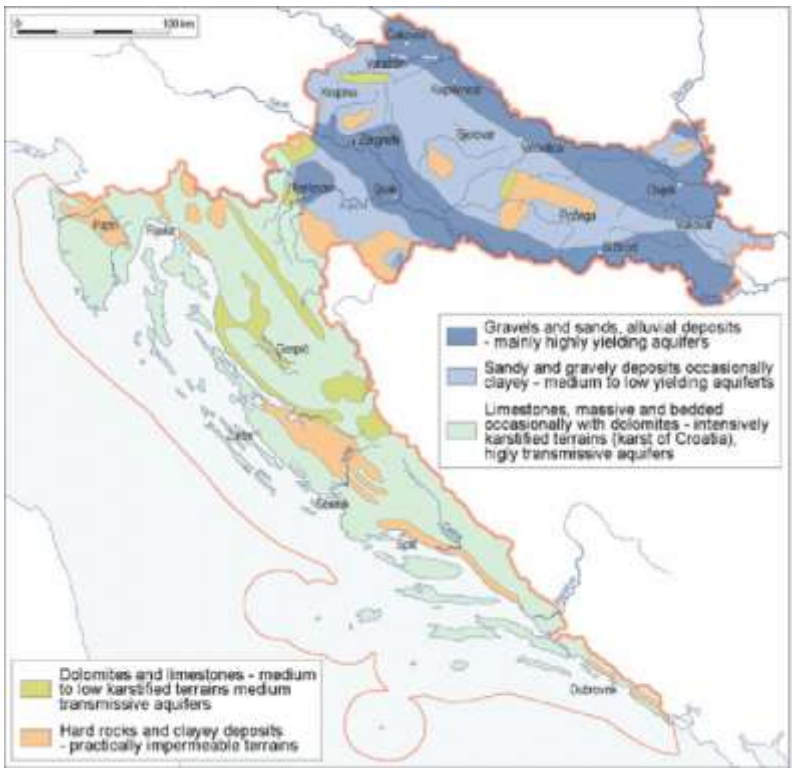


Figure 3.9. Simplified Hydrogeological map of Croatia (Majer and Prelogović 1993)

Figure 3.10. The topography of Croatia

Croatia's climate is determined by its position in the northern mid-latitudes and the corresponding weather processes on a large and medium scale. The most important climate modifiers over Croatia are the Adriatic and the Mediterranean, the Dinarides' orography with their form, altitude and position relative to the prevailing air flow, the openness of the north-eastern parts to the Pannonian plain, and the diversity of vegetation. Continental Croatia has a temperate continental climate and throughout the whole year it is in a circulation zone of mid-latitudes, where the atmospheric conditions are very variable. They are characterised by a diversity of weather situations with frequent and intense exchanges during the year. These are caused by moving systems of low or high air pressure, often resembling vortices hundreds and thousands of kilometres in diameter. During the cold part of the year, stationary anticyclonic weather types, with foggy weather or low clouds and a very gentle air flow, are prevalent. In spring, fast-moving cyclonic weather types (cyclone and trough) are characteristic, resulting in frequent and sudden weather changes, from rainy to dry periods, from calm to windy, from colder to warmer. In summer, the zero pressure gradient fields and a cooling night breeze blowing down mountain slopes are interrupted by cold fronts passing through. They bring in fresh air from the Atlantic, with very strong air mixing, increased wind, thunder and showers from dense clouds with vertical development. In autumn, periods of calm anticyclonic weather are very common, but there are also rainy days as cyclones pass over this territory. Calm weather in early autumn characterised by warm and sunny days and fresh nights with heavy dew and low fog patches over streams and rivers, which dissipate quickly by the morning. In late autumn, calm weather is cold, foggy and gloomy; in open plains and in the hills, where there is light wind, rime sticks to branches and wires, and there is a short period of sunshine through fog around noon. The climate of continental Croatia is modified by the maritime influence of the Mediterranean, which is stronger in the area south of the Sava River than in the north, and which weakens towards the east. The next local climate modifier is orography (the Mount Medvednica, the mountains in the NW part of Croatia - Hrvatsko

Zagorje, the mountains around the Požega Valley), which, for example, facilitates the intensification of short-term heavy precipitation on the windward side of the orographic obstacle or the appearance of precipitation shadow on the leeward side. At higher altitudes, in the mountainous districts of Gorski kotar and Lika and the Dinaric Alps, there is a mountain climate that differs from the wider area primarily by its air temperature and snow regime. The Croatian Littoral is also in a circulation area of mid-latitudes with frequent and intense weather changes most of the year. In summer, however, this area comes under the influence of the subtropical zone, as a result of the influence of the Azorean anticyclone, which prevents cold air outbreaks to the Adriatic. One of the most important climate modifiers in this area is the sea, so the climate can be referred to as maritime. With the direct influence of the Northern Adriatic cyclogenetic effect, the climate in this area is extremely mo dified by the highly developed orography of Gorski kotar and the Dinarides In summer, on the Adriatic, stationary clear weather prevails in the zero pressure gradient field of about 1015hPa. Due to the general pressure gradient in the Mediterranean and the position of the Adriatic, there are north-western winds (etesians) in the open sea, a gentle wind in the Northern Adriatic, moderate wind in the Middle Adriatic, and, occasionally, strong wind closer to the Strait of Otranto.

According to the Köppen climate classification, where the mean annual temperature course and precipitation amount are considered, most of Croatia has a temperate rainy climate with an average monthly temperature higher than -3°C and lower than 18°C in the coldest month. Only the highest mountain areas (>1200 m asl) have a snow-forest climate with an average temperature lower than 3°C in the coldest month. Inland, the warmest month of the year has an average temperature lower than 22°C, in the coastal area higher than 22°C, and more than four months within one year have a monthly average temperature higher than 10°C. The lowland, continental part of Croatia has a Cfwbx" climate. With the previously mentioned temperature characteristics, there are no extremely dry months during the year, and the month with the smallest amount of precipitation is in the cold part of the year. The mountainous area of Lika and Gorski kotar, and the higher parts of Istria belong to the Cfsbx" climate class, while the mountain peaks (higher than 1200 m asl) belong to the Dfsbx" class. In these areas there are no dry periods, the highest monthly amount of precipitation is in the cold part of the year, and the winter rainy period is divided into the autumn-winter and the spring maximum. On the islands and in the coastal area of the Middle and Southern Adriatic, there is a prevalent olive climate (Csa), which means that the dry period is in the warm part of the year, and the driest month has even less than 40 mm of precipitation, less than a third of the amount in the rainiest month in the cold part of the year. There are also two precipitation maxima (x") in the larger part of the area. According to the Thornthwaite climate classification, based on the relation between the amount of water necessary for potential evapotranspiration and obtained from precipitation, there are five types of climates, from perhumid to arid. Croatia has perhumid, humid and subhumid climates. In the largest part of lowland, continental Croatia there is a prevalent humid climate, and a subhumid climate only in Slavonia. The perhumid climate prevails in the highlands. In coastal Croatia, there are perhumid, humid and subhumid climates. In the Northern and Middle Adriatic, a humid climate prevails in inland Istria, the hinterland of the Kvarner Bay and in Dalmatia, which is more humid than the Istrian coast and the Middle Adriatic. In the Kvarner Bay, beside the cyclogenetic effect, the mountainous hinter land generates high amounts of precipitation, because of its orographic effect that intensifies precipitation.

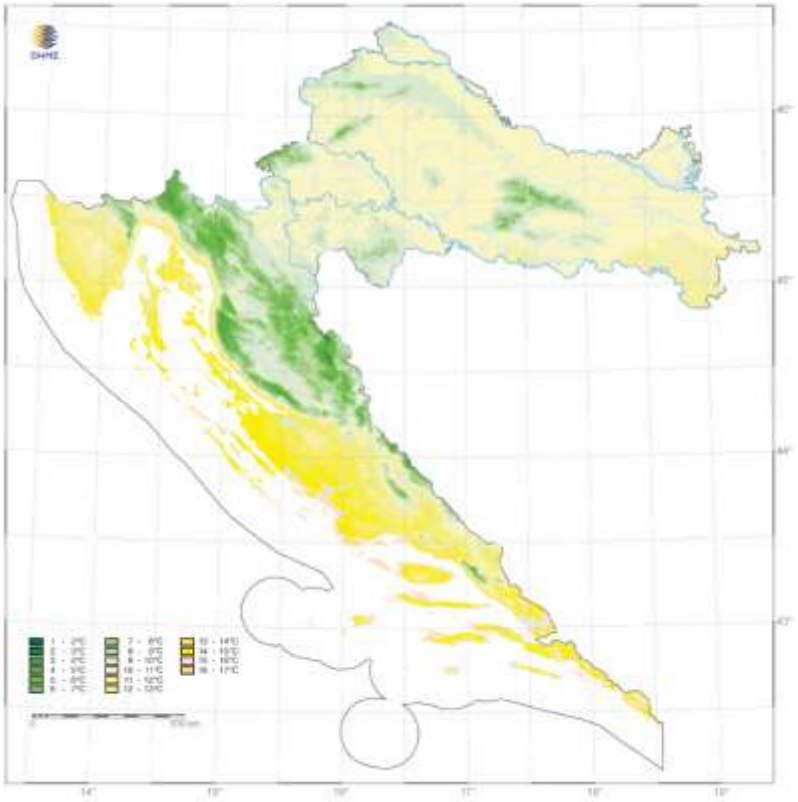


Figure 3.11. Mean annual air temperature (DHMZ)

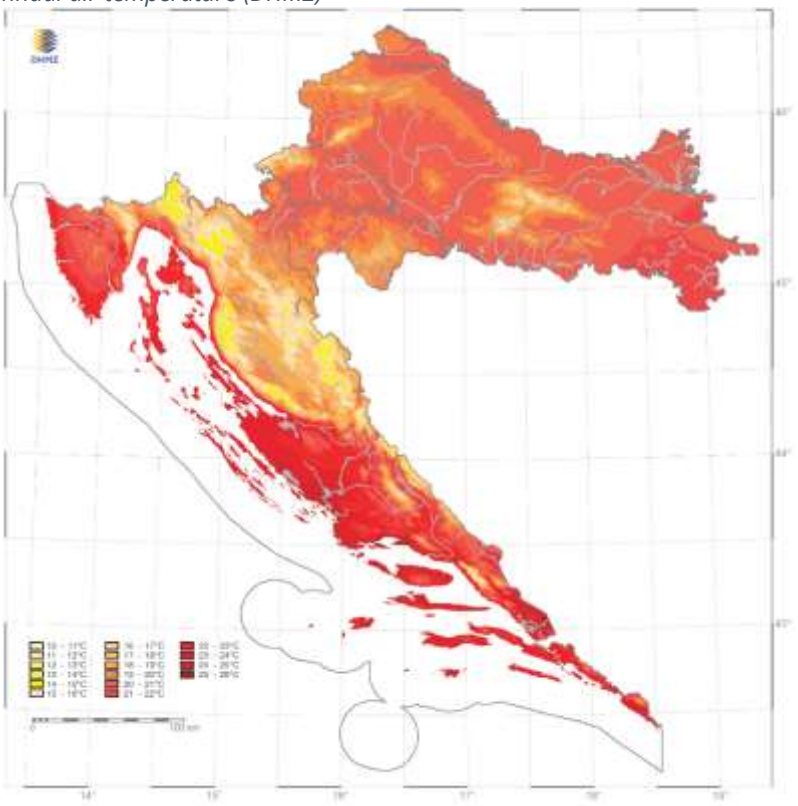


Figure 3.12. Mean air temperature in July (DHMZ)

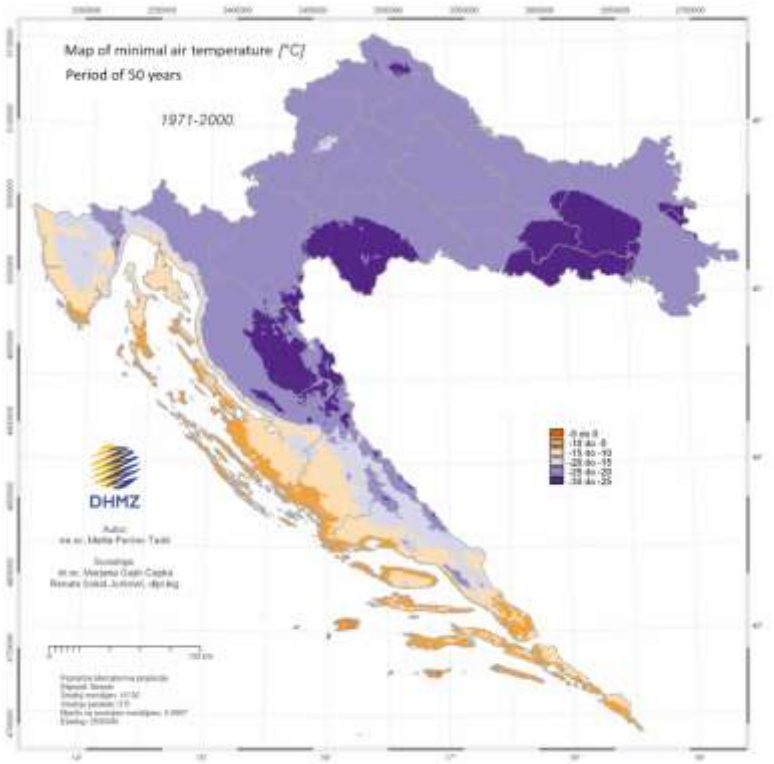


Figure 3.13. Minimal air temperature for the period of 1971 - 2000

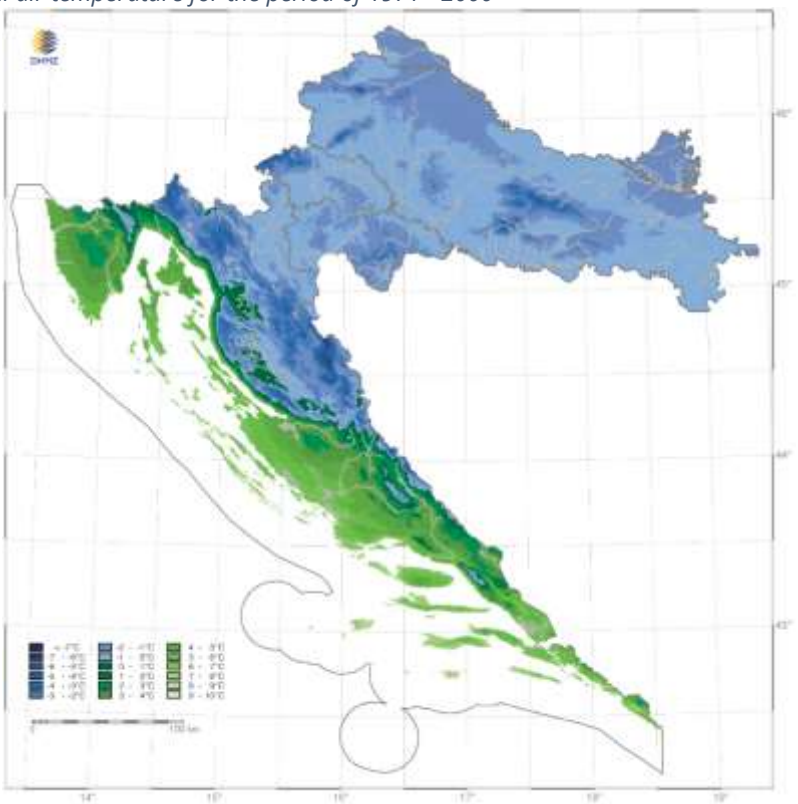


Figure 3.14. Mean air temperature in January (DHMZ)

3.5. Environmental regulations and restrictions related to shallow geothermal development

The trend of increasing the number of installed shallow geothermal systems in Croatia is somewhat slower than in the rest of Europe. The true assessment of the amount of energy that is obtained from such sources is difficult to assess, given that there is no responsible state body in the Republic of Croatia that keeps records of the number of installed systems. The exception is open heat exchanger systems, which require a permit from Croatian Waters, and later the supervision of a hydrogeologist when putting the installed wells into operation. Deep and shallow heat exchangers of closed systems in Croatia are managed as simple construction objects according to the *Ordinance on simple and other buildings and works* from 2018 issued by the Ministry of Construction and Spatial Planning. Article 3) and Article 5) define that works related to the installation of shallow geothermal systems can be carried out without a building permit, as follows:
Article 3. Item 11b. "Without a building permit and a main project, works can be carried out: On an existing building that does not have more than three apartments, that is, three functional units or a construction (gross) area that does not exceed 600 m^2, and in which the existing heating and domestic hot water heating system is replaced by a system that is solved by utilizing the thermal energy of the soil using heat pumps whose underground heat exchangers do not transfer to neighboring particles."
Article 5, paragraph 10b. "Works can be carried out without a building permit, and in accordance with the main project on the existing building, if this Ordinance does not prescribe otherwise, and in which the existing heating and domestic hot water heating system is replaced by a system that is solved by utilizing the thermal energy of the soil using heat pumps whose underground heat exchangers do not transfer to neighboring particles.
If however, building is more than 600 m2 and has more than three separate units, entire project design must be included in the main project design (Architectural main project; Mechanical engineering main project, Electric main project) and approved by local authority which issues construction permits.
When dealing with open loop systems that require usage of water wells (production and injection) that produce water from shallow aquifers regulation is well known and assigned by Croatian water national agency. Procedure for obtaining a permit for the use of underground water in heating and cooling systems with heat pumps in Croatia is as follows:

1.) Water management conditions permit
Content, method and documentation required for issuing water law conditions according to the Ordinance on Issuing Water Law Acts (Official Gazette 78/10). Documentation and permits are carried out by a company that holds all relevant permits for the performance of geotechnical works, drilling and construction of wells for energy use (Ministry of Agriculture - http://www.mps.hr/default.aspx?id=8455 Popis.xls). The following must be attached to the request for the issuance of water management conditions permit for the conductance of regional and detailed geological surveys, aquifer research works and for interventions that may permanently, occasionally or temporarily affect the water regime, for which a location permit is not issued:
- data on existing neighbouring exploratory boreholes (if any)
- a program of investigative works with a description of the method of conducting the research
- a proposal for a technical solution for regulating the water regime.

When water legal conditions are issued at the request of a party, proof of the paid administrative fee must be attached. The authority responsible for spatial planning and construction when deciding upon a party's request needs to receive documentation for the issuance of water legal conditions that must

be met by the intervention in the area, depending on the type and complexity of the intervention, containing
A) conceptual design for intervention in a space that contains:
- information about the location (description, extract from the cadastral plan, land extract code)
- basic technical data about the procedure (purpose, dimensions, capacity of flow)
- technical-technological solution for the engineering design of heat pump systems)
- data on the required quantities, quality and method of water supply from aquifer
- data on quantities, degree of pollution, planned method of pretreatment and discharge of waste water into environment (if any)
- basic technical-technological solution for drainage and wastewater treatment
B) a study on the impact of the intervention on the environment and a decision on the acceptability of the intervention on the environment with a list of protection measures and a program for monitoring the state of the environment when a mandatory environmental impact assessment has been carried out for the intervention in question
C) act on assessment of the acceptability of interventions for the ecological network, if this assessment was not carried out in the process of assessing the impact of interventions on the environment.
Along with the application for issuing a water law permit for the discharge of waste water and the use of water, the following are attached:
- data on the name and registered office of the user of the water permit,
- basic data on the user's activity and the location for which the water permit is issued,
- an overview of the wider area with an indication of the building,
- location permit, act of the competent authority according to the special regulation on construction on the basis of which construction can be started, use permit, water law conditions and water law certificate, minutes from the technical inspection of the representative responsible for water management affairs,
– concession contract for cases provided for in Article 163 of the Water Act
- proof of paid administrative fee.
2.) Ordinance on the calculation and collection of fees for water use (Official Gazette 84/10)
Article 2, paragraph 9 - "Intake of water for heating and cooling of residential and commercial premises": The fee paid by the taxpayers referred to in Article 2, point 9 of this Ordinance is determined according to the expression:
N= N4xV4 in which:
N = total compensation amount
N4 = amount of fee for water use according to Article 5 of the Regulation on the amount of fee for water use (Official Gazette 82/10)
V4= amount of water in m3 for the calculation period.
3.) Regulation on the amount of water use fee (Official Gazette 82/10)
Article 5 - "The amount of the fee for the use of water for heating and cooling residential buildings and business premises, except for thermal and thermo-mineral waters, amounts to 1,3 Eurocents per cubic meter (1 m3) of the affected water"
4.) Ordinance on the register of extracted and used quantities of water (Official Gazette 81/10)
Article 1.
Paragraph 1 - "The Obligors from Article 1, paragraph 1 of this Ordinance is obliged to register the quantities of water from Annex 1, Annex 2 or Annex 3 of this Ordinance by means of a measuring device (water meter) and to keep a record of this."
Paragraph 2 - "Obligors from Article 1, Paragraph 1 of this Ordinance, as well as all other obligors who, on the basis of a water permit or concession contract, capture water in an amount above 10,000 m3

per year, are obliged to install equipment for telemetry monitoring, collection, control and registration of billing data (hereinafter: Telemetry monitoring equipment), which will register data from Annex 1, Annex 2 and Annex 3 of this Ordinance.
Article 6.
Paragraph 1 - "Obligation parties from Article 1, Paragraph 1 of this Ordinance are obliged to submit data from the register of captured and used quantities of water to Croatian Waters, via the data reporting form from Annex 3 of this Ordinance, depending on the type of water use in accordance with Article 74 of the Act on waters (OG 153/09):
- monthly for quantities of affected water equal to or greater than 10,000 m3/year,
- quarterly for amounts of affected water of more than 1,000 m3/year and less than 10,000 m3/year,
- annually for quantities of affected water less than or equal to 1,000 m3/year"
Article 8.
ATTACHMENTS that the Obligors must fill out and submit to Croatian Waters in relation to NN 81/10 include:
Paragraph 1.
"Appendix 1 - Form of record of affected water quantities for obligees, except suppliers of water services of public water supply"
Annex 3 – Application forms for taxpayers from Article 1, Paragraph 1 of the Ordinance, namely:
– Form 3a,
– Form 3b“
"Appendix 4 - Application forms for taxpayers from Article 1, paragraph 2 of the Ordinance, namely:
– Form 4a,
– Form 4b,
– Form 4c,
– Form 4d,
– Form 4e“

4 Country status report for Hungary

4.1. Introduction to shallow geothermal energy utilization

The utilization of shallow geothermal energy refers to heat production from the upper 100-200 meters of the Earth's crust. Heat extraction is achieved with heat pumps, transferring energy to the surface through heat exchanger surfaces established underground or by extracting water from shallow wells ([67], [68].

Geothermal heat pumps, also known as ground-source heat pumps (GSHP), are systems that integrate a heat pump with either a Borehole Heat Exchanger (BHE) (closed loop systems) or utilize ground water produced from a water well or utilize outflowing water, i.e. thermal water from a spa (open loop systems). When operating in heating mode, these systems utilize the earth as a heat source, with a fluid (typically water or a water-antifreeze mixture) serving as the medium to transfer heat from the earth to the evaporator of the heat pump, effectively harnessing geothermal energy. Conversely, in cooling mode, they utilize the earth as a heat sink. Geothermal heat pumps can provide both heating and cooling functions at virtually any location, offering remarkable flexibility to meet various demands [68].

Heat pump systems harnessing underground heat from shallow reservoirs appear to be the fastest-growing segment in the utilization of geothermal energy ([87]). Unlike many other methods of utilizing geothermal energy, heat pump systems do not necessitate optimal geothermal conditions, making them deployable and operable in almost anywhere ([67]). Decarbonizing the heating and cooling industries within the next three decades is an immense task that requires urgent action. The advantages offered by heat pumps position this technology as a key player in driving the transition toward a sustainable European energy system ([76]).

Hungary is well known for its thermal water resources, the utilization of which for balneological purposes dates back to historical times. The exploitation of the heat potential in thermal waters has come to the forefront with the widespread adoption of deep drilling technology, however, the opportunities provided by shallow geothermal energy remain largely untapped in Hungary ([87].

The number of ground-source heat pumps (GSHP) installations has been steadily increasing in recent years in Hungary. Many new applications, particularly for communal heating/cooling, are being implemented in new buildings by newly established companies. However, there are no reliable registers for GSHPs, because systems shallower than 20 meters do not require licensing or notification to authorities in Hungary [92].

The deep geothermal potential in Hungary is conservatively estimated at 65-70 PJ/year, while the shallow-depth, heat pump technology predicts an additional 30-40 PJ/year of geothermal energy utilization [106]. Comparing this to the current geothermal energy utilization of around 9 PJ/year, it can be clearly stated that shallow and deep geothermal energy could play a key role in the domestic heating-cooling sector, as emphasized by the National Energy Strategy of Hungary [101, 95].

Although the performance of heat pump systems is generally on the order of kilowatts thermal (kW_{th}) [72], there are high-capacity ground-source heat pump systems in Hungary, such as the one at the Pápa military airbase, where, as part of a NATO investment, the country's largest shallow geothermal system was completed with 270 100-meter-deep boreholes. Its heating capacity is 1.65 MW_{th}, while its cooling capacity is 0,72 MW_{th} ([92, 101].

As outlined in the National Geothermal Strategy of Hungary, the objective is to increase the contribution of geothermal energy to gross heat energy production to around 12% by 2030, By 2035, it is anticipated that the share of geothermal energy in total heat production could be elevated to 25-

30%. Through the implementation of new initiatives, it is projected that 0,5-0,7 billion cubic meters of natural gas could be replaced by 2030, with a total displacement of 1-1.2 billion cubic meters by 2035. Alongside the development of deep geothermal energy, the National Geothermal Strategy underscores the importance of harnessing shallow geothermal energy resources. The utilization of heat pump systems can play a significant role in reducing CO_2 emissions, particularly if the energy required for their operation is sourced from renewable sources [95].

4.2. Country statistics of installed shallow geothermal systems and general energy balances

Heat pumps play a crucial role in the transition towards sustainable heating and cooling solutions, offering significant energy efficiency and environmental benefits. Understanding the trends and statistics surrounding heat pump installations, sales, and their impact on energy consumption and greenhouse gas emissions is essential for policymakers, industry professionals, and consumers alike.
Between 2014 and 2020, the worldwide heat pump market experienced a consistent annual growth rate of 10%, in 2020, the global installation of heat pumps reached 58 million units (IRENA 2023). However, sales dipped by 3% in 2020 due to the pandemic ([96], only to rebound with an 11% increase in 2022. The air-water heat pump market in China experienced a notable 12,6% growth in 2021, reaching approximately 2.2 million units; and in the US, the heat pump sector has exhibited consistent expansion, surpassing gas boiler sales annually since 2020 ([90]).
By the end of 2022, nearly 20 million heat pumps had been installed across Europe, which represents approximately 34% of the total global heat pump installations. This is noteworthy considering that Europe's share of the world's GDP is around 15% and its population accounts for approximately 10% of the global population.
Despite the significant number of heat pumps installed in Europe, traditional heating systems still maintain a significant presence, with 68 million gas boilers and 18 million oil boilers still in operation within the EU ([103]). Moreover, the distribution of heat pump installations across member states is uneven, with colder countries like Sweden, Finland, and Estonia exhibiting higher per capita rates. Ground-source heat pumps, in particular, are predominantly found in key markets such as Sweden (with over 600 000 installations) and Germany (with more than 400 000 installations). Collectively, these countries account for half of all ground-source heat pumps installed in Europe. according to the European Geothermal Energy Council (EGEC).
Heat pump technology has been progressively gaining market share from traditional fossil fuel boilers in the recent years, and this trend is accelerating. Space heating heat pumps held a market share of 19.6% in 2020, While certain markets in the lower and mid-range sectors are experiencing rapid growth in market share (such as France, Czech Republic, Lithuania, Slovakia, Poland, Netherlands ([78]), others like the UK, Ireland, and Hungary are still in the early stages of their growth trajectories (Table 4.1.).

Table 4.1. Heat pump market shares development by country - space heating (78).

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
AT	14.0%	13.8%	14.9%	16.4%	18.3%	18.5%	23.5%	26.3%	26.0%	27.6%	30.6%
BE	1.4%	2.3%	2.8%	2.4%	2.6%	4.1%	4.2%	4.7%	5.0%	5.8%	6.1%
CH	36.6%	35.8%	35.6%	34.5%	34.6%	36.2%	38.9%	41.0%	45.0%	45.2%	53.3%
CZ	4.7%	4.7%	5.2%	5.5%	6.1%	6.5%	9.7%	11.1%	12.7%	15.6%	16.2%
DE	8.7%	8.9%	8.9%	8.5%	8.1%	8.0%	9.6%	10.8%	11.4%	11.3%	14.1%
DK	35.4%	39.4%	47.3%	49.8%	45.1%	54.3%	56.5%	69.2%	72.0%	75.8%	80.4%
EE	69.8%	72.0%	74.3%	76.4%	77.5%	77.6%	80.7%	80.5%	79.9%	80.5%	82.5%
ES	14.6%	18.0%	13.7%	14.7%	15.2%	18.8%	21.8%	24.0%	23.9%	24.4%	27.5%
FI	85.9%	87.5%	86.6%	87.4%	88.1%	86.6%	87.4%	88.9%	90.5%	92.5%	93.5%
FR	14.1%	14.7%	14.2%	14.1%	16.3%	17.4%	18.2%	18.8%	19.1%	30.5%	31.2%
HU	1.1%	.9%	.8%	1.0%	.5%	.6%	.8%	.7%	.2%	.3%	4.9%
IE	2.1%	1.8%	2.0%	2.2%	3.2%	4.9%	6.1%	5.9%	4.8%	8.3%	9.7%
IT	10.2%	10.4%	10.5%	10.9%	10.4%	11.3%	18.9%	17.6%	18.2%	19.3%	21.1%
LT	2.4%	2.7%	2.9%	3.2%	4.5%	5.9%	6.9%	27.8%	30.6%	45.2%	47.0%
NL	1.7%	1.9%	2.0%	1.7%	1.6%	1.8%	3.4%	5.2%	7.2%	8.4%	11.2%
NO	97.9%	97.3%	96.7%	96.0%	95.4%	96.0%	96.9%	96.5%	96.7%	96.6%	96.3%
PL	1.6%	1.6%	1.9%	1.9%	2.8%	3.4%	3.9%	4.4%	4.7%	6.9%	11.2%
PT	39.7%	40.4%	32.0%	35.7%	30.1%	28.2%	42.2%	44.6%	39.6%	46.3%	50.3%
SE	89.8%	89.7%	89.4%	90.1%	90.6%	90.8%	91.3%	91.4%	91.0%	90.9%	90.8%
SK	1.3%	.8%	1.1%	1.4%	1.7%	1.8%	3.9%	4.6%	7.5%	6.1%	7.0%
UK	1.1%	1.1%	1.1%	1.0%	1.0%	1.1%	1.0%	1.2%	1.4%	1.6%	2.0%
Total	11.2%	11.4%	10.8%	10.5%	10.7%	11.5%	13.4%	14.5%	15.3%	17.8%	19.6%

Heat pump sales have experienced rapid growth, with 1.62 million units sold in Europe in 2020 (Figure 4.1). Sales grew approximately 34% in 2021 and by 39% in 2022, reaching more than 3 million units (2.75 million in the 18 member states covered). Approximately 90% of these sales were for space heating, with the rest for hot water. Belgium, Czech Republic, Slovakia, and Poland nearly doubled their heat pump sales in 2022 [78].

Assuming an average expected lifespan of 20 years, there are currently approximately 20 million units operating across our continent, of which 17.86 million are used for heating spaces. With 120 million residential buildings in Europe, the proportion of apartments utilizing heat pump heating has now reached 15%, aligning with the global average [78].

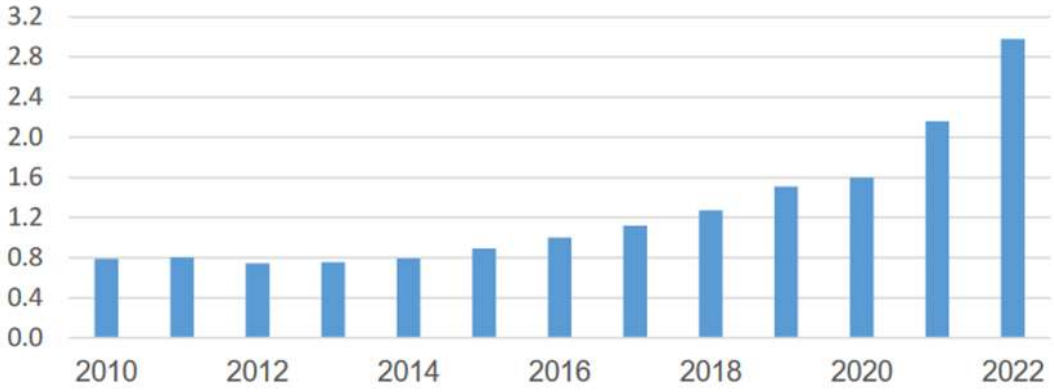


Figure 4.1. Heat pump sales in Europe, 2010-2022 in millions [78]

Heat pump sales per household more than doubled between 2018 and 2022 in all countries except for Spain, Denmark, Estonia, and Sweden. A mere ten countries accounted for 87% of the total volume of sales in Europe. Among the top five markets in 2022 were France (621 776 units, +15,8%), Italy (513 535, +35.2%), Germany (275 697, +59,0%), Sweden (215 373, +61,3%), and Poland (207 992, +112,0%; [78]).
In Hungary, heat pump sales saw a significant increase in 2020 compared to previous years. For the previous decade, the annual sales of heat pumps did not exceed 1000 units per year, but in 2020, sales surpassed 6000 units (Figure 4.2.).

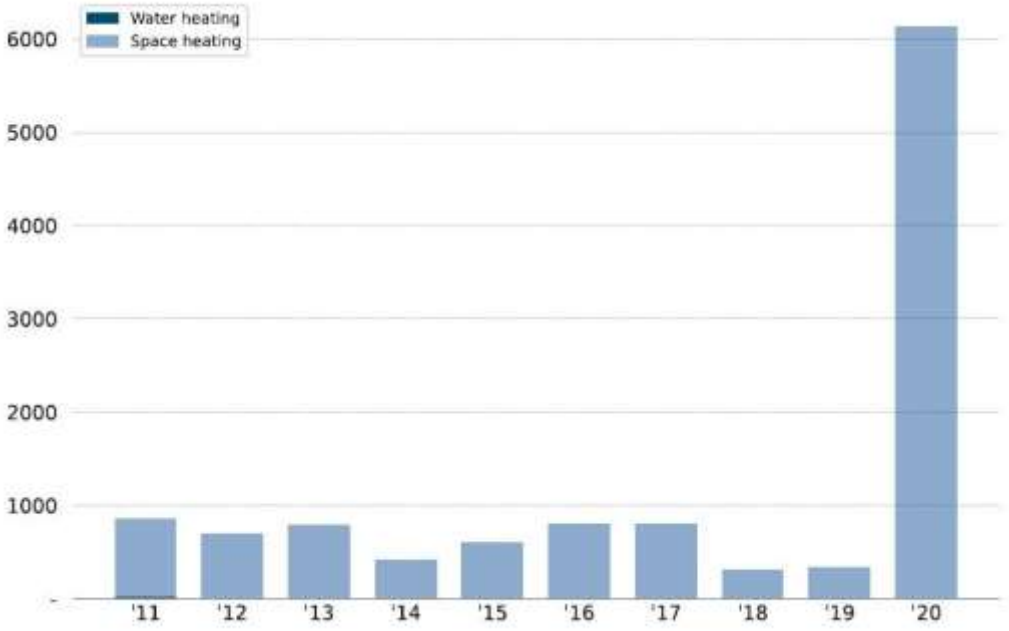


Figure 4.2. Annual heat pump sales in Hungary between 2011 and 2020 (EHPA 2021).

In Hungary, 15433 heat pumps were sold in 2022, representing a 101% increase, which sounds promising (Figure 4.3.). However, even with this growth, fewest heat pumps were sold relative to its size among the member states, with only 3.77 heat pumps sold per thousand households, though that is 54 times the level of 2018 (Figure 4.4.).

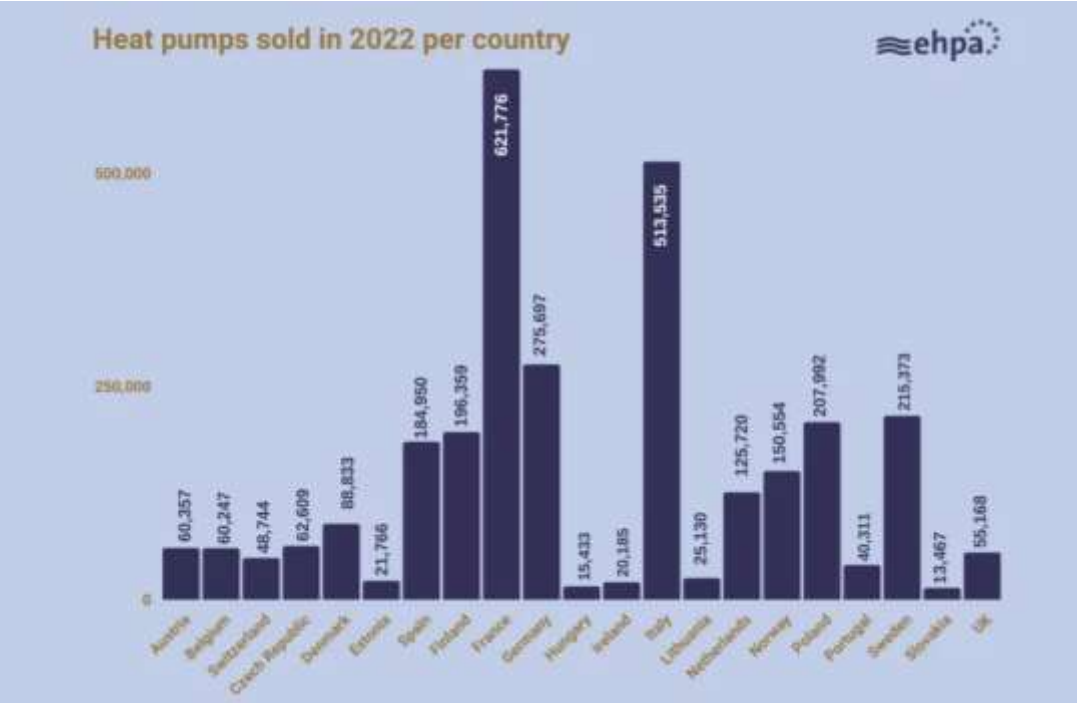


Figure 4.3. Heat pump sales in Europe per country in 2022 [78]

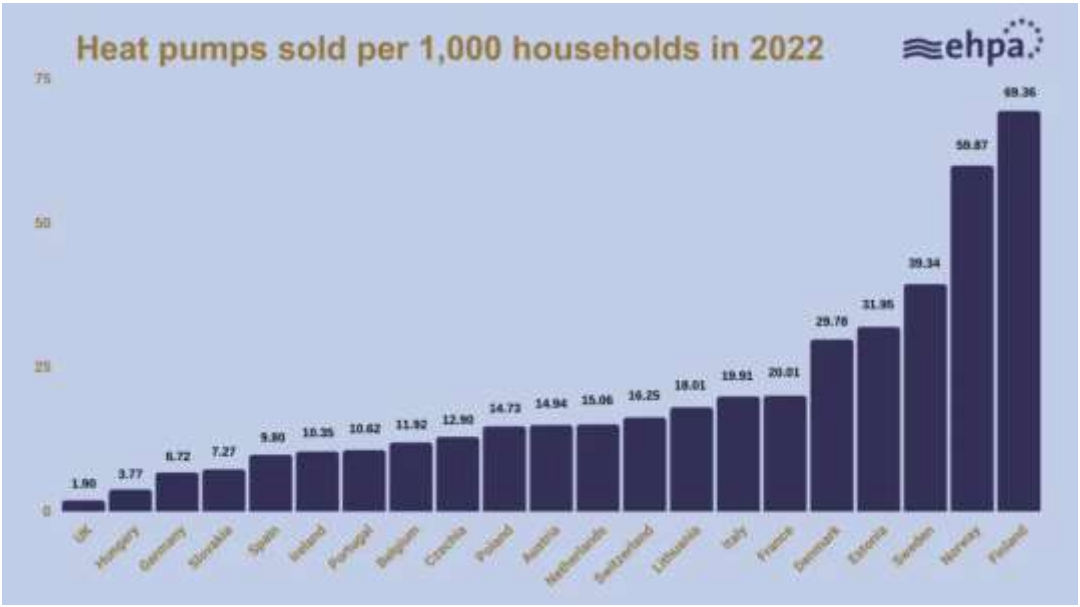


Figure 4.4. The number of heat pumps sold per 1,000 households in 2022 [78]

The number of operational heat pumps in Hungary has steadily increased over the last decade. By 2020, the count had reached 13,000 units, primarily utilized for space heating purposes (Figure 4.5.). During the 2010s, ground-water systems dominated the market, but in 2020, there was a notable rise in the of air-water heat pumps as well (Figure 4.6.).

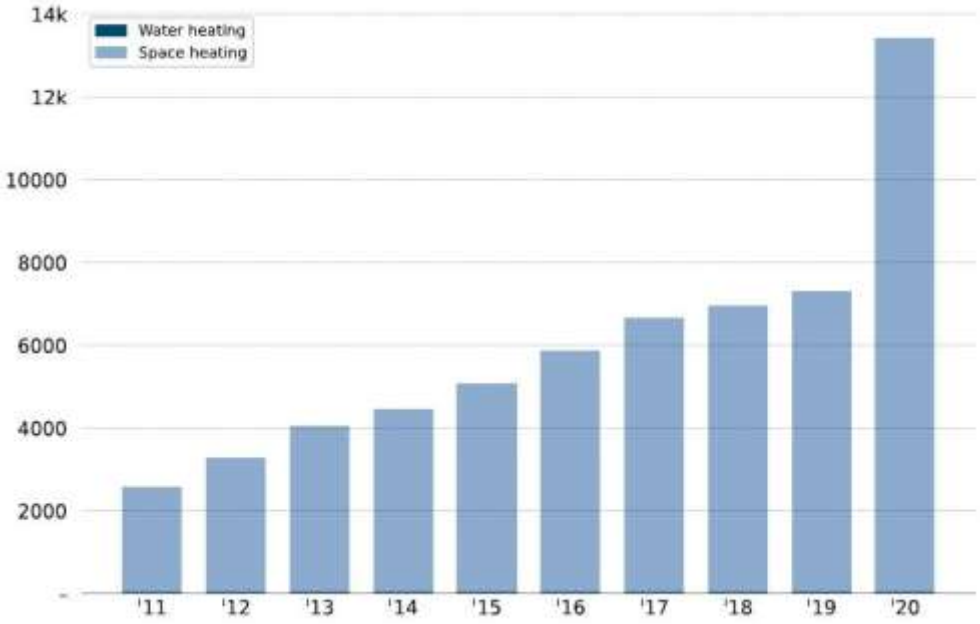


Figure 4.5. Heat pumps in operation, by type of heating in Hungary [78]

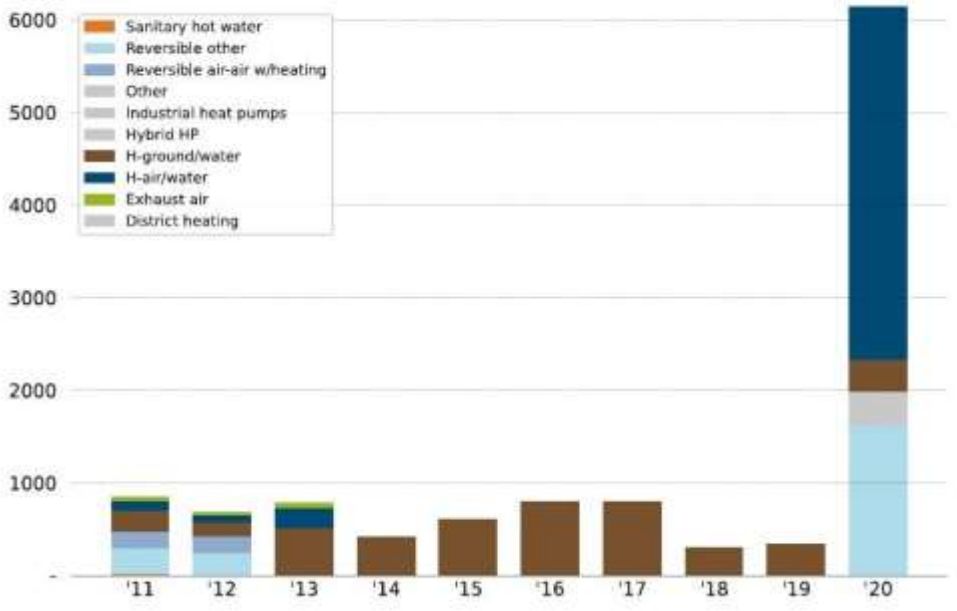


Figure 4.6. Heat pump sales development by type of heat pump ('H-' indicates primary heating function) in Hungary [78]

The market for air-water heat pumps, primarily utilized for heating purposes, experienced significant growth in several countries in Europe (Figure 4.7.). Poland witnessed a remarkable 108% increase, followed by Denmark with a 51% growth, Germany with 44%, Belgium with 36%, and Sweden with 34%, driven by strong policy incentives in these countries. In Hungary, the market for air-water heat pumps underwent a substantial transformation, soaring from virtually non-existent to over 5000 units sold in 2020 (Figure 4.6.).

However, despite the significant increase in total HPs sold in Hungary, there is still a huge backlog in Hungary in terms of penetration of GSHPs, as it is shown in Figure 4.8. E.g. in Sweden there are approx. 60 times more installed GSHPs per capita than in Hungary.

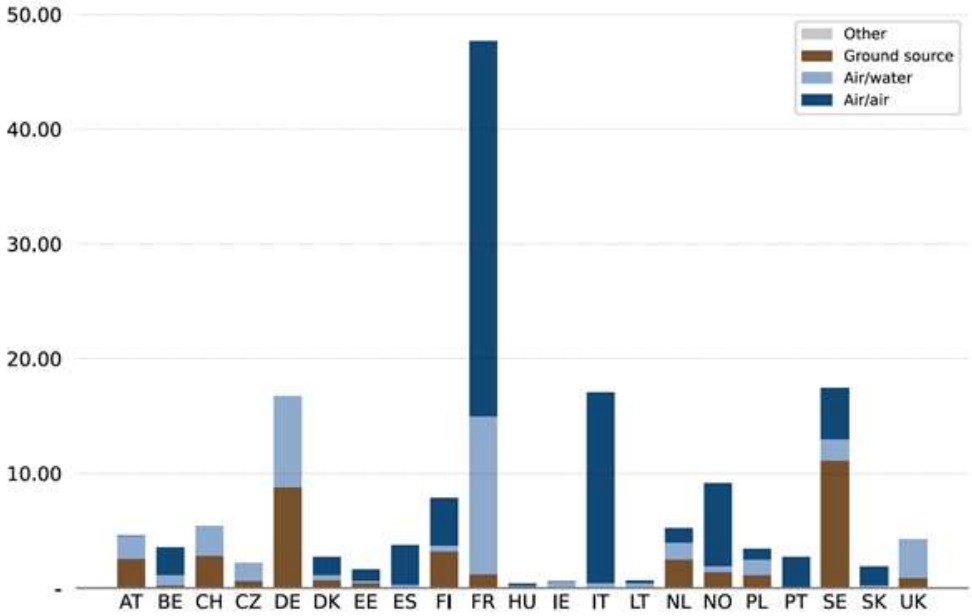


Figure 4.7. The distribution of renewable energy production from heat pumps in Europe. France leads in renewable energy production from heat pumps, followed by Sweden, Germany, and Italy [78]

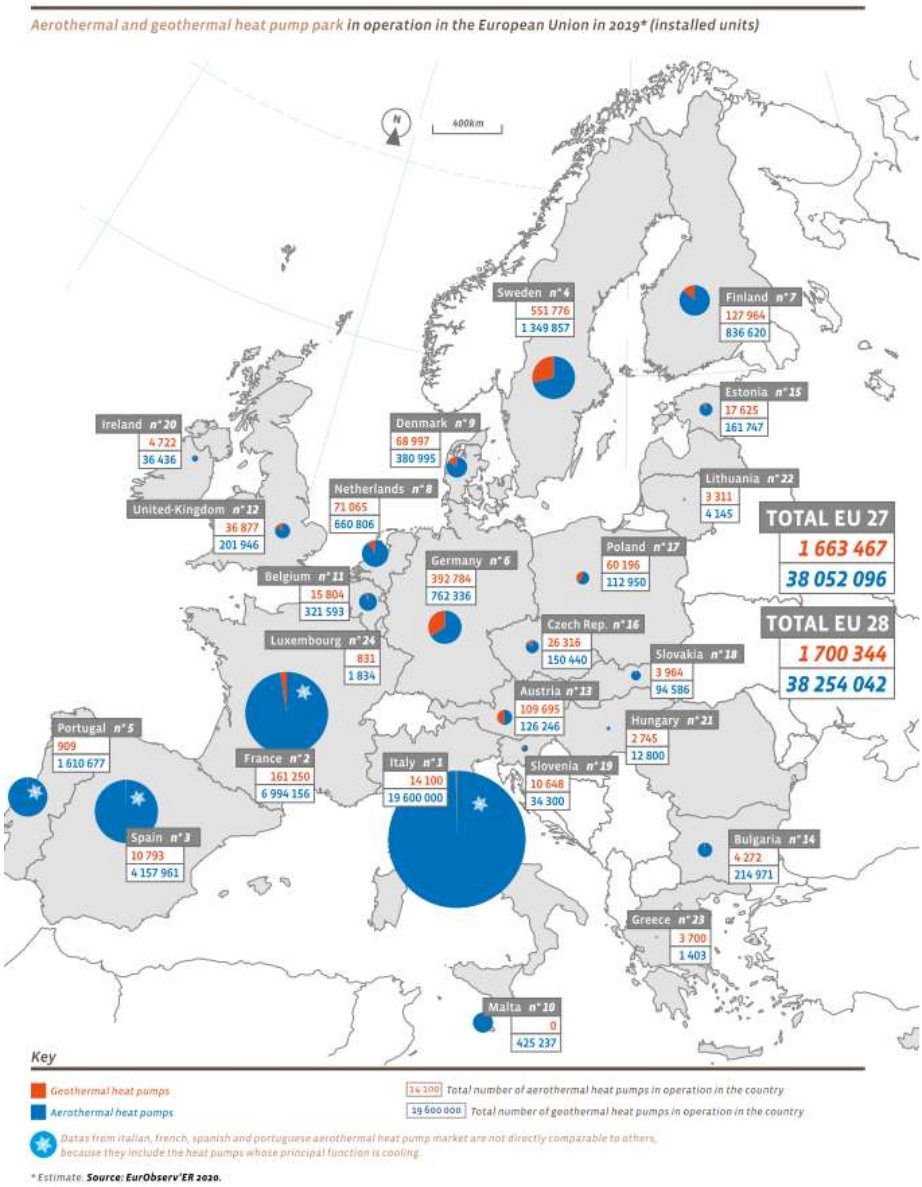


Figure 4.8. Aerothermal and geothermal heat pump park in operation in the European Union in 2019. ([] EurObserv'ER 2020).

According to the National Energy and Climate Plans (NECPs) of 2019, all Member States anticipate a rise in final energy consumption (FEC) attributed to heat pumps between 2020 and 2030, Spain leads with the highest increase at 1,046%, followed by Hungary at 467%, Belgium at 234%, and Poland at 195%. Italy is forecasted to have the highest FEC in 2030, estimated at 5.7 million tonnes of oil equivalent (Mtoe), followed by France at 4,5 Mtoe [102].

In 2020, the heat pump stock (heat pumps sold over the past twenty years) contributed 41,07 million tonnes (Mt) of greenhouse gas emission savings (Figure 4.9.). However, even with the 14,4% growth achieved in 2020, this progress remains only a step in the right direction. The current growth rate of heat pump markets across Europe falls short of what is needed to achieve the decarbonisation of

heating and cooling by 2050, Addressing this challenge requires bold decisions from governmental leaders to confront the underlying issue: a distorted price mechanism that favours the utilization of fossil fuels and fossil fuel technology.

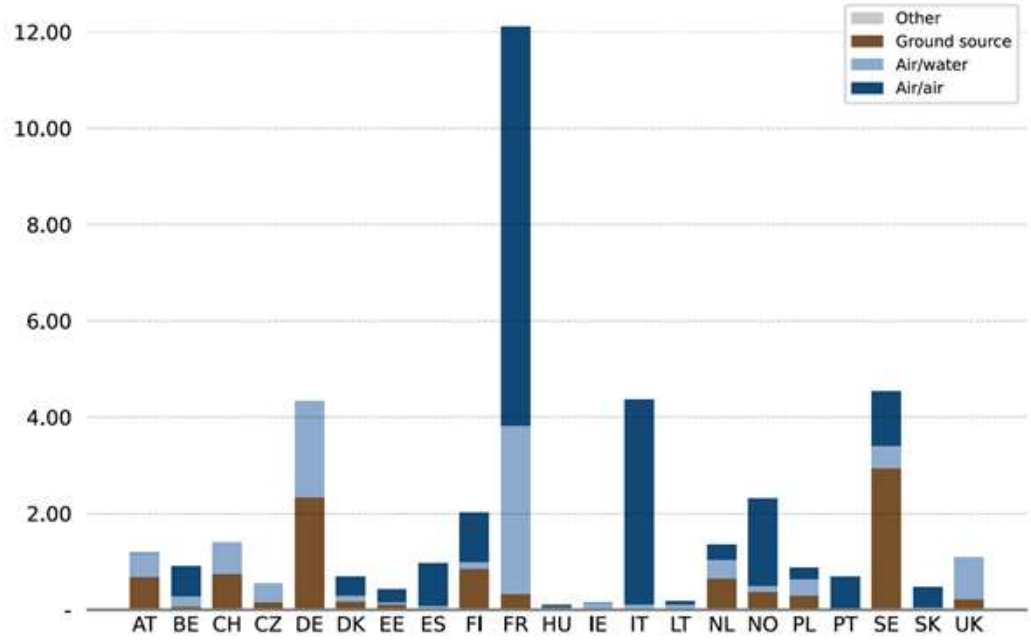


Figure 4.9. Greenhouse-gas emission savings based on sales 2020, per country (in Mt)

4.3. Overview of current regulations, incentives and general policy related to shallow geothermal

Main regulations relevant for shallow geothermal energy in Hungary

In general, energy and, particularly, renewable sources of energy, in Hungary are regulated by EU regulations and national law.

The Electrical Energy Act (2007. évi LXXXVI. törvény a villamos energiáról) mentions geothermal energy as renewable source of energy. The Mining Act (1993. évi XLVIII. törvény a bányászatról) treats the utilisation of geothermal energy as part of mining of mineral raw materials. This law regulates the research, extraction and utilisation of geothermal energy in Hungary. According to the Act geothermal energy sources are, at their place of occurrence, owned by the state. By extraction it becomes the property of the mining company. Research and extraction – except for medical and agricultural-related – is authorised by the mining supervision authority. For extraction of geothermal energy the state is entitled for a share, in form of mining royalty, which is paid by the mining company or the legal person, which extracts the energy. Research is only possible with the permission of the mining supervision authority, and only possible from defined parts of the earth's crust, which is to be registered by the relevant authority.

In 2021 the establishment of the Supervisory Authority of Regulated Activities has been enacted (2021. évi XXXII. törvény a Szabályozott Tevékenységek Felügyeleti Hatóságáról), which is an independent regulatory state body in Hungary that regulates often unrelated domains and performs tasks that is subordinated only to state legislation. This body also regulates the allocation of rights for research on geothermal energy research, extraction and all related activities. This authority has the right to issue

its own legal instruments, decrees, including the 12/2022. (I. 28.) SZTFH decree on the rules of construction authority procedures for certain specific structures under the jurisdiction of the mine supervision. This decree stipulates geothermal energy extraction and its use for energy production purposes as specific structures subject to the official construction permit of the mining supervision.
According to the recent amendment of the Mining Act, the newly established Supervisory Authority, in order to encourage extraction and use as widely as possible, may, by decree, limit the number of research areas extracted by one company. The mining supervision will keep a public record of the geothermal research areas. As a general rule, geothermal energy can only be extracted and utilized on the basis of a fixed-term contract, upon agreement of the Minister of Energy. The mining contractor must undertake to extract the annual amount of geothermal energy planned to be used. It is also an essential requirement that the extracted water should be entirely pushed back, according to technical and geological possibilities. On the other hand, extraction and utilisation of geothermal energy up to the 150 meters part above the earth's crust can be authorised by the mining supervision with a simplified procedure, without entering into a contract [76, 83].
Concerning agriculture-related use of thermal energy, in form of extracting thermal water, it is still an activity subject to water law permit, which is to be authorised through the territorially competent Disaster Management Directorates (93).

General policy framework

In general, there is no general policy framework directly targeting shallow geothermal energy utilisation, however promotion of renewable sources of energy, in general, is on the agenda, in line with the EU Green Transition policy and national development documents.
Main strategic document for Hungary is the National Energy and Climate Action Plan (NECAP) of Hungary, which sets out the following:

- in terms of electricity “Hungary plans to increase the share of energy production based on renewable energy sources (…) to at least 20% by 2030” (Ministry of Innovation and Technology, n.d.; 42);
- in heating and cooling a major potential is identified for the efficient use of biomass and exploitation of geothermal energy potential in both district heating and in the agro-industry (Ministry of Innovation and Technology, n.d.).

According to the NECAP, the use of geothermal energy accounts for around 7% of the renewables. In terms of electricity a moderate increase is expected until 2030, while in the heating and cooling sector an increase of 58% is foreseen until 2030 (Ministry of Innovation and Technology, n.d.).
As far as instruments are concerned, the NECAP provides details on the REAS scheme (Renewable Energy Aid Scheme) started in 2017, which provides support to the market integration of renewable energy generation, as well as supporting RES projects with a technology-neutral approach. Most of the funding was spent for photovoltaic energy production facilities up to 0,5 MW. As another instrument, the Green District Heating Programme foresees the use of geothermal energy, by replacing current natural gas-based heating systems.

Current incentives and schemes for promotion of shallow geothermal energy

To date, in general, renewable energy support schemes have focused on the deployment of solar photovoltaic capacities. The large potential for scaling up renewable energy in geothermal and wind remains unexploited. The above-mentioned law amendment is meant to prepare the upscaling of geothermal energy utilisations. Besides administrative changes, the state has joined forces to set up capacities for energy extraction and utilisation.
In spite of these tendencies, currently there is no targeted national funding available in Hungary for geothermal energy applications, based on reuse of existing wells, however it is expected for the near future.
Currently available schemes that, inter alia, fund geothermal energy related investments:

(1) Swiss-Hungarian Cooperation Programme Period II, Thematic area Energy efficiency and renewable energy sources, Programme SM06-GEO "Geothermal energy sources for district and urban heating"

The public consultation on the programme closed on 22 January 2024. These are currently being processed and, as a result, the text of the call for proposals is being clarified and finalised with the programme partner, the Ministry of Energy, and the Swiss partner. More information: https://svajcialap.hu/programok/energiahatekonysag-es-megujulo-energiaforrasok.
The scheme is expected to finance the following activities:

- Upgrading, rehabilitation and conversion of existing active or closed, producing or recovering thermal wells with geothermal potential, but which are not in use at the time of this call for proposals, into publicly owned barren hydrocarbon wells to increase sustainable geothermal energy production.
- Increasing the capacity of production and recovery wells for geothermal energy production by carrying out other upgrading and well engineering works;
- Bringing closed thermal, thermal or barren hydrocarbon wells into geothermal thermal production by refurbishment or conversion.

Completion period of the funded projects is 24 months.

(1) REPowerEU

In response to the difficulties and turbulence on the world energy market, the European Commission has developed and launched the REPowerEU plan, which provides assistance in an amount of 4.6 billion EUR to Hungary. The plan outlines reforms and investments. Under the foreseen reforms the Hungarian government commits the setup of a regulation framework for geothermal energy, including the simplification of permission procedures. The defined deadline is the fourth quarter of 2024. Under the main investment, the plan does not directly target geothermal energy, mentions as a potential for heating of public service facilities and residential building. In general, geothermal energy should be primarily financed under cohesion programmes and national instruments [97].
The document foresees the setup of support scheme for geothermal-based heat production projects, including those focusing on shallow geothermal, envisaging the finalisation of the drilling activities until

the middle of 2026. The scheme is planned to be implemented by the Hungarian Development Bank, in form of discounted loans for the research phase and non-repayable grants for the drilling activities [97].

The REPowerEU credit line scheme targets, inter alia, the following investments:

- Greening industrial parks for energy: both for electricity and heating. Any mix of technologies can be used, but it is particularly important to ensure that the mix of technologies is in line with each other and with demand. As part of the basic infrastructure of the industrial parks, it is proposed to support the creation of a closed energy network, without connecting to the national grid, which is suffering from capacity problems. This may be particularly relevant in isolated plants, with an increasing proportion of energy supply based on renewable energy sources, at a favourable price and in a sustainable manner, since they rely on locally produced green energy. The investment may also include industrial-scale heat pumps and other activities to recover residual heat. This includes the installation of electricity storage capacity and an energy management system capable of balancing the volatility of demand and supply, as well as the fluctuations resulting from the use of weather-dependent renewable energy sources. The use of residual heat is also possible, however, it is determined by the distance from the source of the heat.
- Geothermal energy investments: encouraging the use of geothermal energy by reducing the financial risks of geothermal drilling for energy purposes (including the injection well). It reduces the risks arising from well drilling by ensuring that the amount of non-refundable subsidies may be awarded in the case of high share of unsuccessful drilling and low in the case of successful drilling. The loan will be available for a range of investments in geothermal energy recovery activities, both above and below ground (heat generation for district heating and/or industrial heat production and electricity generation). In addition, the loan will be available for the installation of equipment for the extraction, treatment and processing of accompanying elements in thermal water (e.g. CO_2 or recoverable solvents). Investments necessary for connection to the grid (electricity and/or heat) may also be financed by the loan.

The relevant investments with their funding allocation are shown on Table 4.2.

Table 4.2. Funding of REPowerEU for Hungary, relevant from shallow geothermal energy point of view [97]

Objective	Funding (billion HUF)	Funding (million EUR)*
Energetical greening of industrial parks	201.14	515.74
Energy efficiency development of businesses	175.49	449.97
Utilisation of geothermal energy	159.58	409.18
Relevant objectives total	536.21	1 374.89

* Exchange rate: 390 HUF/EUR

(2) Territorial and Settlement Development Operational Programme Plus 2021-2027

The Territorial and Settlement Development Operational Programme Plus 2021-2027 (TSDOP+) is financed by the European Regional Development Fund and the European Social Fund. Energy-related investments are financed from the specific objective (SO) 2.2 (renewable sources of energy), inter alia, the following areas of intervention relevant from shallow geothermal energy point of view [105]:

- Satisfying local heating and cooling as well as electricity demand based on decentralized renewable energy sources, at individual and community level, primarily solar, biomass, geothermal, heat pump-based systems;
- Creating a connection to an existing local community heating plant or waste heat utilization system powered by renewable energy sources, including the establishment and investments of energy communities

The call of the action 2.1.1 “energy refurbishment of local governmental buildings” supports the following eligible activities that are relevant from shallow geothermal energy point of view [104]:

- Modernization and replacement of heat generating equipment based on fossil energy, and/or upgrading the related heating and hot water systems, reaching at least “DD” category or C_{2023}.
- Installation of heat pump and its connection to the heat transfer system.
- Development and modernization of spas of local and regional importance for energetic purposes: building energy developments, heat generators, heat distributors, air handlers and building air conditioners; installation of central cooling equipment and replacement of a compressor liquid cooler, mechanical system modernization, heat pump installation, buffer storage design; establishment and expansion of thermal water wells, renovation, well technology development; utilization of the heat content of leachate, swimming pool and thermal water (e.g. with a heat pump); utilization of generated waste heat outside the spa area (limited to public buildings).

Besides the mentioned investment activities, each project must include installation of measurement equipment for monitoring of produced energy, possibilities of installing automatic central and local regulation, education activities of the users as target groups.

In case of installation of heat pumps up to 100 kW of heating power, the equipment must comply with the Commission Decision 2007/742/EC, including the minimum COP values as per the Annex to Commission Decision [104].
Efficiency requirements:

- In the case of electrically driven heat pumps must comply with MSZ EN 14511 standard series, MSZ EN 14825 standard or equivalent technical requirements, as well as the provisions of the Commission Decision;
- In the case of gas-powered heat pumps, must comply with MSZ EN 12309 standard series, MSZ EN 14825 standard or equivalent technical requirements and the provisions of the Commission Decision;
- Minimum COP values based on the Annex of Commission Decision No. 2007/742/EC.

When using a ground-water and water-water heat pump, min. 65% of the annual heat demand must be supplied by the heat pump. When using an air-water and air-air heat pump, min. 50% of the annual heat demand must be supplied by the heat pump. Each equipment must have the relevant supporting documentation [104].
The assistance provided by the scheme is non-repayable grant, with a co-financing rate of 100% (80% ERDF, 20% national co-financing provided automatically). In case of project elements for local infrastructure development, the amount of subsidy can't be more than the difference between the eligible costs and the operational profit. In case of projects below 2 million EUR the amount of subsidy can't be more than 80% of the eligible costs[104]. The scheme sets various thresholds in light of CO_2 emission savings, as well as maximum amounts for investment elements according to different sources of renewable energy and different types of heat pumps (expressed in HUF/kW).
Implementation period of the projects is 36 months.

(3) Environmental and Energy Efficiency Operational Programme Plus 2021-2027

The Environmental and Energy Efficiency Operational Programme Plus 2021-2027 (EEEFOP+), concerning the relevant specific objectives (SO), is financed by the Cohesion Fund. Investments relevant for the project topic are financed from the SO 2.1 (energy efficiency) and SO 2.2 (renewable sources of energy). Financing takes place through the combined use of non-repayable grants and repayable loans,
Under SO 2.1 the following areas of interventions are relevant from shallow geothermal energy point of view:

- Building engineering interventions: modernization of systems and equipment responsible for heating and cooling, as well as domestic hot water;
- Utilisation of renewable energy sources in building refurbishment;
- Modernisation and improving the efficiency of district heating systems.

Under SO 2.2 the following areas of interventions are relevant from shallow geothermal energy point of view:

- Installation of modern boilers and heat pump systems utilising renewable energy sources;
- Electronic heating systems based on renewables;

Beneficiaries include ESCO companies, local population, civil organisations, SMEs, facility owners, public administration bodies, churches, district heating companies.
Calls under the two SOs are already closed, no new funding is foreseen.

4.4. General country geology, hydrogeology and thermogeological parameters

Hungary, although located in a non-active volcanic area, possesses geothermal characteristics that are remarkable not only within Europe but also on a global scale, which can be attributed to two factors. Firstly, the temperature increases more rapidly with depth compared to the global average, there is a high geothermal gradient, averaging at 45 °C/km.
Secondly, significant portions of the country's territory characterised by clastic sedimentary rocks, fractured limestone and dolomite underground with high permeability. To bring the heat of natural geothermal systems to the surface, a fluid medium is necessary. Thermal water– which is at least 30°C – and according to domestic definition, available in over 70% of the territory of the country. [86]
The reason for the favourable geothermal conditions – which place Hungary in the forefront of Europe – lies in the development history of the Pannonian Basin. The heat flow of the area significantly surpasses the continental average (65 mW/m^2) at 90-100 mW/m^2, as a consequence of lithospheric thinning during the formation of the basin in the middle Miocene (17,5-12,5 Ma) [99, 100, 85]. The thickness of the crust in the region is 25-30 km, which is less than half of the average crustal thickness of the European continent. The high-temperature asthenosphere – due to lithospheric thinning – is closer to the surface, resulting in an elevated geothermal gradient and heat flow within the crust.
The average heat flow in the Pannonian Basin is approximately 90 mW/m^2. Over an area of 93,000 km2, this heat flow amounts to 8,37 GW of heat output. The annual geothermal heat quantity transported by the heat flow is 264 PJ. This would represent the replenishing heat asset derived from the Hungarian heat flow. According to data from the Central Statistical Office (KSH), in 2021, the total primary energy consumption in the country was 1154,8 PJ, of which geothermal energy accounted for only 6,6 PJ.
The distribution of heat flow in Hungary is not consistently high, as it varies based on factors such as lithospheric thinning and other geological and geophysical processes. Groundwater flow has the most significant impact on temperature distribution within the crust [85]. In the surroundings of the Transdanubian Mountains, the Bükk, and the Aggtelek-Gömör karst region, the heat flow is lower (50 mW/m^2) than the continental average. In these areas, the infiltration of cold karst water into fractured, karstic carbonate rocks reduce the heat flow. Several kilometres deep, the water warms up, then rises upwards, reaching the surface in hot springs at the foothills. Upward flow is concentrated in small areas, while seepage occurs over a large area, resulting in a much smaller area of heated zones compared to cooled ones [89] (Figure 4.10.).

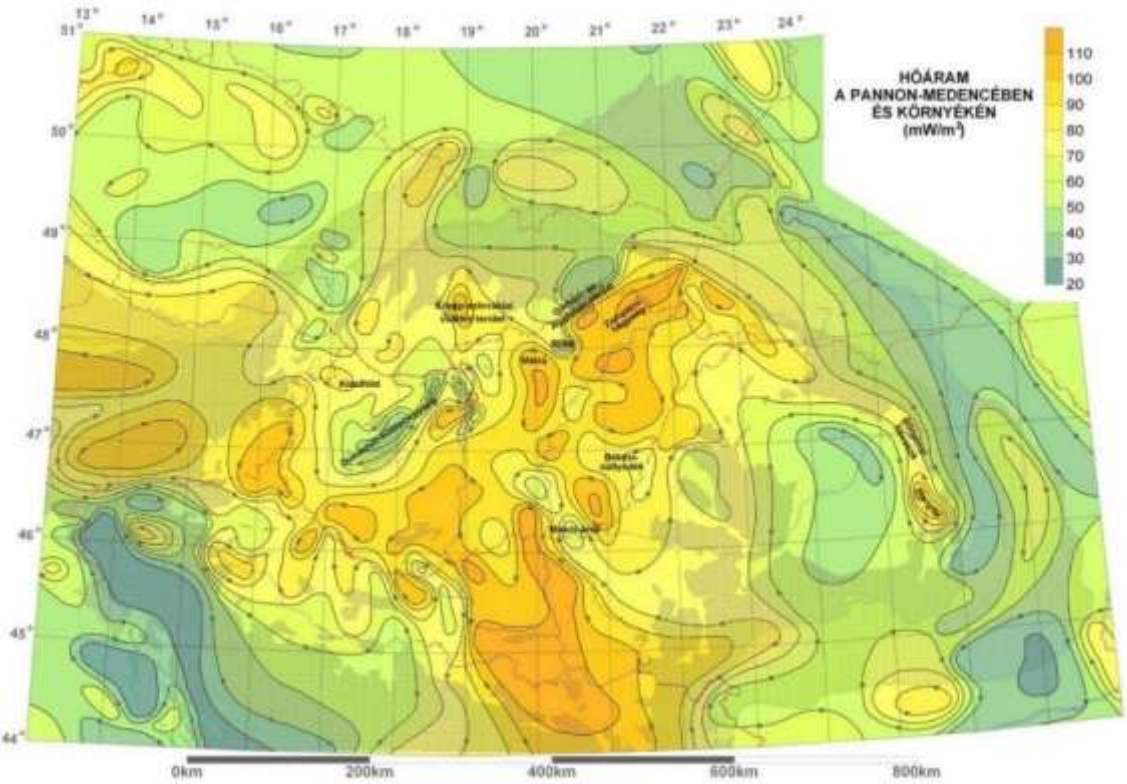


Figure 4.10. The heat flow in the Carpathian Basin and its surroundings [75]

The heat flow is also lower in the Little Hungarian Plain than the average. This is partly due to the fact that cold karst water flow can be found beneath the Little Hungarian Plain, and partly because the 7-8 km thick sedimentary layers reduce the heat flow (Figure 4.11.).

Areas with the highest heat flow are situated in the Mecsek Mountains and over the Battonya high, which is covered with 800–1000 meters thick sediments. This is because the heat flow is directed towards the basement highs, which consist of highly conductive crystalline and metamorphic rocks. Conversely, basin areas filled with thick sedimentary sequences exhibit lower heat flow density, around 80 mW/m^2, such as in the Little Hungarian Plain, Makó Trough, and Békés Basin in the Great Hungarian Plane (Figure 4.11.). Due to volcanic activity, the heat flow is higher in the inner part of the Carpathian arc, particularly in the Mátra Mountains, the Zemplén Mountains (Figure 4.11.) [88, 84].

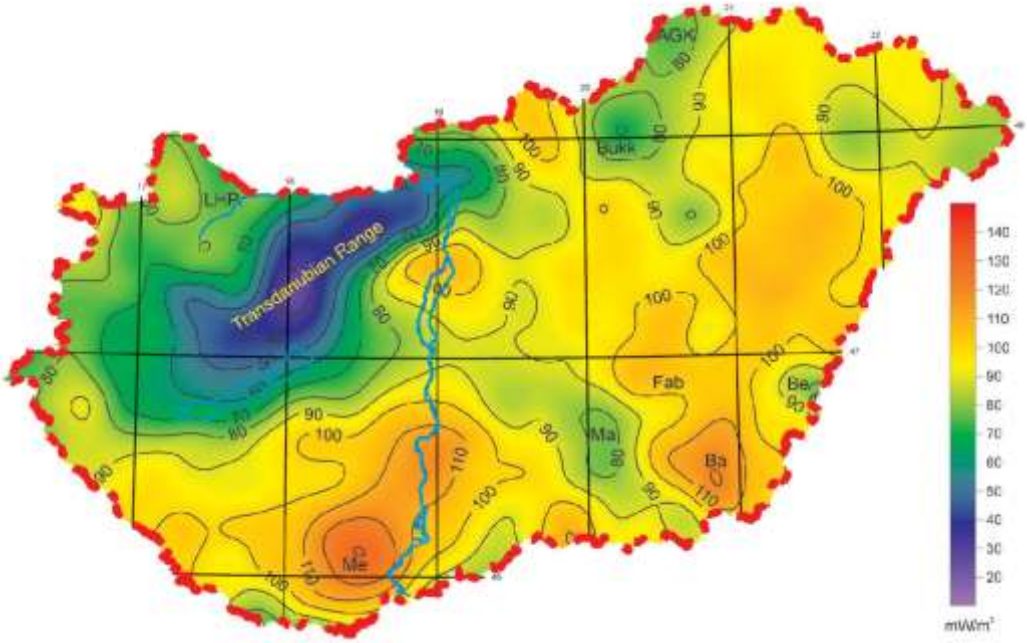


Figure 4.11. Heat flow in Hungary. The contour interval is 10 mW/m² (Lenkey et al. 2021).

Temperature is one of the key parameters when considering the utilization of geothermal energy. The underground temperature is the lowest in the Transdanubian Mountains due to the karst water. Similarly, the temperature is low beneath the Little Hungarian Plain and in the Makó Trough. At a depth of 500 meters, except for the cold areas, the average temperature is 35-40°C. Higher temperatures, ranging from 45-70°C, are caused by the heating effect of water flow, which is most effective in the upper 500 meters (Figure 4.12.A). At greater depths, the temperature of the water gradually becomes less different from the surrounding environment, thus eliminating the temperature anomaly caused by the water flow. At a depth of 1000 meters, the average temperature is 55-65°C. In warmer areas such as the Mecsek Mountains, the Battonya High, and the northeastern part of the Great Hungarian Plain, the temperature exceeds 70°C (Figure 4.12.B). At a depth of 2000 meters, the average temperature is 110-120°C, while in the warmer areas, the temperature reaches 130-140°C (Figure 4.12.C) [89].

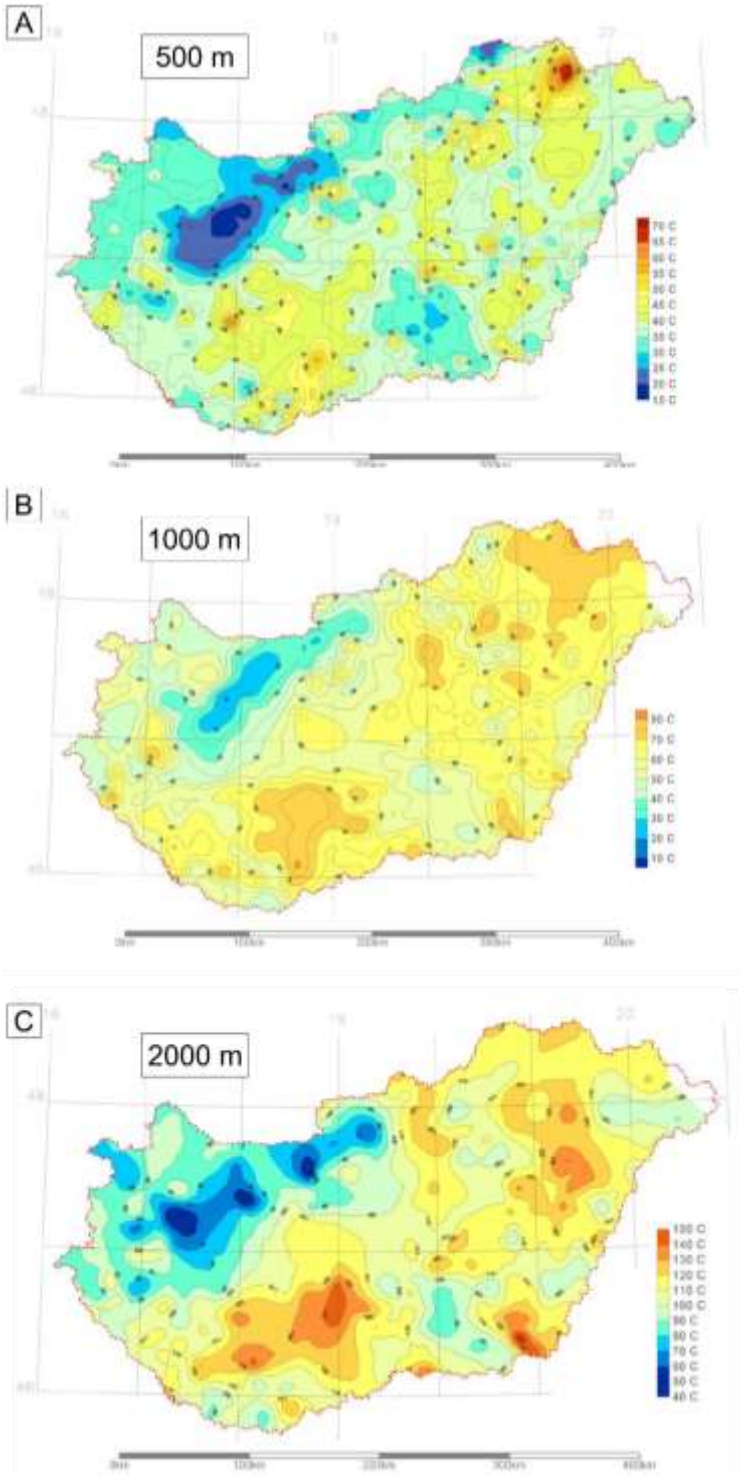


Figure 4.12. The temperature distribution at a depth of 500 (A), 1000 (B), 2000 (C) meters below the surface [74]

The thermal conductivity and the extractable heat performance depend not only on the mineral composition of the rocks but also on porosity and saturation with water. It is advantageous if there is water flow in the pores because in such cases, heat conduction is accompanied by heat convection. Therefore, loose, high-porosity sediments characterized by high groundwater levels are the most ideal

media for the installation of GSHPs. Based on these findings, regions of Hungary can be categorized for GSHP system installation. Favourable conditions are prevalent in the Great Hungarian Plain and Little Hungarian Plain, while hilltop areas featuring Miocene or Oligocene loose sedimentary rocks offer acceptable conditions. Conversely, unfavourable conditions are typically encountered in hillside and mountainous regions characterized by older sedimentary rocks, as well as in igneous and metamorphic areas [71].

Except for mountainous areas, Neogene sediments are found beneath the surface in Hungary, with thickness varying between a few hundred meters and 8 kilometres (Figure 4.13.). The thickest sediments are located under the Little Hungarian Plane (8 km), the Drava trench (4 km), and certain areas of the Great Hungarian Plain (Makó Trench, 7 km and Békés Basin, 7 km). The upper part of the Neogene reservoir, the Quaternary and Upper Pannonian aquifer system, consists of alternating layers of gravel, sand, sandstone, silt, clay, and marl, forming a hydraulically unified reservoir. The reservoir is characterized by regional groundwater flow, with recharge areas located in regions of higher altitude, such as the Nyírség and the Danube-Tisza Interfluve, and discharge areas are located in the lowest altitudes of the plains. The hydraulic conductivity of the Upper Pannonian sand and sandstone (Nagyalföld Aquifer) is 10^{-5} m/s, with well yields of up to several tens to 100 m^3/h achievable ([89].

The sediments beneath the Great Hungarian Plain consist mainly of marl and clay. These rocks are predominantly aquitard in nature (Algyő Aquitard K=10^{-8}-10^{-7} m/s; Endrőd Aquitard K=10^{-9} m/s), although sandstone bodies occur between aquitards: Szolnok Aquifer, K=10^{-7}-10^{-6} m/s. Overpressure is experienced everywhere within or beneath the aquitards, although its location varies by region (Figure 4.13.) ([89] .

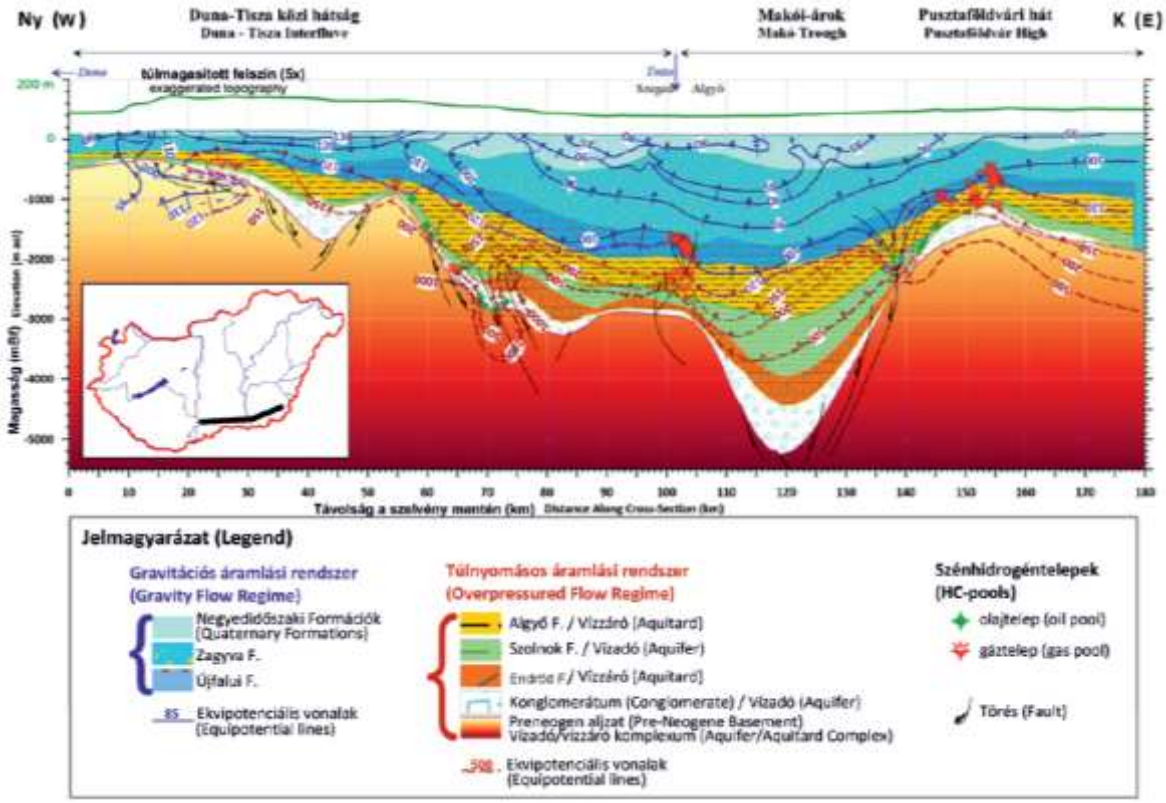


Figure 4.13. Schematic hydrostratigraphic profile across the Great Hungarian Plain with location of the section [101]

The thermal response test (TRT) measurements for vertical geothermal heat pump systems have a particularly significant impact on sustainable and economical operation [73]. Ádám [71] initiated TRT measurements at 27 locations across Hungary, beginning in 2006. Ádám [71] has demonstrated that a BHE system can be sustainably operated within the geological conditions of Hungary, if the BHE system utilized for both cooling and heating purposes.

The multi-stage, complex utilization approach of thermal waters is still novel, although increasingly popular. An advantage of using heat pumps in such applications is that energy can be extracted without increasing water extraction or compromising water quality. Heat pumps could extract 10 PJ/year of energy from the heat of the wastewater of spas and other geothermal projects in Hungary [70].

Most of the Hungarian baths released the still quite warm, 20-30°C thermal water without further cooling. According to Erőss et al. [79], the combined wastewater from the thermal baths of Budapest, along with effluent springs and pool wastewaters, carries a total of 25 MW_{th} of waste heat, which could be utilized by heat pumps.

Nowadays, there are several examples of utilizing the heat energy of the discharged warm waters through heat pump extraction principle, such as in Harkány (2,2 MW), Kecskemét (300 kW), and Miskolctapolca (300 kW). In Harkány, two 1,1 MW heat pump systems were installed for the discharge water of the thermal baths (27-28°C). Previously, the extracted 62°C water was cooled without energy utilization to 30-35°C used in the pools, then after it was discharged into the drainage channel with a few degrees of heat loss. Today, this waste heat-utilizing heat pump system provides thermal energy not only to the bath buildings but also to several public institutions, apartments, and hotels in the town [94].

The energy needs of Hévíz spa and Szent András Rheumatology Hospitals are provided by a heat pump system capable of heating-cooling and producing hot water for use, totalling nearly 2 MW. The temperature of the discharged medicinal water is 25-30°C, from this source-side temperature, heat pumps produce heating water which is 70-80°C (94).

Thanks to recent developments at the Sárvár spa, the water in the outdoor pool is now tempered with a heat pump system ensuring multi-stage extraction of the thermal energy of the medicinal water, and the solution is also applied in part of the indoor baths ([94].

The Nagykőrös spa utilizes the heat of the discharged thermal water for heating and maintaining the temperature of three pools, preheating domestic hot water, and also for heating the building. The result of the comprehensive energy approach is spa, compared to the traditional system designed with a power requirement of 274,2 kW, the installed heat pump system operates at planned temperature levels with a total power of 144 kW [80].

At the Mórahalom spa, 4 thermal wells supply the water, and the thermal heat is also utilized for heating purposes in a comprehensive manner. In the latest major development of the spa, the heat of the discharged thermal water was utilized with heat pumps for heating the spa and the buildings of the town, as well as for providing domestic hot water ([101].

A complex geothermal heating system was built in Nagyatád, where a total of 5 municipality buildings are heated by the utilization of the wastewater heat of the thermal water of Nagyatád Spa and two additional buildings will be connected to the system in the near future. Total heating capacity of the system is approx. 600 kW. The thermal waste heat energy is utilised by collecting the outflowing thermal water of the Spa in an underground buffer tank of 250 m^2, transferring the heat energy of the thermal waste water to the clean water which is circulated to the municipality buildings through open system (not pressurized) water pipelines. The heat is utilised at each of the municipality buildings by special hot water – water heat pumps tailor-made to the heating needs of the different buildings. Due to the direct hot water utilization by the heat pumps, the SCOP of the heating is extremely high, reaching 6,0, The geothermal waste water system replaces 90-95% of total fossil gas demand of the

buildings. The system is combined with PV systems deployed on the roofs of the municipality buildings, covering the electricity needs of the installed heat pumps ([] Márton Gy., Fodor Z. 2023).

4.5. Current energy cost comparison for residential and non-residential sector with estimated capital cost of drilling and equipment for shallow geothermal

Current energy prices on the stock market in Hungary are as follows:
- Fossil gas price: 33,55 EUR/MWh (June 2024);
- Electricity price: 89,15 EUR/MWh (June 2024).

Data sources:
https://hudex.hu/hu/piaci-adatok/foldgaz/napi-adatok#bom []
https://hudex.hu/hu/piaci-adatok/villamos-energia/napi-adatok#month []

In Hungary a fixed energy price is defined for households, as follows:
- fossil gas: 102 HUF/Nm^3 up to 1729 Nm^3/year consumption, above: 732 HUF/Nm^3;
- electricity: 35,2 HUF/kWh up to 2523 kWh/year consumption, above: 70,1 HUF/kWh.

For district heating, the energy prices are also partly fixed, based on the NFM Decree 50/2011. (IX. 30,) on establishing the price of district heat sold to the district heating provider and the fee for the district heating service provided to residential users and separately managed institutions.
The decree fixes the following prices:
- Price of district heat (sold by the heat producer (heat power station) to the district heat provider (district heating company), both the base and heat prices are fixed for each of the operating DH system separately;
- Price of heat sold to households: fixed at the heat price of 30 September 2014 minus 3,3%;
- Price of heat sold to “separately managed institutions”: central government and its institutions, local government and its institutions, both the base and heat prices are fixed for each of the operating DH system separately.

All other prices are market prices, which means that neither private companies nor non-profit and civil organisations are provided with reduced fossil gas prices and electricity prices. Also, local government institutions not connected to district heating systems have to buy fossil gas and electricity from the market. For them the government offers a yearly contract for a specified quantity of energy consumption, but its price is related to the stock market prices. This situation caused huge problems for local governments and also for private companies in the period of the energy crisis after the beginning of the Ukraine war when the energy prices went soaring up. It seriously endangered the daily operation of public buildings and companies.

This unbalanced pricing system causes no real energy consciousness for households (as their prices are fixed) and high uncertainty for local governments and private companies (as they are exposed to market volatility).

There is no effective price incentive system in Hungary for boosting up usage of geothermal energy, including GSHPs. The energy pricing is ignorant of usage of geothermal energy:

- In terms of district heating, neither the district heating heat producer companies (heat power stations), nor the district heating companies receive any incentives for using geothermal energy. If a DH system invests in geothermal energy utilization aiming at reduction of heat production costs and replacing fossil gas consumption, it is followed by reduction of its fixed heat price. It is because the fixed pricing system is controlled and calculated by the Hungarian Energy and Utilities Regulatory Office (Magyar Energetikai és Közmű-szabályozási Hivatal) further to 4. § of the NFM Decree 50/2011. (IX. 30,) and they reduce the fixed heat price according to its production costs.
- In terms of local heat production, there is an incentive called H tariff. This is exclusively available only for households installing heat pumps (including GSHPs) for the heating season from 15 October until 15 April. Price of H tariff electricity: 23,5 HUF/kWh. It can be applicable for households, but on one hand it is complicated to install (separate electricity meter is needed to be installed certified by the electricity provider) and the price advantage is minimal compared to the fixed electricity price of 35.2 HUF/kWh. The major problem is that it is totally unavailable either for public institutions (either central or local governments) or for private companies and NGOs. Consequently, the heat consumers with higher heat demand cannot use this incentive.

Considering the fact that GSHP systems require substantial investment costs, comprehensive and effective incentive system would be needed to be introduced to foster installation of geothermal heating systems, including GSHP systems. The fixed energy prices (both for households and for district heating systems) and the lack of price incentives for geothermal heat production seriously contribute to the slow penetration of GSHPs in Hungary.

Estimated investment costs:

Geothermal wells:
Drilling of two new geothermal wells (production and reinjection wells) with a depth of 2000 metres costs around 6 million EUR.
Wells drilled to shallow aquifers (1000-1500 metres deep) is cheaper, this option can be feasible for Upper Pannonian sandstones, typically for the Hungarian Great Plain, for Inner-Somogy and for the Little Hungarian Plain. A pair of geothermal wells for shallow layers costs around 3-4 million EUR.

Closed loop BHE heat pump system:
Investment costs of a 500 kW BHE heat pump system is calculated as follows (net prices):

- Investment preparations (studies, main design plans):	50000 EUR
- Boreholes 100 metres deep, pipelines, circulating pumps, machinery:	400000 EUR
- Heat pump system (installed brine-water (b-w) heat pumps):	280000 EUR
- *Total:*	*730000 EUR*

Open loop groundwater heat pump system:
Investment costs of a 500 kW open loop groundwater heat pump system is calculated as follows (net prices):

- Investment preparations (studies, main design plans):	75000 EUR
- Water wells 30-50 metres deep, pipelines, circulating pumps, machinery:	300000 EUR
- Heat pump system (installed water-water (w-w) heat pumps):	275000 EUR
- *Total:*	*650000 EUR*

Open loop thermal waste water heat pump system:
Investment costs of a 500 kW open loop thermal waste water utilization heat pump system is calculated as follows (net prices):

- Investment preparations (studies, main design plans): 50000 EUR
- Buffer tank (250 m3 underground): 100000 EUR
- Pipelines (500 m), circulating pumps, machinery: 270000 EUR
- Heat pump system (installed hot water-water (w-w) heat pumps): 280000 EUR
- *Total:* *700000 EUR*

In terms of its efficiency, GSHP systems have higher seasonal coefficient of performance (SCOP) values than aerothermal (air-air or air-water heat pump) systems. Aerothermal systems can produce SCOP of 2.5-3.0, GSHP systems can be characterized by the following SCOP values:

- Closed loop BHE heat pump system: 3,5-4,5;
- Open loop groundwater heat pump system: 3,5-4,5;
- Open loop thermal waste water heat pump system: 5,5-6,5.

It can be stated that GSHPs have significantly lower investment costs than geothermal well based heating systems. If under a MW of heating demand is present, GSHP systems can be regarded as the most cost-effective solutions.

Closed loop BHE heat pump system is the most common solutions for application of GSHP technology. Considering its relatively higher investment costs at a larger scale (around 400-500 kW), but taking also into account its applicability in various areas (especially in Hungary with favourable geothermal gradients), this technology is optimal to be applied for relatively lower heat capacity demands (50-300 kW).

Open loop groundwater heat pump system has the lowest calculated investment cost, but abundant groundwater is needed to be available (min. 300-400 l/min). Therefore, this system is optimal for alluvial plains and areas close to rivers and for heating of larger buildings or group of buildings in close proximity (with heat capacity demand of 300-500 kW).

Open loop thermal waste water heat pump system can be applicable where abundant outflowing hot water is present, typically at thermal spas or by utilizing the waste heat of thermal water of a geothermal district heating system before thermal water reinjection. It is also applicable at industrial companies with significant waste heat production. This technology has relatively higher investment costs at a larger scale, but taking into account its extremely high SCOP value, when waste water heat is available, this solution is the most optimal to be applied for heating larger buildings or group of buildings (with heat capacity demand of 300-500 kW).

4.6. Environmental regulations and restrictions related to shallow geothermal development

Relevant national acts regulating shallow geothermal energy utilisation:

- The Electrical Energy Act (2007. évi LXXXVI. törvény a villamos energiáról) mentions geothermal energy as renewable source of energy. It also defines the category of “small power plant”: with a nominal capacity of less than 50 MW.
- The Mining Act (1993. évi XLVIII. törvény a bányászatról) treats the utilisation of geothermal energy as part of mining of mineral raw materials. This law regulates the research, extraction and utilisation of geothermal energy in Hungary. According to the Act geothermal energy sources are, at their place of occurrence, owned by the state. By extraction it becomes the property of the mining company. The Act regulates the mining fee. There is no mining fee on the extracted geothermal energy below 30 °C. The Mining Supervision authorises the research, extraction and utilisation of geothermal energy through the extraction of thermal water, with the exception of the extraction of thermal water for primarily medicinal or primarily agricultural purposes.
- Supervisory Authority of Regulated Activities Act (2021. évi XXXII. törvény a Szabályozott Tevékenységek Felügyeleti Hatóságáról): enacted the establishment o the state body responsible, inter alia, for allocation of rights for research on geothermal energy, extraction and all related activities. This authority has right to issue decrees for regulating the domains within its jurisdiction (SZTFH decree).
- Water Management Act (1995. évi LVII. törvény a vízgazdálkodásról): regulates water right permit for the use of underground waters and the levying of water resource contribution, which is not relevant for push backed thermal water.
- Energy Efficiency Act (2015. évi LVII. törvény az energiahatékonyságról): regulates the basic principles of energy efficiency and the use of renewable energy sources in energy efficiency interventions.
- The Cultural Heritage Protection Act (2001. évi LXIV. törvény: Törvény a kulturális örökség védelméről) says modernisation of a monument – including complying with energy efficiency requirements and principles of energy saving – cannot cause irreparable damage or loss of the values of protected monuments.

Lower level legal instruments relevant for application of shallow geothermal energy:

- SZTFH decree 12/2022. (I. 28.) on the rules of construction authority procedures for certain specific structures under the jurisdiction of the mine supervision: lays down certain specific regulations concerning mine supervision, including geothermal energy extraction. This regulation stipulates that geothermal energy extraction not requiring the extraction of underground water, up to 150 m depth requires only notification, no building permit is necessary.
- SZTFH decree 20/2022 (I. 31.) on certain rules of enforcement of the Mining Act 1993: XLVIII: regulates extraction and pushback of geothermal water and extension, administrative procedures related to extraction (permits, their extension, research reports etc.).
- KVvM decree 101/2007. (XII. 23.) on technical requirements of intervention in underground water resources and water well drilling: includes provisions related to water facilities for hot water and geothermal energy utilisation.

- Gov. decree 147/2010, (IV. 29.) on general rules for activities and facilities for water utilization, protection and damage prevention: allows the use of thermal water for heat supply and energy generation. When utilising thermal water a multi-purpose and water saving approach should be applied. When installing a thermal water plant safe disposal of utilised water should be sought. Under environmental aspects, also the water supply aspects should be taken into consideration. Extracted thermal water may only be diverted into the water distribution system if the water meets the quality requirements on drinking water quality. If the thermal water is mineral or medical, the necessary water treatment technology should be applied, not affecting the medicinally significant factors of the water. As for pushback: underground water extracted exclusively for energetic purposes should be, if possible, pushed back into the same aquifer after utilisation. This may be replaced with harmless diverting or disposal.
- Gov. decree 176/2008 (VI. 30,) on the certification of the energetic characteristics of buildings: regulating the principles of energy certification.
- Gov. decree 253/1997. (XII. 20,) on the national settlement planning and construction requirements: regulating the applicability of renewable sources of energy in public utility infrastructure, delineation of areas used for renewable energy utilisation, the rational utilisation of natural resources. The regulation lays down the principle that buildings should be designed in a way to enable its connectivity of renewable energy sources.
- Gov. decree 122/2015. (V. 26.) on the implementation of the law on energy efficiency: promotes geothermal energy in meeting the renewable energy target in heating and cooling.
- EKM decree 9/2023. (V. 25.) on determining the energetic characteristics of buildings: regulates the buildings' parameters in details from energy point of view, including geothermal and geothermal district heating. It also defines the category of "nearly zero energy building".
- NFM decree 50/2011. (IX. 30,) on establishing the price of district heat sold to the district heating provider and the fee for the district heating service provided to residential users and separately managed institutions: describes the prices and profit rates for district heating, taking into consideration different, including renewable, energy sources.

5 Country status report for Romania

The Pannonian Depression, which encompasses the western part of our country, including the Banat and the west of the Western Mountains and a part of Transylvania and the territory of Hungary and the former Yugoslavia, is an area rich in geothermal deposits. **Error! Reference source not found.**
In the west part of the country, drilling has been done and geothermal waters have been exploited for therapeutic purposes for over 100 years, but geothermal water was already used in Romania during the Roman Empire time. In the last quarter of a century, systematic actions were initiated to prospect and evaluate both the geothermal deposits and the hydrocarbon deposits in this part of the country. Through these, it was found that in the Western Plain, in all geological formations, there are aquifer layers with very varied capacities and thermophysical properties. **Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.**
In western part of Romania, the thermal flows on the surface have values of the order of 85 MW/m^2, higher than those in other areas. **Error! Reference source not found.**
The most important thermal aquifer system of the Pannonian Depression is the system at the base of the Upper Pannonian, highlighted by surveys. The waters in this system are generally eruptive, due to the high content of dissolved gases. **Error! Reference source not found.**
The thermal level of the geothermal waters in the western part of the country is low: 30 - 90^{O}C. For this reason, they can be used especially for therapeutic purposes, preparation of domestic hot water, etc. **Error! Reference source not found.**
In 2007, domestic hot water was supplied to 800 apartments in the city of Oradea and Bihor County, 12 apartments, some vegetable greenhouses, beaches, swimming pools, hotels were heated. **Error! Reference source not found.**
In Timis County, geothermal water is used for linen smelters, for heating, for therapeutic purposes, for the preparation of domestic hot water. **Error! Reference source not found.Error! Reference source not found.**
Hydrothermal resources are distributed in Romania as follows **Error! Reference source not found.**:

1. **Pannonian aquifer**: ◦2500 km², basement Neocene sandstone, 800 – 2400 m depth, 50-85°C, TDS 4-5 g/l, carbonate scale, CH_4
2. **Oradea reservoir**: (310 l/s recharge), 75 km², Triassic limestone & dolomites, 2200 – 3200 m depth, 70-105°C, TDS 0,9-1.2 g/l
3. **Bors confined reservoir:** 12 km², Triassic limestone & dolomites, 2500 m depth, >120°C, TDS 13 g/l, 5 Nm³/m³ gas content (70% CO_2, 30% CH_4), very high scaling potential
4. **Beius reservoir:** 47 km², Triassic calcite & dolomite, 1870 – 2370 m depth, 84°C, TDS 0,5 g/l, CO_2, H_2S traces, Depth: 2.5 – 3 km
5. **Ciumeghiu reservoir:** 5 MWth potential, gritstone, 2200 m depth, 105°C, TDS 5-6 g/l, 3 Nm³/m³ CH_4
6. **Cozia-Calimanesti reservoir:** 28 km², Senonian siltstones, 2700 – 3250 m depth, 70-95°C, TDS 15.7 g/l, 1-2 Nm³/m³ CH_4
7. **Otopeni reservoir (North Bucharest):** 300 km², Limestone & dolomites, 2000 – 3200 m depth, 58-84°C, TDS 1.5-2.2 g/l, 30 ppm H_2S

Figure 5.1. presents the main uses of geothermal energy in 2011 in Romania **Error! Reference source not found.**.

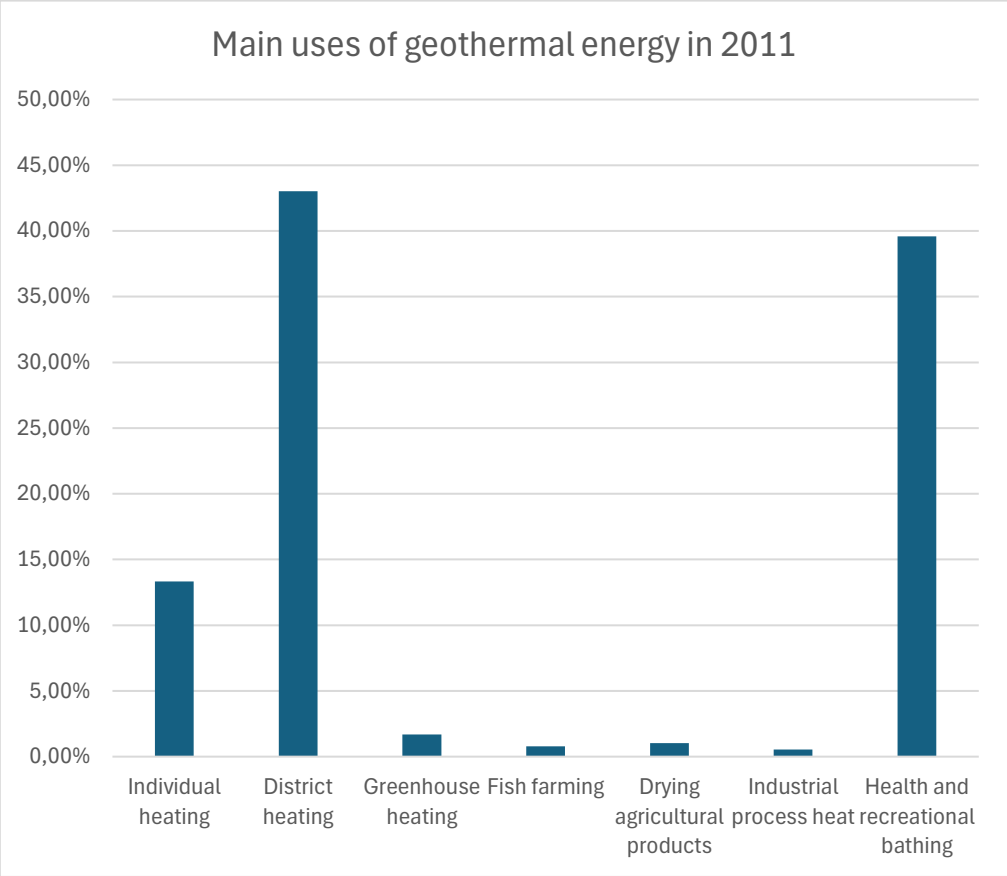


Figure 5.1. Main uses of geothermal energy in 2011 in Romania

Romania obeys European laws in the field. Thus, the following regulations are highlighted, which can be found on the following links. These aspects will be detailed in the third part of this report **Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.**.

1. European Parliament 2019-2024 Committee on Industry, Research and Energy 2023/2111(INI) 25.9.2023 DRAFT REPORT on geothermal energy (pdf 14 pages) (https://www.europarl.europa.eu/doceo/document/ ITRE-PR-752863_RO.pdf)
2. European Parliament Legislation (https://www.europarl.europa.eu/doceo/document/TA-9-2024-0049_RO.html)
3. Ministry of Regional Development and Public Administration Ministry of Energy "Report on the assessment of the national potential for the implementation of high-efficiency cogeneration and efficient centralized heating and cooling" (pdf 102 pages) (https://energy.ec.europa.eu/document /download/073c69b1-2865-4fb0-bc91-6591be94b337_en?filename=Report%20on%20evaluation%20potential.pdf)
4. Ministry of the Environment - country report for the environment (pdf 143 pages) (https://www.mmediu.ro/app/webroot/uploads/files/Raport%20de%20mediu_aug%202020, pdf)

Regarding the absolute values of the potential for the use of renewable geothermal sources, the following can be said: In Romania, 66 sources of geothermal water have been identified with an annual potential of 10,106 Gj and at the moment approximately 30% of the existing potential is being exploited (Figure 5.2.) **Error! Reference source not found.**.

Figure 5.2. Potential geothermal sources in Romania

The environmental assessment procedure in Romania, was started at the beginning of 2017, during the course of the procedure the need to update the Energy Strategy emerged. Thus, a first version was created, entitled "Energy Strategy of Romania 2016-2030, with the perspective of 2050", published on December 19, 2016, a second version being published in 2019, later, in 2020, being elaborated the updated version of the Strategy for period 2020-2030, with the perspective of 2050, This takes into account the changes produced recently at national and global level (the Strategic Investments Program of national interest and the inclusion in the list of primary energy resources – hydropower, wind and solar energy, waste with destination energy and geothermal energy) **Error! Reference source not found.**.

In Romania, there are several ongoing and completed projects that use geothermal energy. Among these we mention some more important ones.

1. Oradea City Hall has accessed a European project of over 18 million euros for the use of geothermal water to heat the Nufărul 1 neighborhood (https://www.zf.ro/zf-transilvania/primaria-oradea-a-accesat-un-proiect-european -over-18-mil-euro-21824074) [7]. The direct beneficiaries of the investment are the approximately 13,500 residents of the Nufărul 1 neighborhood, respectively 6,217 apartments, public institutions and economic agents that have commercial spaces on the ground floor of the blocks in the neighborhood. The financing of the project is ensured through the Large Infrastructure Operational Program 2014-2020, Priority Axis 6 - Promoting clean energy and energy efficiency in order to support an economy with low carbon emissions, Specific Objective 6.1. Increasing energy production from less exploited renewable resources (biomass, biogas, geothermal), production sector **Error! Reference source not found.**.
2. Ministry of European Investments and Projects (https://mfe.gov.ro/) Minister Marcel Bolos after visiting a 21 million euro project in Oradea County for the exploitation of geothermal

energy said that the costs of hot water and heat will no longer be a problem **Error! Reference source not found.**.

3. UEFISCDI GEOTHERMICA Project (https://uefiscdi.gov.ro/geothermica), Project acronym: GEOTHERMICA, Program acronym: HORIZON 2020, Implementation period: 2017-01-01/2021-11-30, Objectives: The overall goal of the collaboration within this project is to accelerate the implementation of geothermal energy. This will be done by funding research and innovation, with an emphasis on improving the geothermal energy business, as well as by establishing a long-term strategic collaboration within the GEOTHERMICA consortium, regarding national level cooperation in the field of geothermal energy between the holders of innovation programs and managers. The GEOTHERMICA project aims at the direct use and generation of electricity from geothermal resources in an optimal way, which includes integrated and combined systems (e.g. heat pumps, other forms of renewable energy, using the underground as a heating and cooling system) **Error! Reference source not found.**.
4. European projects (https://ondrill.ro/fonduri-europene/) SC FORAJE ONDRILL SRL, starts the project with the title "Consolidation of the position on the market through the technology of the company FORAJE ONDRILL SRL, in order to restore the capacity of resilience", project code 159233, no. contract 242/POC/411/AS within the measure "4.1.1. "Investments in productive activities"" within the state aid scheme established by Emergency Ordinance no. 82 of 16.06.2022 regarding some measures for granting grants from non-refundable external funds for investments intended for service provision capacities and re-technology, to restore the capacity for resilience, related to the Competitiveness Operational Program 2014-2020, in the context of the crisis caused by COVID-19. The total value of the project is 1,512,972.01 lei, of which: Grant amount = 841,555.00 lei, Co-financing value = 671,417.01 lei., Project start date: 11.01.2023, Project completion date: 31.12.2023. The general objective of the project is represented by the increase of the Applicant's capacity to implement projects of construction works of water construction projects, in order to alleviate the effects caused by the crisis in the context of the COVID-19 pandemic and the war in Ukraine, through investments in refurbishment and acquisition of efficient, green and digital equipment and machinery **Error! Reference source not found.**.

5.1. Country statistics of installed shallow geothermal systems and general energy balances

According to Euro Stat the share of renewable energy sources in heating and cooling for Romania in 2004-2016 is presented in Table 5.1. **Error! Reference source not found.**:

Table 5.1. The share of renewable energy sources in heating and cooling for Romania in 2004-2016 [11]

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
EU-28	10.3	10.9	11.5	12.9	13.3	14.9	15.0	15.6	16.4	17.0	18.1	18.7	19.1
Belgium	2.9	3.4	3.7	4.5	5.0	6.0	6.1	6.6	7.3	7.4	7.7	7.8	8.1
Bulgaria	14.1	14.3	14.8	13.9	17.3	21.7	24.4	24.9	27.5	29.2	28.3	28.6	30.0
Czech Republic	9.9	10.9	11.2	12.4	12.9	14.2	14.0	15.3	16.1	17.6	19.3	19.6	19.9
Denmark	20.6	22.8	23.8	26.9	28.1	29.5	31.0	32.3	33.6	35.1	38.5	40.1	41.7
Germany	6.3	6.8	7.0	8.4	7.4	8.2	9.8	10.5	10.4	10.6	12.2	12.9	13.0
Estonia	33.2	32.2	30.7	32.7	36.5	41.8	43.3	44.1	43.1	43.2	45.2	49.6	51.2
Ireland	2.9	3.5	3.8	3.9	3.7	4.3	4.5	4.9	5.1	5.5	6.6	6.6	6.8
Greece	12.8	12.8	12.5	14.4	14.3	16.5	17.9	19.4	23.4	26.5	26.9	25.6	24.2
Spain	9.5	9.4	11.4	11.3	11.7	13.3	12.6	13.6	14.1	14.1	15.7	16.8	16.8
France	12.5	12.3	11.7	12.9	13.4	15.1	16.2	15.9	17.1	18.3	18.9	19.7	21.1
Croatia	29.4	30.0	29.1	29.1	28.6	31.1	32.8	33.7	36.4	37.1	36.0	38.5	37.5
Italy	5.7	8.2	10.1	13.3	15.3	16.4	15.6	13.8	17.0	18.1	18.9	19.3	18.9
Cyprus	9.3	10.0	10.4	13.1	14.5	16.3	18.2	19.2	20.7	21.6	21.6	22.5	23.0
Latvia	42.5	42.7	42.6	42.4	42.9	47.9	49.7	44.7	47.3	49.7	52.2	51.8	51.9
Lithuania	30.4	29.3	29.2	29.1	32.0	33.7	32.5	32.8	34.5	36.9	40.6	46.1	46.5
Luxembourg	1.9	3.6	3.6	4.4	4.6	4.7	4.7	4.8	5.0	5.5	7.2	7.1	7.3
Hungary	6.5	9.9	11.4	13.5	12.0	17.0	18.1	20.0	23.3	23.7	21.2	21.2	20.8
Malta	1.1	1.0	1.4	1.5	1.7	2.0	7.8	12.2	13.2	15.7	14.5	14.1	15.3
Netherlands	2.2	2.4	2.8	3.0	3.1	3.4	3.1	3.7	3.9	4.1	5.1	5.5	5.5
Austria	20.1	22.0	23.1	25.2	25.3	27.7	29.0	30.0	31.1	33.0	32.4	32.4	33.3
Poland	10.2	10.2	10.2	10.5	10.9	11.5	11.7	13.1	13.4	14.1	14.0	14.5	14.7
Portugal	32.5	32.1	34.2	35.0	37.5	38.0	33.9	35.2	33.2	34.6	34.0	33.4	35.1
Romania	17.6	18.0	17.6	19.4	23.2	26.4	27.2	24.3	25.8	26.2	26.7	25.9	26.9
Slovenia	18.4	18.9	18.6	20.4	19.2	27.6	28.1	30.3	31.5	33.4	32.4	33.9	34.0
Slovakia	5.1	5.0	4.5	6.2	6.1	8.2	7.9	9.3	8.8	7.9	8.9	10.8	9.9
Finland	39.5	39.1	41.4	41.4	43.3	43.1	44.2	45.9	48.4	50.8	52.0	52.5	53.7
Sweden	46.7	51.9	56.4	58.7	61.1	63.6	60.9	62.2	65.8	67.1	68.0	68.6	68.6
United Kingdom	0.7	0.8	0.9	1.0	1.9	2.3	2.7	3.0	3.2	4.0	4.7	6.3	7.0
Norway	25.5	28.0	28.4	29.3	30.8	31.8	33.3	34.5	33.5	32.7	31.1	32.2	31.7
Iceland	52.2	53.4	56.9	58.6	62.0	62.1	63.9	65.2	64.6	59.0	58.1	63.4	71.1
Albania	33.1	37.8	31.0	33.1	37.1	34.7	31.3	31.4	39.1	37.8	31.0	34.6	33.8
Montenegro	:	52.9	51.4	49.1	46.0	62.1	76.5	81.3	79.8	68.5	67.6	68.5	69.2
Former Yugoslav Republic of Macedonia	23.4	24.7	24.9	22.5	24.6	29.2	26.5	27.3	29.6	31.8	35.0	34.4	31.7
Serbia	14.0	15.6	15.8	13.2	16.7	26.5	23.2	21.1	23.2	25.2	28.8	26.5	24.2

Source: Eurostat (online data code: nrg_335a)

ec.europa.eu/eurostat

The most important producer of geothermal energy in Romania is Transgex SA Oradea. The main operations of the company take place in the municipalities of Oradea and Beiuș, as well as in the town of Livada in Bihor County. Beiușul is the only city in Romania where centralized urban heating is powered exclusively by geothermal energy **Error! Reference source not found.**.

According to Vision 2025-2030: the "shallow" geothermal energy potential of Romania is estimated at 183 thousand toe/year based on the aquifer resources in the geothermal "1" area (Bucharest, Constanta, Arad, Timisoara, Craiova) **Error! Reference source not found.**. Figure 5.3. shows the geothermal areas in Romania.

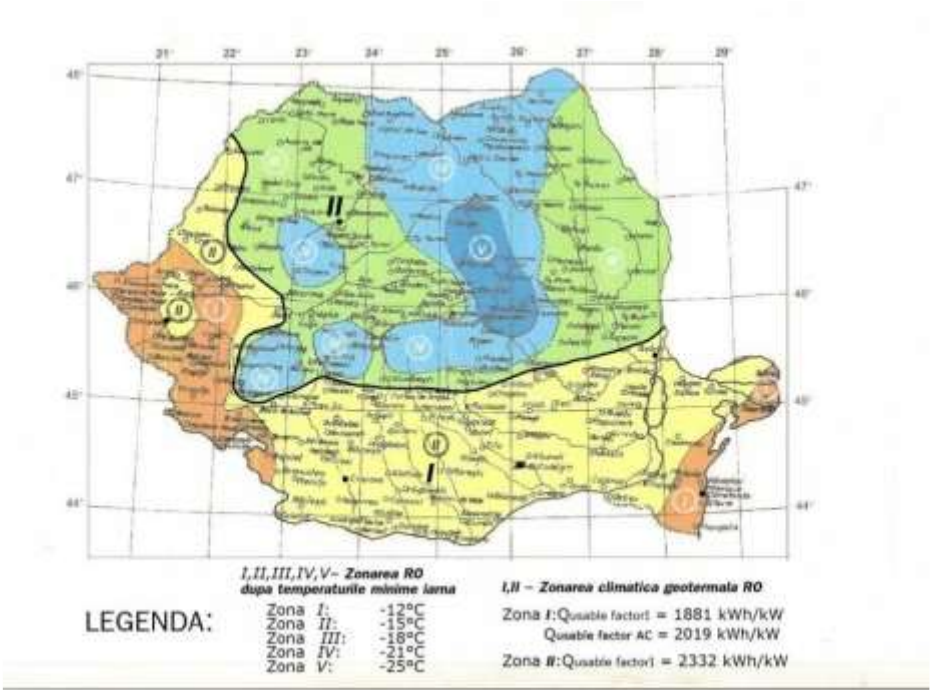


Figure 5.3. The geothermal areas in Romania (Source: FOREN 2014 Conference - Bucharest June 15 - Geo Section) ***Error! Reference source not found.***

The following statistically determined values are used [kWh/kW]:

- I, II – Geothermal areas
- Area I: $Q^{H}_{usable\ factor}$medium/val. Buc. = 1881/2129
- $Q^{AC}_{usable\ factor}$medium/val. Buc. = 2019/1774
- Area II: $Q^{H}_{usable\ factor}$= 2332
- t_{ext}= -18°C

With these values it is determined:

- Annual heating energy: $Q^{H}_{usable}=N^{H} \times Q^{H}_{usable\ factor}$[kWh]
- Annual cooling energy: $Q^{AC+V}_{usable}=N^{AC} \times Q^{AC}_{usable\ factor}$[kWh]

Where:

- $N^{H}$and N^{AC}in [kW] are the thermal powers of the heat pumps used.

Romania has the experience and technologies necessary to exploit the national geothermal energy potential, "deep & shallow", estimated at 725 thousand toe/year **Error! Reference source not found.Error! Reference source not found.**.

It is appreciated that this level is minimal because, practically, any city in the country can explore its geothermal energy resource (surface or deep) and, in combination with high energy efficiency cogeneration units (renewable or not) can fulfil the requirement of Law 121/2014: "Energy Efficient Centralized Heating and Cooling"**Error! Reference source not found.Error! Reference source not found.**.

In the journal *Sustainability* from the year 2020, an article is presented about Energy Poverty in European Union: Assessment Difficulties, Effects on the Quality of Life, Mitigation Measures. This article presents some evidence from Romania **Error! Reference source not found.**. The article underlines the Information on population incomes and energy potential in Romania (Table 5.2.). The map of geothermal potential in Romania can also be found (Figure 5.4.) **Error! Reference source not found.Error! Reference source not found.**.

*Table 5.2. Information on population incomes and energy potential in Romania[**Error! Reference source not found.***

Romanian's Counties	Net Income Lei* per Habitant	Sun Power kWh/m^2	Wind m/s	Geothermal T (°C)	Natural Gas
Alba	2023	1300	7		1131.06
Arad	2133	1370	5	80	137.06
Arges	2222	1320	5		265.89
Bacau	2047	1300	8		358.46
Bihor	1900	1290	7	85	220
Bistrita-Nasaud	1871	1250	9		501
Botosani	1921	1270	7		52.9
Braila	1840	1390	9		100.12
Brasov	2383	1300	8		912.22
Buzau	1890	1390	8		342.04
Calarasi	2013	1400	6		31.76
Caras-Severin	1912	1300	7		199.31
Cluj	2670	1290	3		533.83
Constanta	2126	1450	10		103.77
Covasna	1837	1290	5		159.76
Dambovita	1946	1370	4		1232.65
Dolj	2082	1400	5		171.9
Galati	2193	1410	8		137.51
Giurgiu	1895	1420	6		115.93
Gorj	2193	1300	3		891.04
Harghita	1791	1250	5		436.95
Hunedoara	1966	1220	5		555.65
Ialomita	1824	1390	8		106.52
Iasi	2278	1280	7		467.89
Ilfov	2913	1400	5	45	676.99
Maramures	1837	1190	4		692.66
Mehedinti	2161	1390	5		10.57
Mures	2128	1320	4		2733.31
Neamt	1883	1330	6		212.2
Olt	2148	1400	6		299.06
Prahova	2189	1370	4		1526.99
Salaj	1915	1300	5		252.44
Satu Mare	1936	1330	5	80	269.88
Sibiu	2468	1290	4		929.12
Suceava	1833	1240	6		183.89
Teleorman	1780	1400	4		21.28
Timis	2501	1340	5	75	234.37
Tulcea	1937	1400	9		33.74
Vaslui	1882	1380	8		91.52
Valcea	1870	1370	5		362.01
Vrancea	1890	1380	6		46

* 1 Euro = 4.85 Lei. Source [66] https://www.gfk.com/ro/noutati/comunicate-de-presa/puterea-de-cumparare-a-romanilor-a-crescut-in-2018-dar-odata-cu-ea-si-polarizarea-regionala.

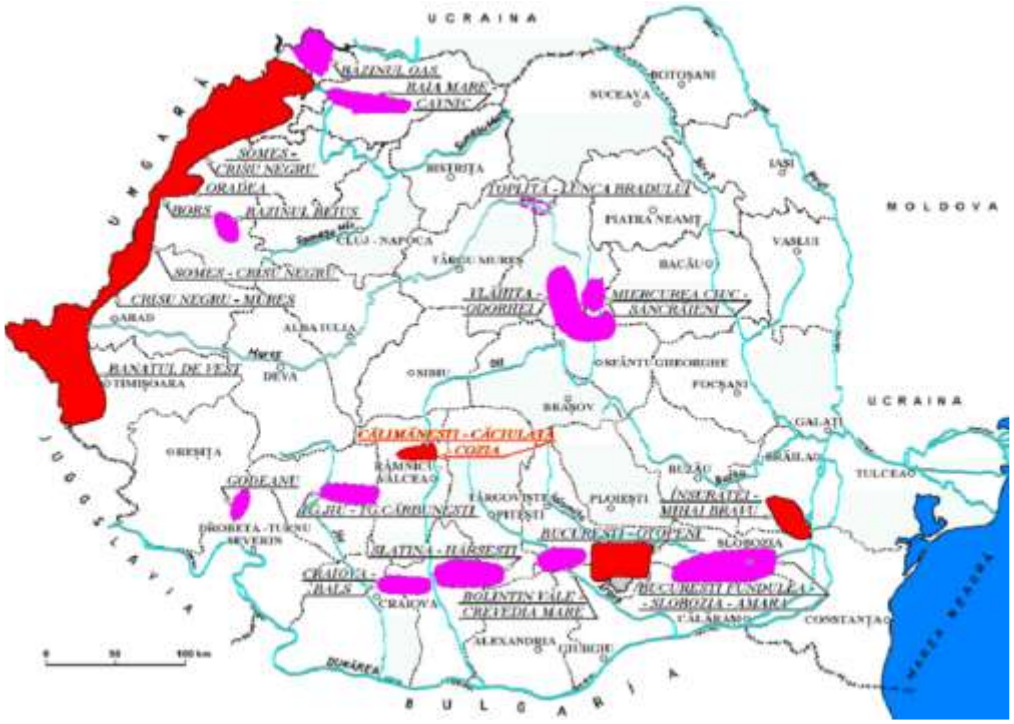


Figure 5.4. Map of geothermal potential in Romania ***Error! Reference source not found.Error! Reference source not found.***

5.2. Overview of current regulations, incentives and general policy related to shallow geothermal

Romania is submitted to the European regulations.

Romanian Laws and regulations concerning geothermal heating and cooling are **Error! Reference source not found.**:

1. Decision_2013_114_UE COMMISSION DECISION of 1 March 2013 establishing guidelines for Member States on the calculation of renewable energy supplied by heat pumps in the case of different heat pump technologies pursuant to Article 5 of Directive 2009/28/EC of the European Parliament and of the Council
2. DIRECTIVE_2006_32_CE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of April 5, 2006 on energy efficiency for end users and energy services
3. DIRECTIVE_2009_28_CE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of April 23, 2009 on the promotion of the use of energy from renewable sources, amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC
4. DIRECTIVE_2012_27_UE_RO OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EUEPBD_2010_31_EC_RO
5. 5. DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 May 2010 on the energy performance of buildings
6. Law_159_2013 on the energy performance of buildings
7. Law_199_2000_republished_27_07 on the efficient use of energy
8. Law_10_1995_republicata_MO_2015 Order of the Minister of Energy for SMEs regarding the minimum aid for technological and business incubators

9. Law_121_2014 on energy efficiency
10. Law_372 on the energy performance of buildings
11. Law_372_2005_republished on the energy performance of buildings
12. List of classified info ANRM National Agency for Mineral Resources declassification documents
13. Order_691_2007 For the approval of Methodological Norms regarding the energy performance of buildings
14. ORDER_799_2012 (Approvals, authorizations, 1 m to art. 27, paragraph 3 replaces 661_2006 p. 15, col. st., f.2 – INHGA expertise)
15. ORDER No. 87 of May 20, 2008 for the approval of the Technical Instructions regarding the classification and value of resources/reserves of natural mineral water, therapeutic mineral water, geothermal water, accompanying gases and non-combustible gases
16. OUG_18_2009 on increasing the energy performance of apartment blocks
17. Plan_crestere_nZEB

European laws and regulations concerning geothermal heating and cooling are Error! Reference source not found.**:**

1. Decisions_2013_114_UE *establishing the guidelines for Member States on calculating renewable energy from heat pumps from different heat pump technologies pursuant to Article 5 of Directive 2009/28/EC of the European Parliament and of the Council*
2. DIRECTIVE_2006_32_EC *on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC*
3. DIRECTIVE_2009_28_EC *on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC*
4. DIRECTIVE_2012_27_EU_EN *on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC*
5. EN_13779_2007 *European Standard Ventilation for non-residential buildings – Performance requirements for ventilation and room-conditioning systems*
6. EN_14511-1_2007 *Belgian Standard Luchtbehandelingsapparatuur, koeleenheden met vloeistof en warmtepompen met elektrisch aangedreven compressoren voor ruimteverwarming en -koeling - Deel 1: Termen en definities*
7. EN_14511-2_2007 *Belgian Standard*
8. EN_14511-3_2007 *Belgian Standard*
9. EN_14511-4_2007 *Belgian Standard*
10. EPBD 2010_31_EC – EN *on the energy performance of buildings*
11. Hähnlein_etal_2010_RSER_legal status_FINAL *International legal status of the use of shallow geothermal energy*

Outline of methodology is done according to the Official Journal of the European Union COMMISSION DECISION of 1 March 2013 establishing the guidelines for Member States on calculating renewable energy from heat pumps from different heat pump technologies pursuant to Article 5 of Directive 2009/28/EC of the European Parliament and of the Council **Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.**.

In accordance with Annex VII to the Directive, the amount of renewable energy supplied by heat pump technologies (E_{RES}) in Romania shall be calculated with the following formula **Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.** :

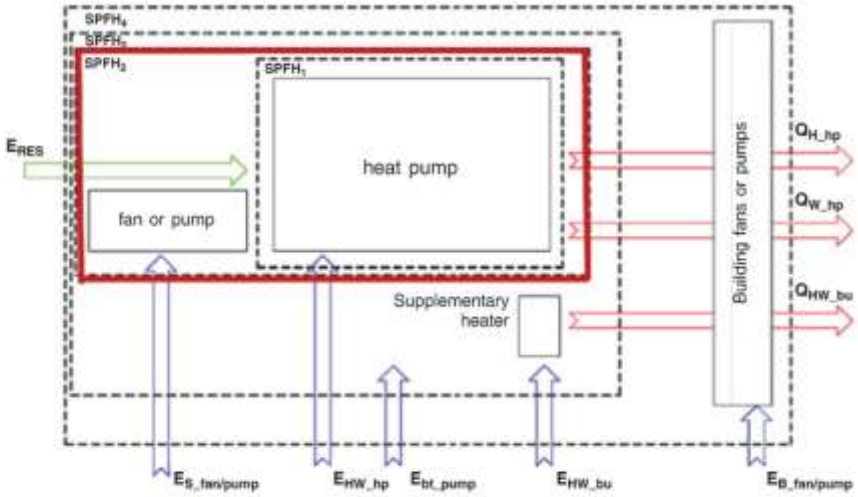
$E_{RES} = Q_{usable} * (1 – 1/SPF)$

$Q_{usable} = H_{HP} * P_{rated}$

Where: — Q_{usable} = the estimated total usable heat delivered by heat pumps [GWh],
— H_{HP} = equivalent full load hours of operation [h],
— P_{rated} = capacity of heat pumps installed, taking into account the lifetime of different types of heat pumps [GW],
— SPF = the estimated average seasonal performance factor ($SCOP_{net}$ or $SPER_{net}$).

Minimum performance of heat pumps to be considered as renewable energy under the Directive Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.**:**
In accordance with Annex VII to the Directive, Romania as Member State shall ensure that only heat-pumps with a SPF above 1,15 * 1/η are taken into account.
With power system efficiency (η) set at 45,5 % it implies that the minimum SPF of electrically driven heat pumps ($SCOP_{net}$) to be considered as renewable energy under the Directive is 2,5 [16][17][18].
For heat pumps that are driven by thermal energy (either directly, or through the combustion of fuels), the power system efficiency (η) is equal to 1. For such heat pumps the minimum SPF ($SPER_{net}$) is 1,15 for the purposes of being considered as renewable energy under the Directive **Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.**.
Romania as Member State should consider, in particular for air sourced heat pumps, how large a fraction of their already installed capacity of heat pumps has a SPF above the minimum performance. In that assessment Romania as Member States may rely on both test data and measurements, although lack of data may in many cases reduce the assessment to expert judgment by each Member State. Such expert judgments should be conservative, meaning that the estimates rather underestimate than overestimate the contribution of heat pumps (4). In the case of air sourced water heaters, it is normally only in exceptional cases that such heat pumps have an SPF above the minimum threshold **Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.**.

System boundaries for measuring energy from heat pumps Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.:
The system boundaries for measurement include the refrigerant cycle, the refrigerant pump and, for ad/absorption, in addition the sorption cycle and solvent pump. The determination of the SPF should be according to the seasonal coefficient of performance ($SCOP_{net}$) according to EN 14825:2012 or seasonal primary energy ratio ($SPER_{net}$) according to EN 12309. That implies that electric energy or fuel consumption for operation of the heat pump and circulation of the refrigerant should be considered. The corresponding system boundary is shown in Figure 5.5 as SPFH2, highlighted in red.



Source: SEPEMO build.

Figure 5.5. System boundaries for measurement of SPF and Q_{usable} [18]

The following abbreviations are used in Figure 5.5.:

$E_{S\_fan/pump}$ Energy used to run fan and/or pump that circulates the refrigerant.

E_{HW_hp} Energy used to run the heat pump itself.

E_{bt_pump} Energy used to run pump that circulates the medium that absorbs the ambient energy (not relevant for all heat pumps)

E_{HW_bu} Energy used to run supplementary heater (not relevant for all heat pumps)

$E_{B\_fan/pump}$ Energy used to run fan and/or pump that circulates the medium that supplies the final usable heat.

Q_{H_hp} Heat supplied from the heat source via the heat pump.

Q_{W_hp} Heat supplied from the mechanical energy used to drive the heat pump.

Q_{HW_hp} Heat supplied from the supplementary heater (not relevant for all heat pumps)

E_{RES} Renewable aerothermal, geothermal, or hydrothermal energy (the heat source) captured by the heat pump.

E_{RES} $E_{RES} = Q_{usable} – E_{S\_fan/pump} – E_{HW\_hp} = Q_{usable} * (1 – 1/SPF)$ Qusable

$Q_{usable} = Q_{H\_hp} + Q_{W\_hp}$

According tu EU Directives Romania is considered to have a cold climate (Figure 5.6.) **Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.**:

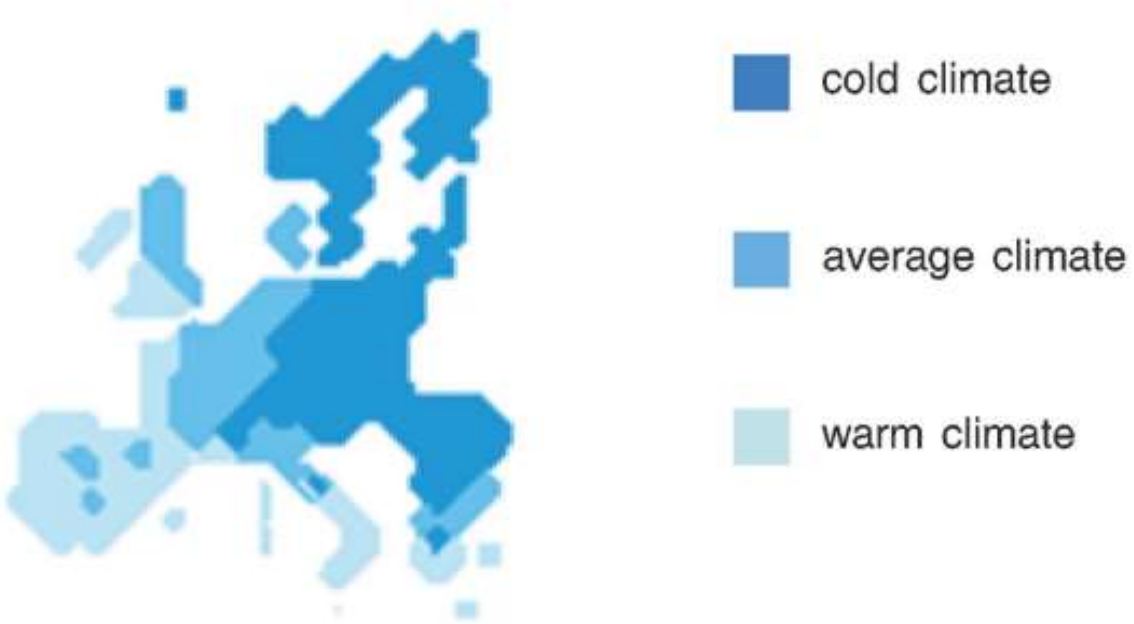


Figure 5.6. Climate condition areas [18]

Default values for SPF and Q_{usable} for heat pumps are shown in
Table 5.3. and Table 5.4. **Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.**:

Table 5.3. Default values for H_{HP} and SPF ($SCOP_{net}$) for electrically driven heat pumps

		Climate conditions					
		Warmer climate		Average climate		Colder climate	
Heat Pump Energy source:	Energy source and distribution medium	H_{HP}	SPF ($SCOP_{net}$)	H_{HP}	SPF ($SCOP_{net}$)	H_{HP}	SPF ($SCOP_{net}$)
Aerothermal energy	Air-Air	1 200	2,7	1 770	2,6	1 970	2,5
	Air-Water	1 170	2,7	1 640	2,6	1 710	2,5
	Air-Air (reversible)	480	2,7	710	2,6	1 970	2,5
	Air-Water (reversible)	470	2,7	660	2,6	1 710	2,5
	Exhaust Air-Air	760	2,7	660	2,6	600	2,5
	Exhaust Air-Water	760	2,7	660	2,6	600	2,5
Geothermal energy	Ground-Air	1 340	3,2	2 070	3,2	2 470	3,2
	Ground-Water	1 340	3,5	2 070	3,5	2 470	3,5
Hydrothermal heat	Water-Air	1 340	3,2	2 070	3,2	2 470	3,2
	Water-Water	1 340	3,5	2 070	3,5	2 470	3,5

Table 5.4. Default values for H_{HP} and SPF ($SCOP_{net}$) for heat pumps driven by thermal energy

		Climate conditions					
		Warmer climate		Average climate		Colder climate	
Heat Pump Energy source:	Energy source and distribution medium	H_{HP}	SPF ($SPER_{net}$)	H_{HP}	SPF ($SPER_{net}$)	H_{HP}	SPF ($SPER_{net}$)
Aerothermal energy	Air-Air	1 200	1,2	1 770	1,2	1 970	1,15
	Air-Water	1 170	1,2	1 640	1,2	1 710	1,15
	Air-Air (reversible)	480	1,2	710	1,2	1 970	1,15
	Air-Water (reversible)	470	1,2	660	1,2	1 710	1,15
	Exhaust Air-Air	760	1,2	660	1,2	600	1,15
	Exhaust Air-Water	760	1,2	660	1,2	600	1,15
Geothermal energy	Ground-Air	1 340	1,4	2 070	1,4	2 470	1,4
	Ground-Water	1 340	1,6	2 070	1,6	2 470	1,6
Hydrothermal heat	Water-Air	1 340	1,4	2 070	1,4	2 470	1,4
	Water-Water	1 340	1,6	2 070	1,6	2 470	1,6

The incentives given by Romanian laws are as follows **Error! Reference source not found.Error! Reference source not found.**:

1. **The Government of Romania**, Administration of The Environmental Fund Law, and Methodologies. Romanians who wish to access funds for heat pumps have at their disposal the "Casa Verde Classic" program, through which they can obtain up to 8,000 lei from the state. Funds for heat pumps – The program regarding the installation of heating systems that use renewable energy, including the replacement or completion of classic heating systems, can be accessed by individuals as well as administrative-territorial units, public institutions, and religious units [19].
2. **Parliament of Romania** Law no. 39/2023 for completing art. 291 para. (3) from Law no. 227/2015 regarding the Fiscal Code. On January 13, 2023, Law 39/2023 was published in the Official Gazette, which reduces the value added tax (VAT) on heat pumps, photovoltaic panels, and solar thermal panels from 19% to 5% [20].

5.3. General country geology, hydrogeology and thermogeological parameters

Geological parameters

From the point of view of geology, the National Institute of Geology from Romania, has 3 supported maps:

A) 1:1000000 (1:1M - https://geoportal.igr.ro/viewgeol1M - Figure 5.7.)
B) 1:200000 (1:200k - https://geoportal.igr.ro/viewgeol200k - Figure 5.8.)
C) 1:50000 (1:50k - https://geoportal.igr.ro/viewgeol50kol - Figure 5.9.)

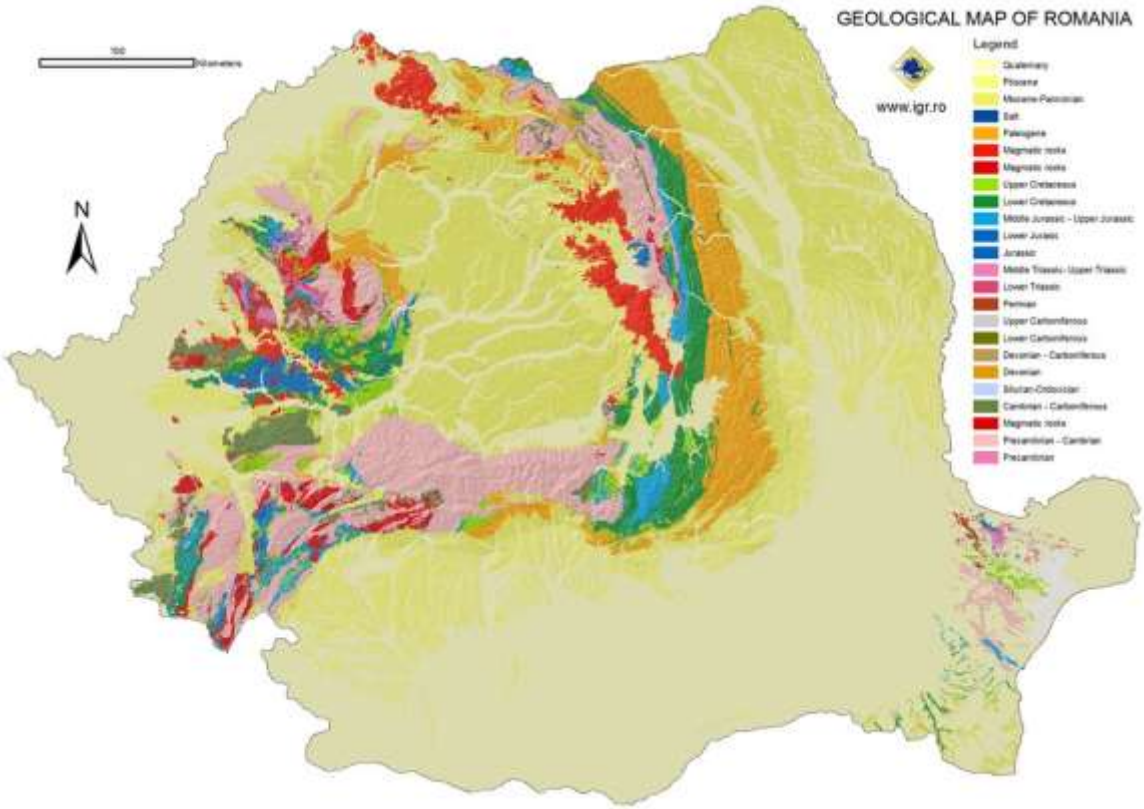


Figure 5.7. Geological map of Romania in scale 1:1000000

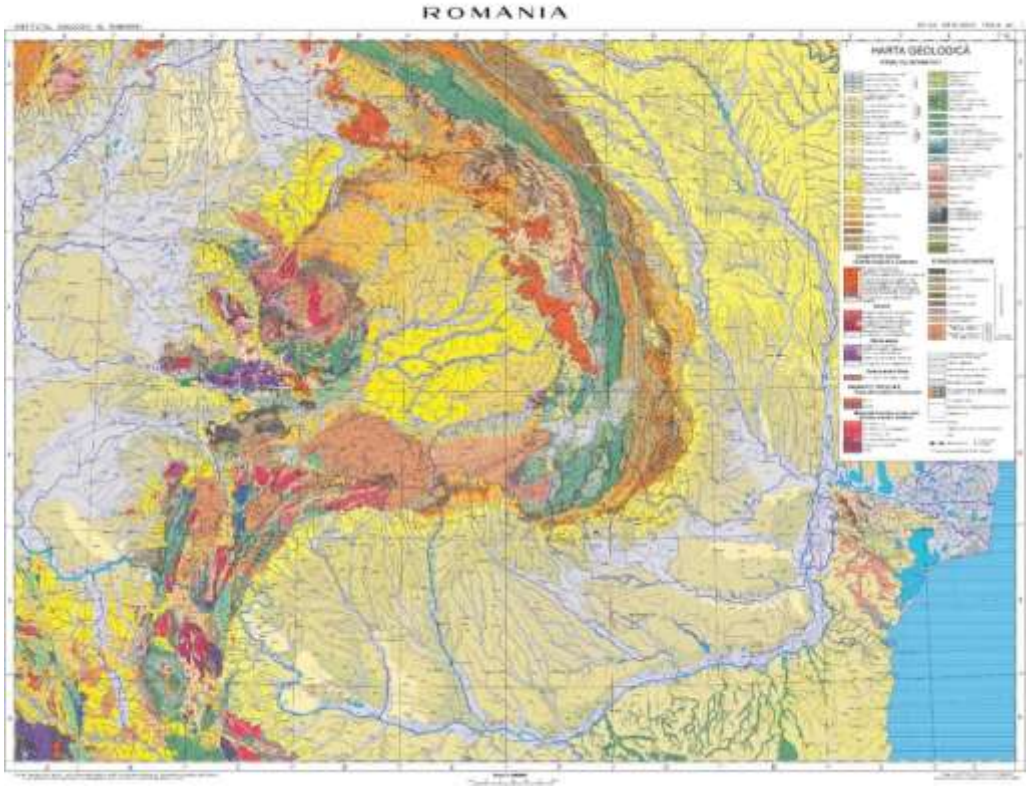


Figure 5.8. Geological map of Romania 1:1000000

For the detail representation of the maps for 1:200000, we have individual sheets for each sector according to Figure 5.9.

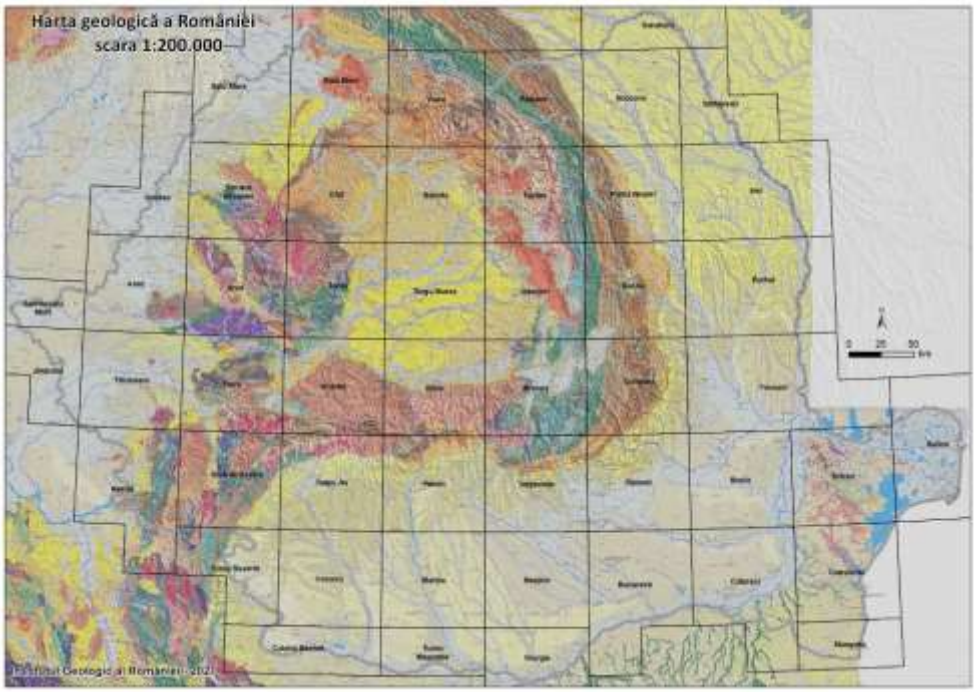


Figure 5.9. Geological map of Romania 1:200000

For each section we have a detailed sheet from the geological point of view according to Figure 5.10

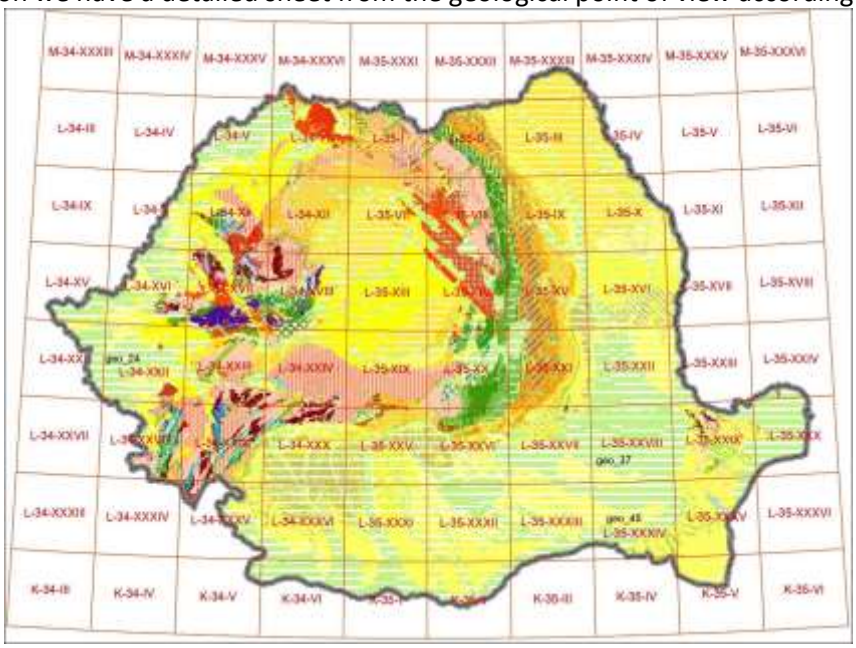


Figure 5.10. Sheet notation for each section of the 1:200k geological map

The representation of the 1:50k geological map is more detailed but in not finish according to Geological Institute of Romania. The segmentation and the available sheets are presented in Figure 5.11. And in Figure 5.13. is

represented the sheet for Obârşia-Cloşani. All the available sheets cand be obtain via the Geological Institute of Romania.

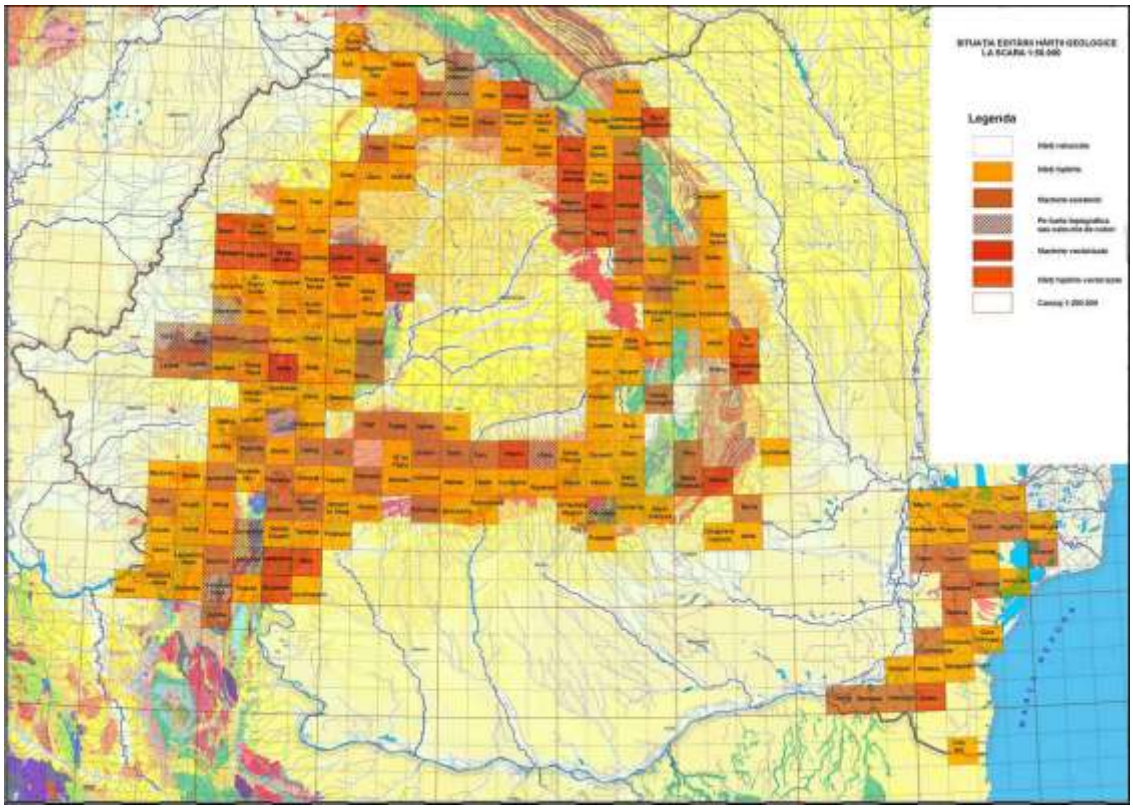


Figure 5.12. Geological map of Romania 1:50000

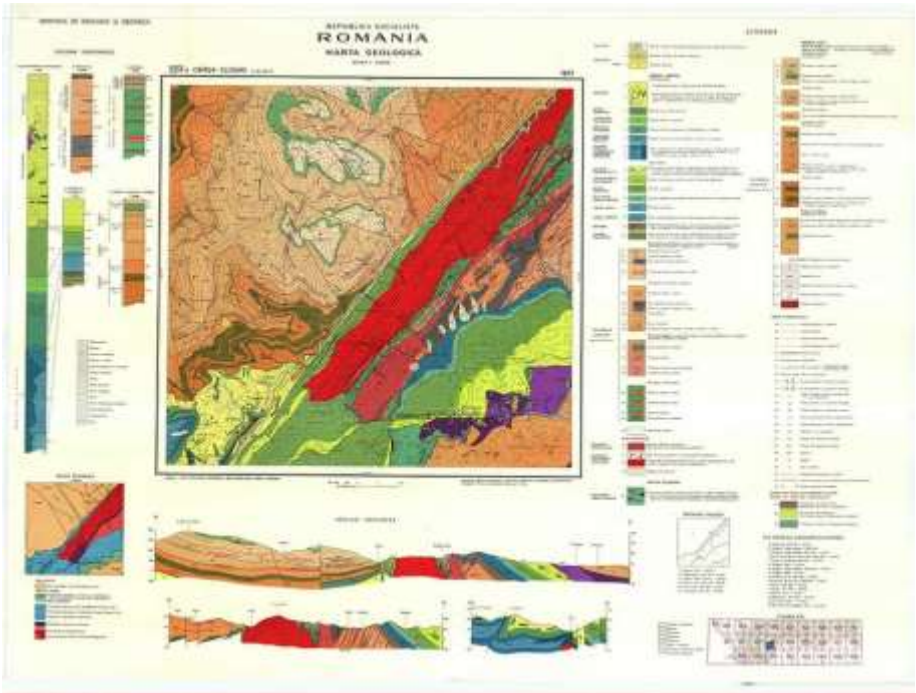


Figure 5.13. The geological map and description for the Obârşia-Cloşani sheet 1:50k

The sheets are detailed in following literature:

1. Avram E. (2018) Harta geologică a României scara 1:50,000, foaia Zizin. Editura Institutului Geologic al României, București. ISBN 978-606-94601-3-9.

2. Avram E., Andreescu I., Baltres A. , Drăgănescu A., Mihăilescu N., Munteanu E., Munteanu T., Seghedi A., Szász L., Vaida M. (2018) Harta geologică a României scara 1:50,000, foaia Cernavodă. Editura Institutului Geologic al României, București. ISBN 978-606-94669-4-0,

3. Avram E., Andreescu I., Baltres A., Mihăilescu N., Munteanu E. (2018) Harta geologică a României scara 1:50,000, foaia Ostrov. Editura Institutului Geologic al României, București. ISBN 978-606-94669-5-7.

4. Avram E., Andreescu I., Bombiță G., Szász L., Drăgănescu A., Pop G., Ghenea C. (2018) Harta geologică a României scara 1:50,000, foaia Adamclisi. Editura Institutului Geologic al României, București. ISBN 978-606-94669-0-2.

5. Avram E., Andreescu I., Munteanu E., Platon R., Stoian L. (2018) Harta geologică a României scara 1:50,000, foaia Băneasa. Editura Institutului Geologic al României, București. ISBN 978-606-94669-1-9.

6. Bordea S., Bordea J., Mantea G., Marinescu F., Ștefănescu M., Ionescu G., Popescu A. (2018) Harta geologică a României scara 1:50,000, foaia Meziad. Editura Institutului Geologic al României, București. ISBN 978-606-94601-2-2.

7. Bordea S., Bordea J., Ștefan A., Mantea G., Dimitrescu R., Dimitrescu M. (2019) Harta geologică a României scara 1:50,000, foaia Stâna de Vale. Editura Institutului Geologic al României, București. ISBN 978-606-9670-03-3.

8. Gheuca I., Bandrabur T., Săndulescu M., Bădescu D. (2018) Harta geologică a României scara 1:50,000, foaia Hărlăgia. Editura Institutului Geologic al României, București. ISBN 978-606-94601-1-5.

9. Iancu V., Marinescu Fl., Hârtopanu I., Conovici M., Stănoiu I., Gridan T., Conovici N., Popescu G., Strusievicz R. (2018) Harta geologică a României scara 1:50,000, foaia Bâlvănești. Editura Institutului Geologic al României, București. ISBN 978-606-94718-6-9.

10, Iancu V., Marinescu F., Stănoiu I., Gridan T., Conovici M., Savu H., Berza T., Țicleanu N., Lupulescu A., Conovici N. (2018) Harta geologică a României scara 1:50,000, foaia Bala. Editura Institutului Geologic al României, București. ISBN 978-606-94718-5-2.

11. Iancu V., Russo Săndulescu D., Rogge-Ţăranu E., Ghenea C., Olteanu R., Mihăilă N. (2018) Harta geologică a României scara 1:50,000, foaia Surduc. Editura Institutului Geologic al României, București. ISBN 978-606-94669-8-8.

12. Lupu M., Popescu G., Munteanu T., Pop G., Bindea G., Stelea I., Munteanu E. (2018) Harta geologică a României scara 1:50,000, foaia Hațeg. Editura Institutului Geologic al României, București. ISBN 978-606-94601-4-6.

13. Micu M. (2018) Harta geologică a României scara 1:50,000, foaia Putna. Editura Institutului Geologic al României, București. ISBN 978-606-94669-6-4.

14. Mirăuţă E., Ghenea C., Ghenea A., Mantea G., Baltres A., Seghedi A., Seghedi I., Szakács A. (2018) Harta geologică a României scara 1:50,000, foaia Cataloi. Editura Institutului Geologic al României, București. ISBN 978-606-94669-3-3.

15. Năstăseanu S., Mărunțeanu M., Stan N., Hârtopanu I., Șerban E. (2019) Harta geologică a României scara 1:50,000, foaia Mehadia. Editura Institutului Geologic al României, București. ISBN 978-606-9670-01-9.

16. Rusu A., Dimitrescu M., Dimitrescu R., Drăgănescu A., Szász L., Ștefan A. (2018) Harta geologică a României scara 1:50,000, foaia Gilău. Editura Institutului Geologic al României, București. ISBN 978-606-94601-6-0,

17. Rusu A., Dimitrescu R., Ștefan A., Boștinescu S., Săbău G. (2018) Harta geologică a României scara 1:50,000, foaia Călățele. Editura Institutului Geologic al României, București. ISBN 978-606-94601-8-4.

18. Rusu A., Lupu M., Nicolae I., Pană D., Popescu G., Szász L., Tatu M. (2018) Harta geologică a României scara 1:50,000, foaia Tureni (Cheile Turzii). Editura Institutului Geologic al României, București. ISBN 978-606-94601-7-7.

19. Savu H., Hann H.P., Marinescu F. (2018) Harta geologică a României scara 1:50,000, foaia Novaci. Editura Institutului Geologic al României, București. ISBN 978-606-94718-7-6.

20, Săndulescu M., Bădescu D. (2018) Harta geologică a României scara 1:50,000, foaia Brețcu. Editura Institutului Geologic al României, București. ISBN 978-606-94601-9-1.

21. Săndulescu M., Bădescu D., Constantin P. (2018) Harta geologică a României scara 1:50,000, foaia Brateș. Editura Institutului Geologic al României, București. ISBN 978-606-94669-2-6.

22. Săndulescu M., Bădescu D., Mărunțeanu M., Băceanu I. (2018) Harta geologică a României scara 1:50,000, foaia Mănăstirea Cașin. Editura Institutului Geologic al României, București. ISBN 978-606-94601-5-3.

23. Săndulescu M., Bădescu D., Russo- Săndulescu D. (2018) Harta geologică a României scara 1:50,000, foaia Țibleș. Editura Institutului Geologic al României, București. ISBN 978-606-94718-9-0,

24. Săndulescu M., Constantin P., Bădescu D., Băceanu I. (2019) Harta geologică a României scara 1:50,000, foaia Gura Humorului. Editura Institutului Geologic al României, București. ISBN 978-606-9670-00-2.

25. Săndulescu M., Mureşan M., Mureşan G., Bandrabur T. (2018) Harta geologică a României scara 1:50,000, foaia Sândominic. Editura Institutului Geologic alRomâniei, București. ISBN 978-606-94669-7-1.

26. Săndulescu M., Mureșan M., Mureșan G., Săndulescu D., Alexandrescu G. (2018) Harta geologică a României scara 1:50,000, foaia Tulgheș. Editura Institutului Geologic al României, București. ISBN 978-606-94669-9-5.

27. Seghedi I., Szász L., Szakács A. (2019) Harta geologică a României scara 1:50,000, foaia Poiana Stampei. Editura Institutului Geologic al României, București.ISBN 978-606-9670-02-6.

28. Ştefănescu M., Constantin P., Ivan V., Melinte M., Ştefănescu M. (2018) Harta geologică a României scara 1:50,000, foaia Siriu. Editura Institutului Geologic al
României, București. ISBN 978-606-94718-8-3.

29. Ștefănescu M., Mihăilă N. (2018) Harta geologică a României scara 1:50,000, foaia Aita. Editura Institutului Geologic al României, București. ISBN 978-606-94718-4-5.

30, Ștefănescu M., Popescu I., Melinte M., Ivan V., Ștefănescu M., Papaianopol I., Popescu G., Dumitrică P. (2018) Harta geologică a României scara 1:50,000, foaia Nehoiu. Editura Institutului Geologic al României, București. ISBN 978-606-94601-0-8.

In the next section we will present the geological maps for the 50 sheets (Figure 5.13-5.62) in the scale for 1:200k according to figure 5.9 and 5.10. :

1. M-35-XIII - Darabani

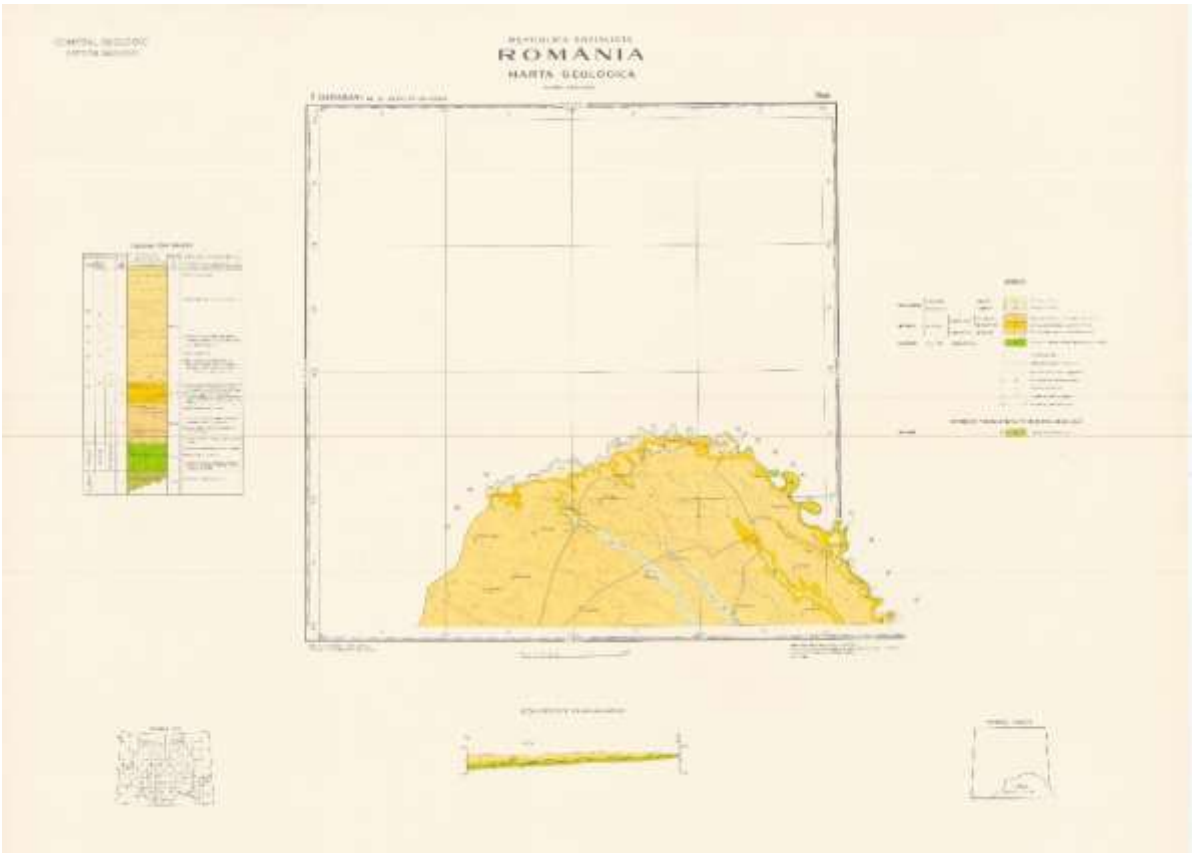


Figure 5.14. The geological map and description of section M-35-XIII - Darabani

2. L-34-V – Satu Mare

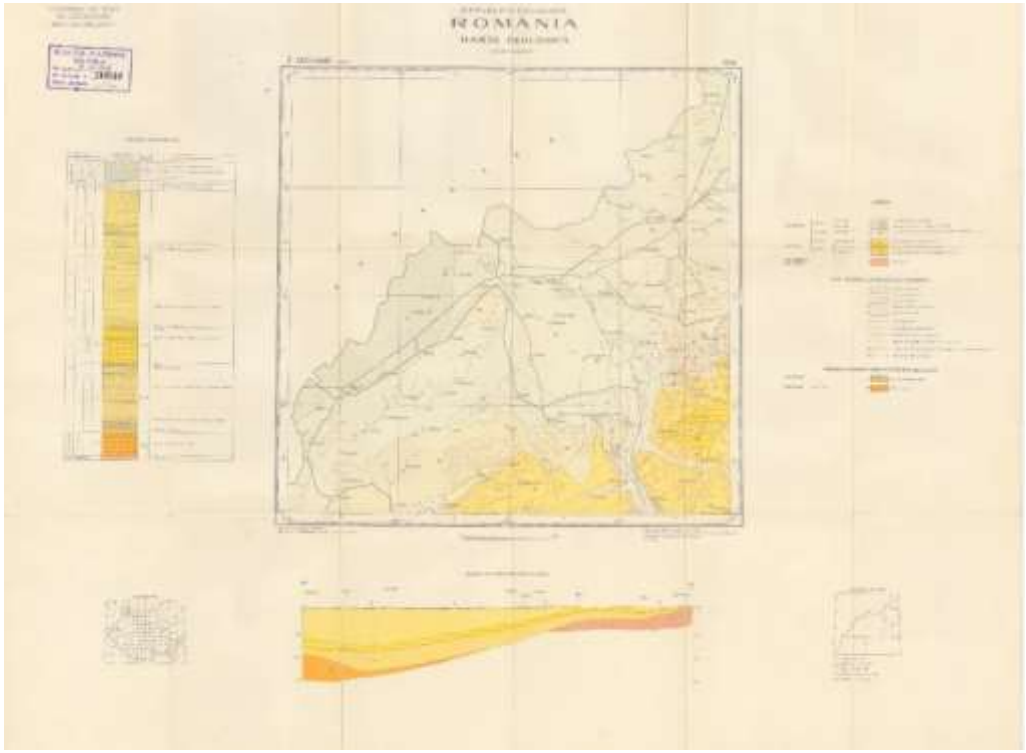


Figure 5.14. The geological map and description of section L-34-V – Satu Mare

3. L-34-VI – Baia Mare

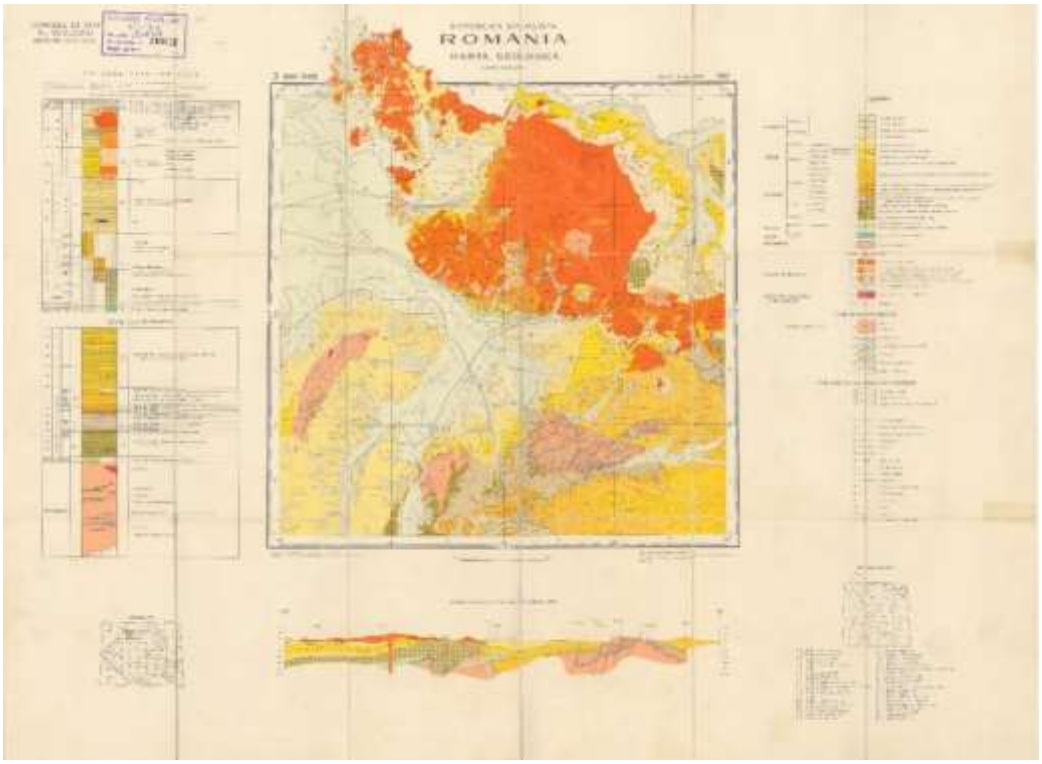


Figure 5.15. The geological map and description of section L-34-VI – Baia Mare

4. L-35-I - Viseu

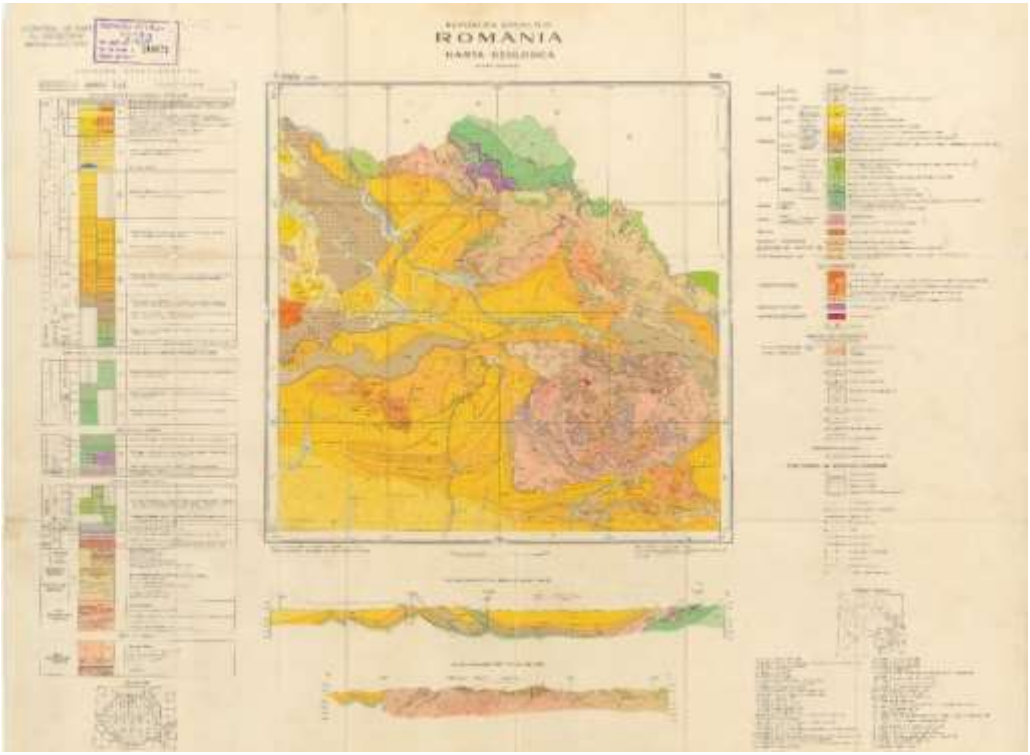


Figure 5.16. The geological map and description of section - L-35-I - Viseu

5. L-35-II – Radauti

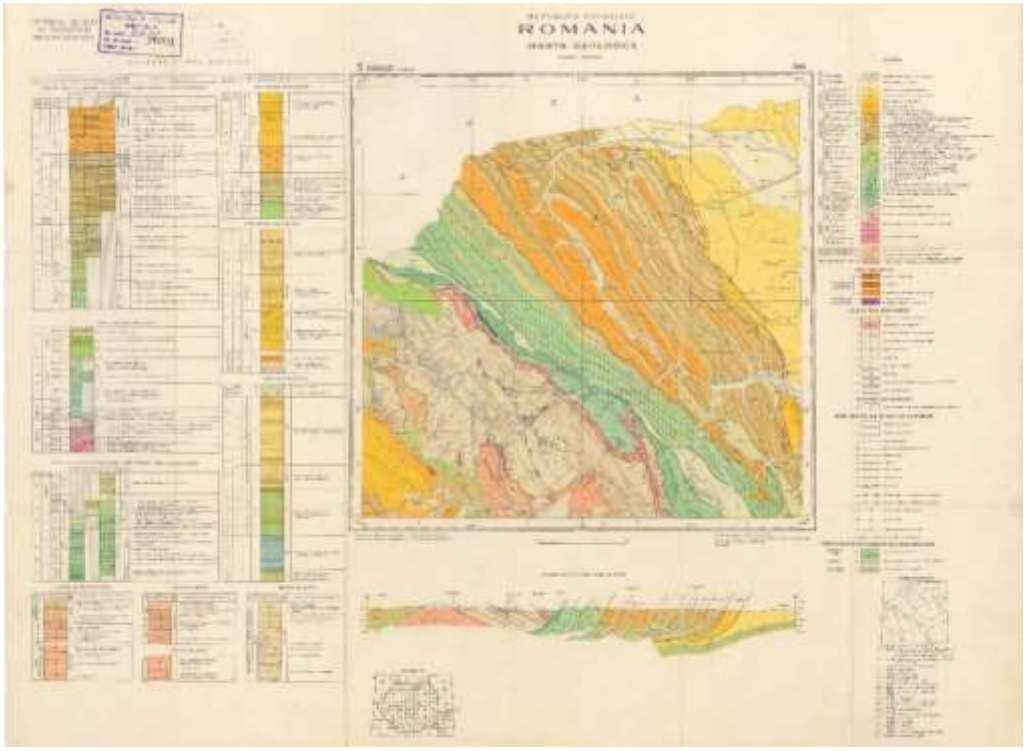


Figure 5.17. The geological map and description of section L-35-II – Radauti

6. L-35-III- SUCEAVA

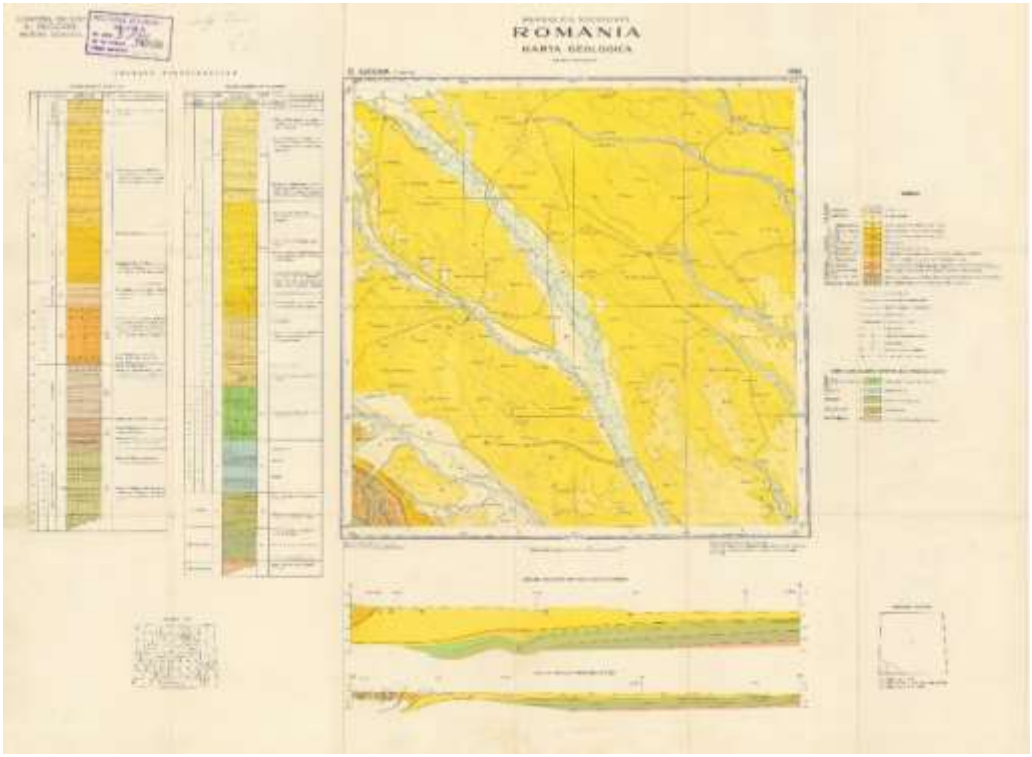


Figure 5.18. The geological map and description of section - L-35-III- SUCEAVA

7. L-35-IV-Stefanesti

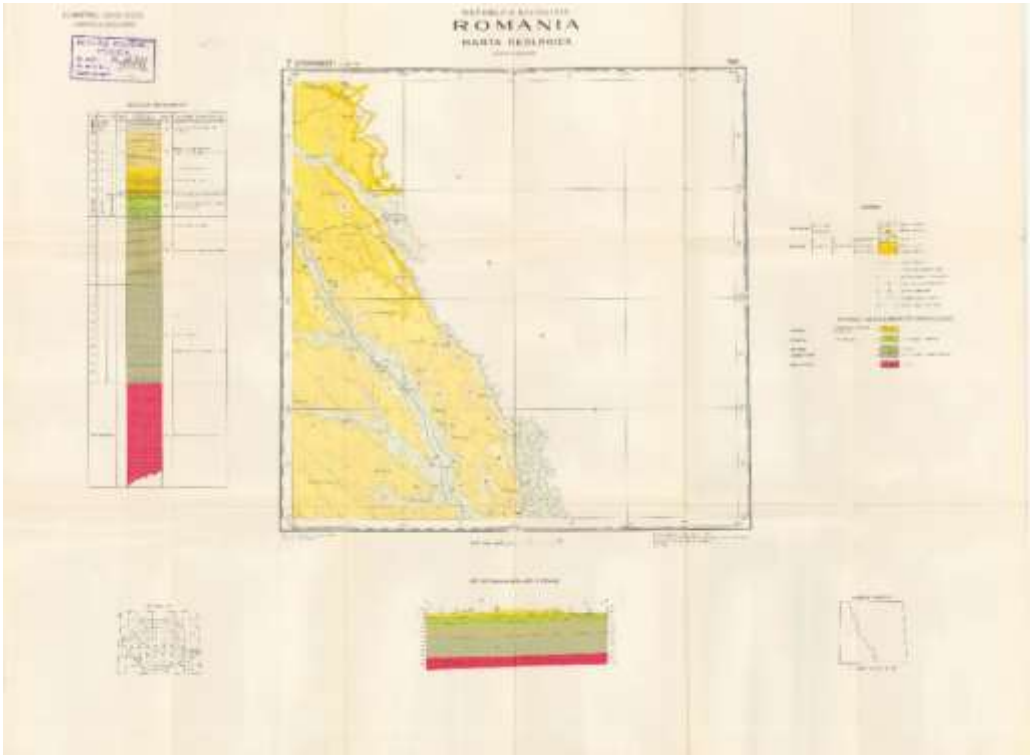


Figure 5.19. The geological map and description of section L-35-IV-Stefanesti

8. L-34-X-Oradea

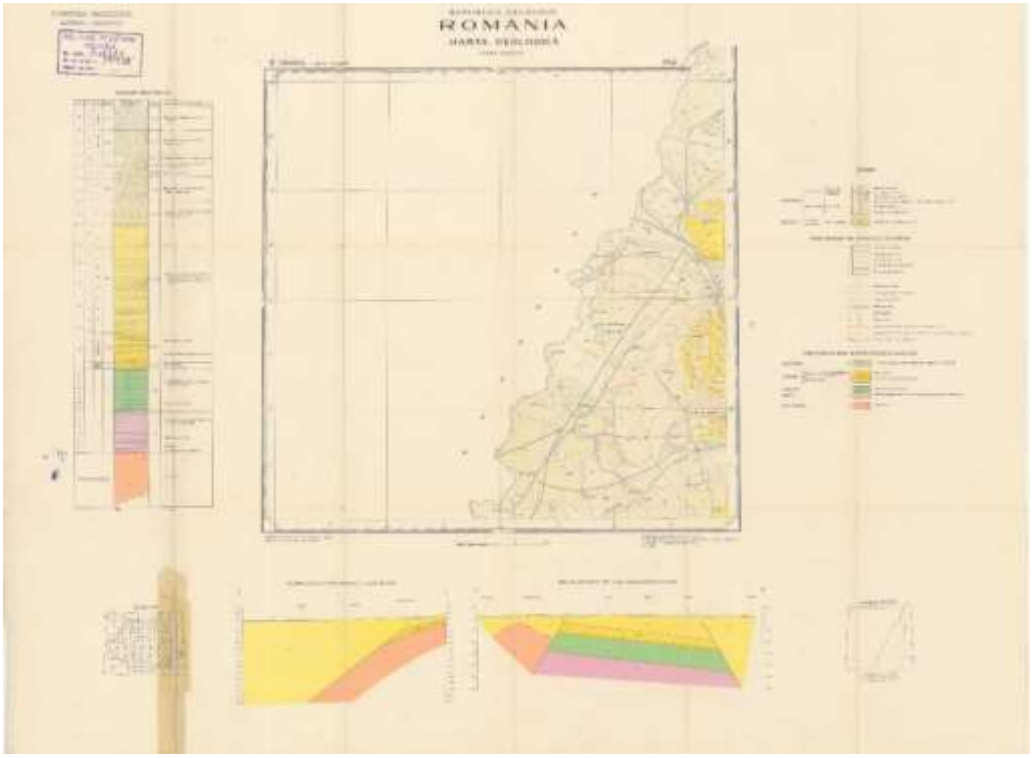


Figure 5.20. The geological map and description of section L-34-X-Oradea

9. L-34-XI- Simleul Silvaniei

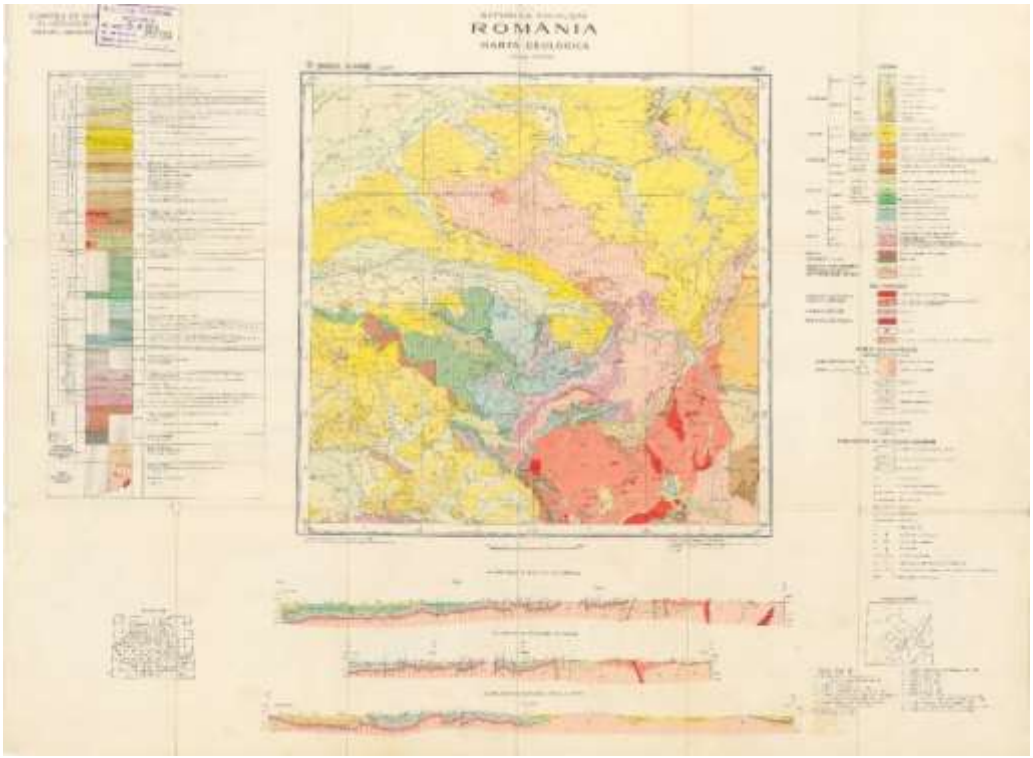


Figure 5.21. The geological map and description of section L-34-XI- Simleul Silvaniei

10. L-34-XII-Cluj

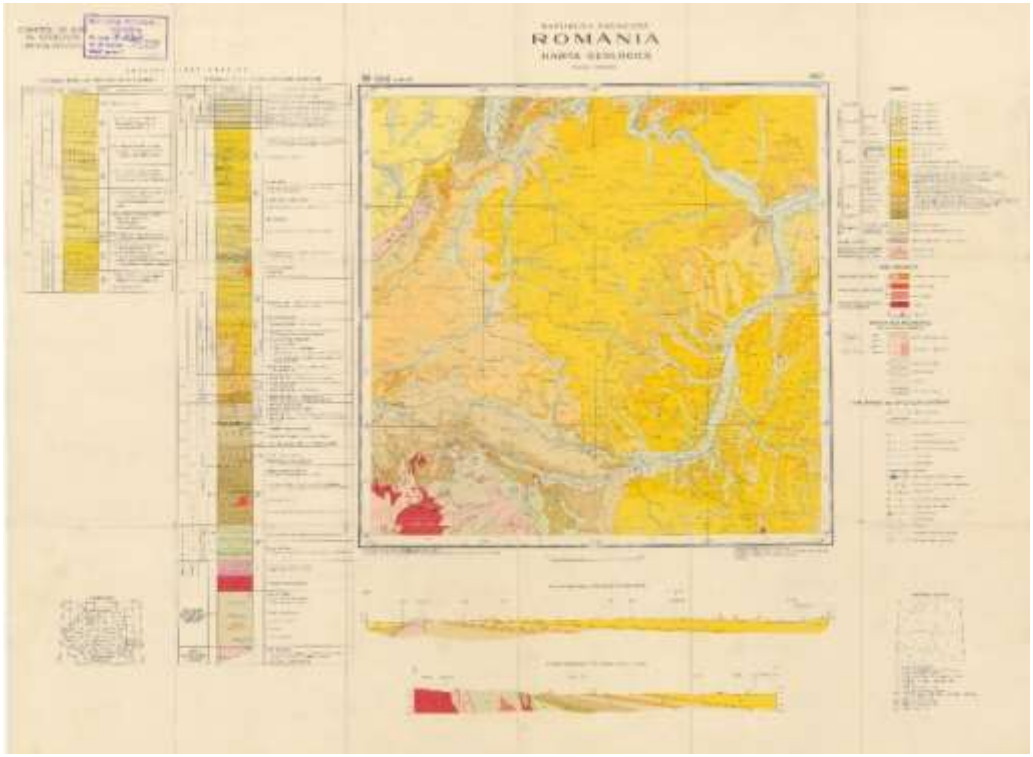


Figure 5.22. The geological map and description of section L-34-XII-Cluj

11. L-35-VII-Bistrita

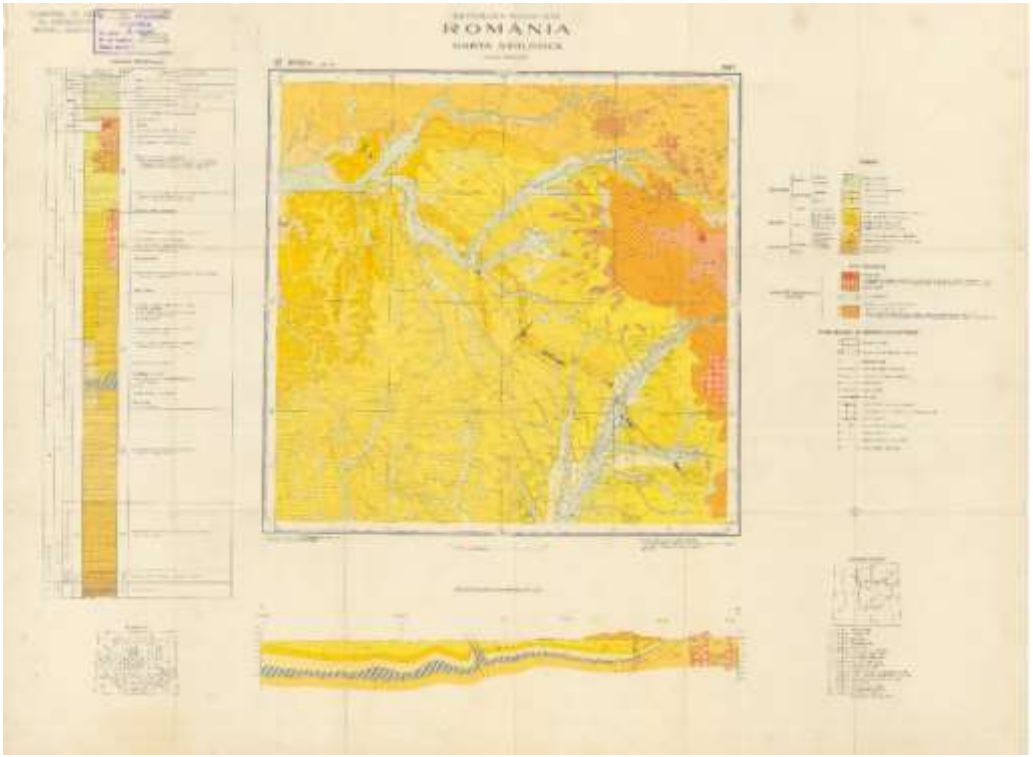


Figure 5.23. The geological map and description of section L-35-VII-Bistrita

12. L-35-VII- Toplita

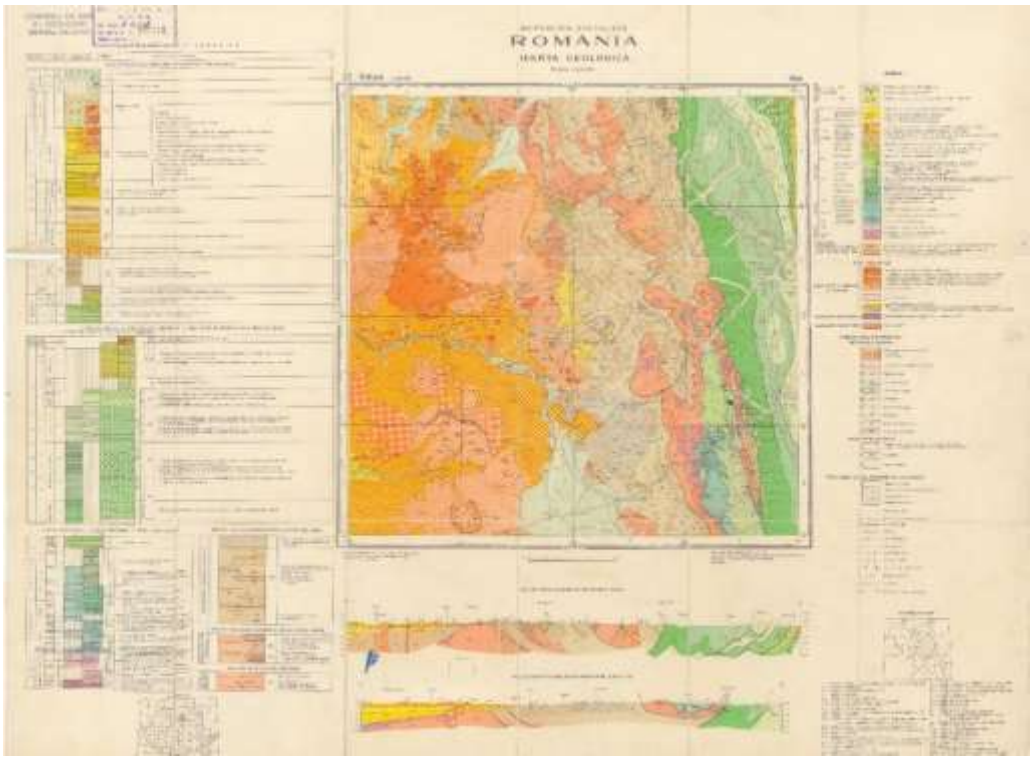


Figure 5.24. The geological map and description of section L-35-VII- Toplita

13. L-35-IX – Piatra Neamt

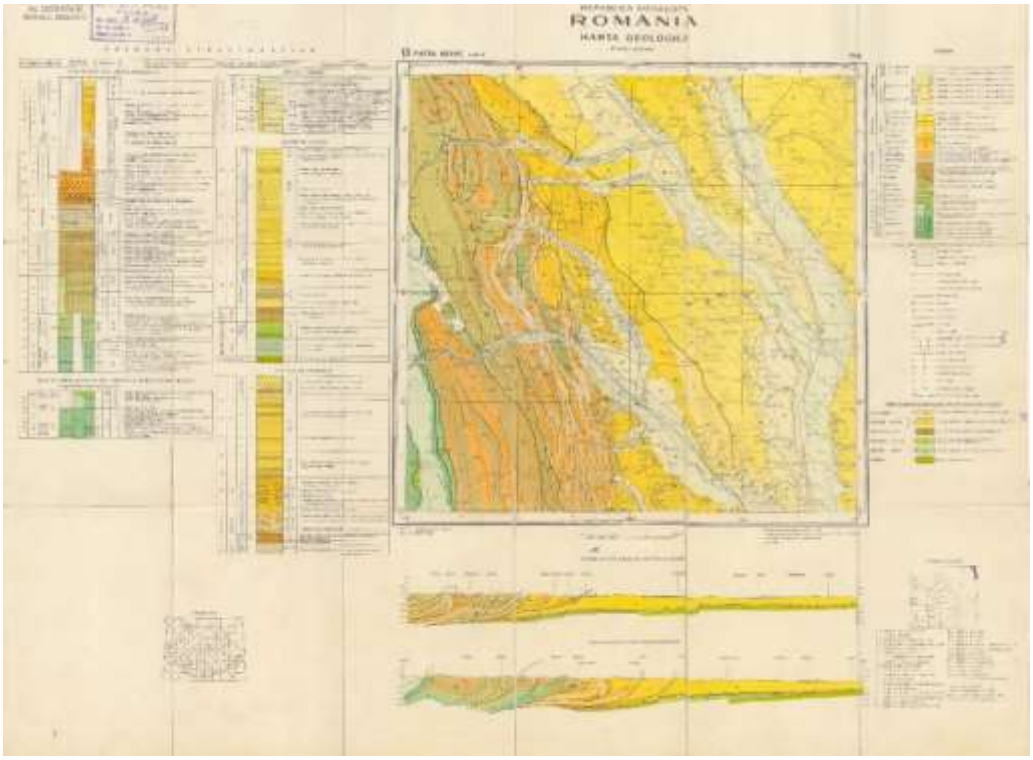


Figure 5.25. The geological map and description of section L-35-IX – Piatra Neamt

14. L-35-X - Iasi

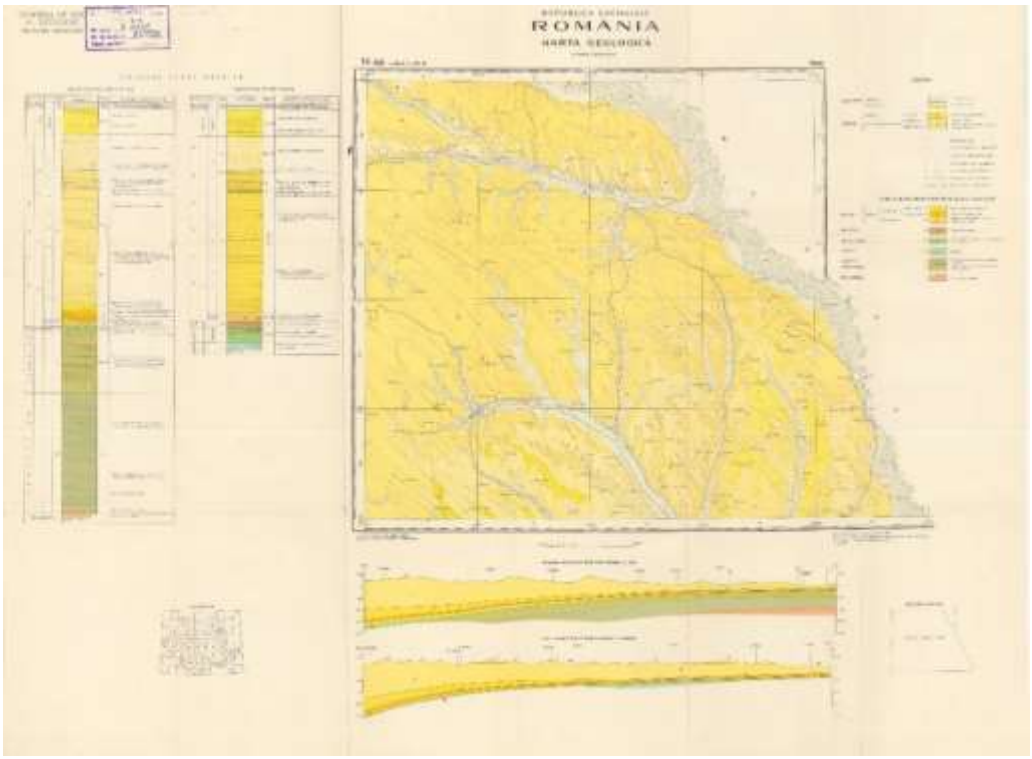


Figure 5.26. The geological map and description of section L-35-X - Iasi

15. L-34-XV-Sinicolaul Mare

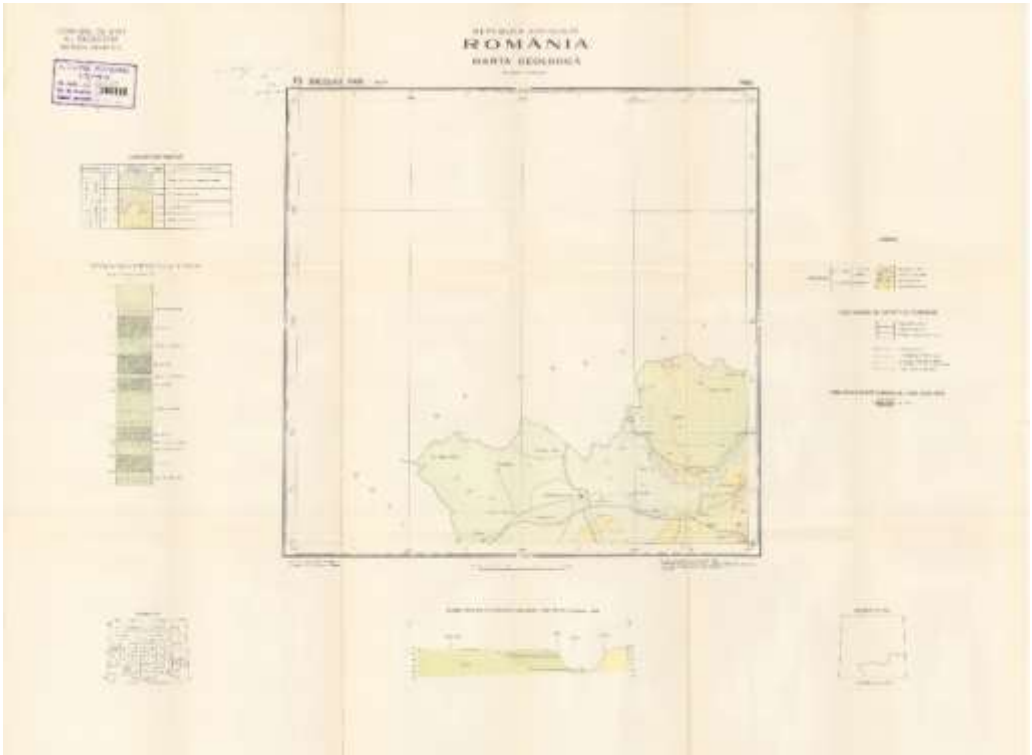


Figure 5.27. The geological map and description of section L-34-XV-Sinicolaul Mare

16. L-34-XVI – Ardad

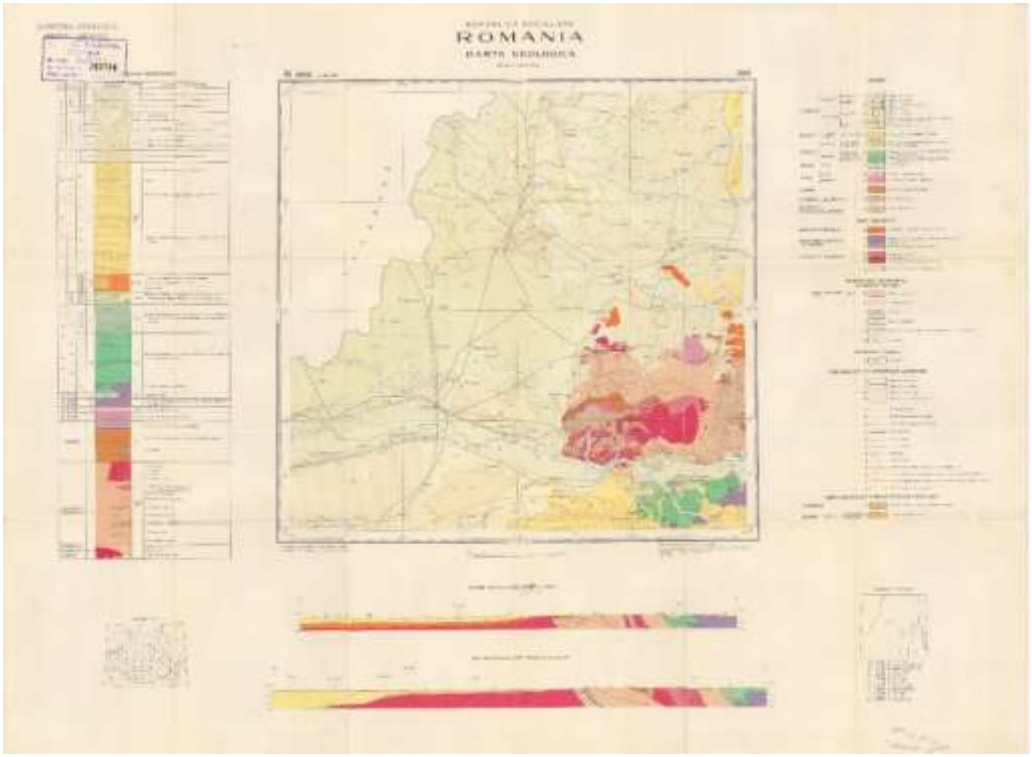


Figure 5.28. The geological map and description of section L-34-XVI – Ardad

17. L-34-XVII- Brad

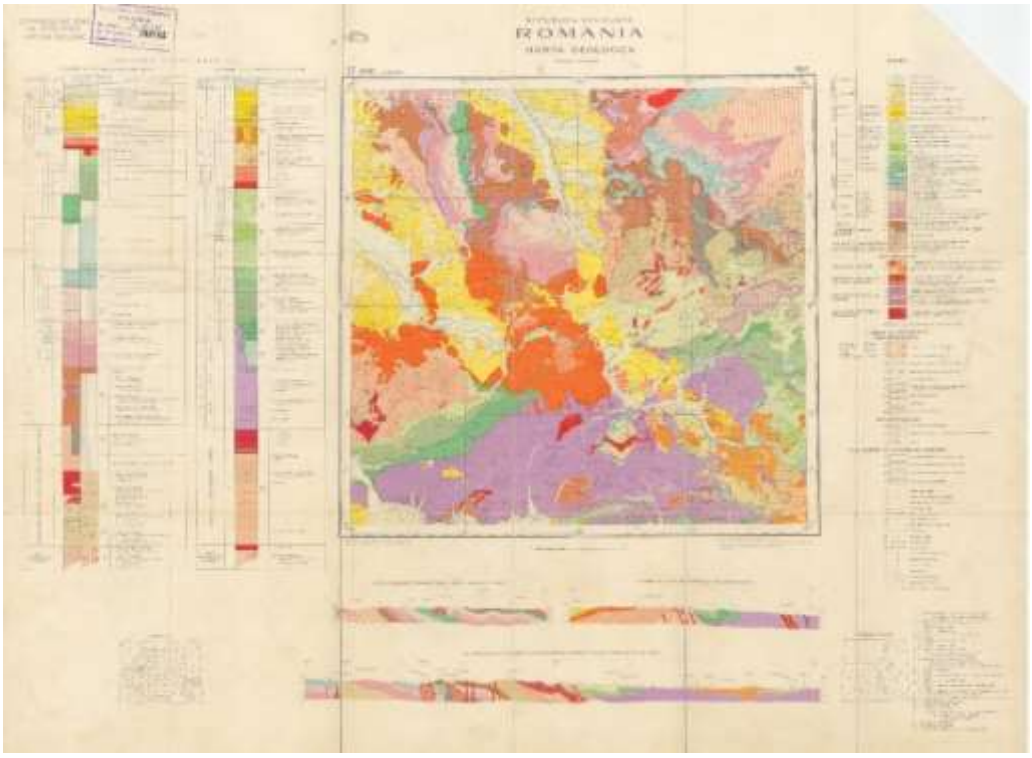


Figure 5.29. The geological map and description of section L-34-XVII- Brad

18. L-34-XVIII- Turda

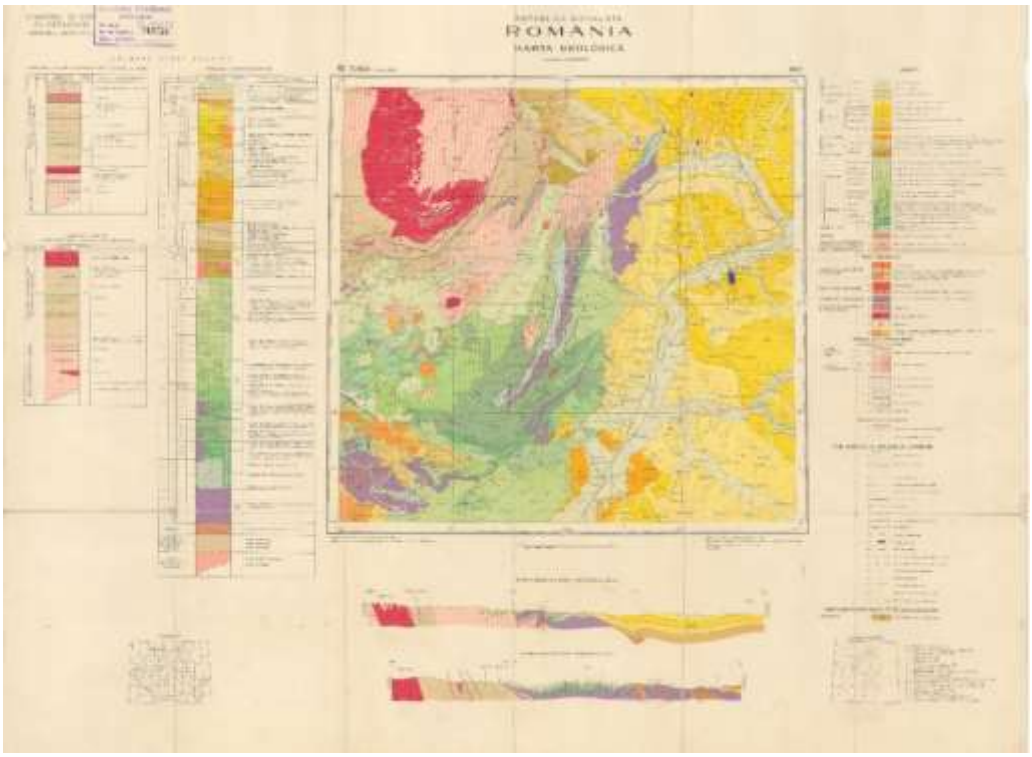


Figure 5.30. The geological map and description of section L-34-XVIII- Turda

19. L-35-XIII- Targul Mures

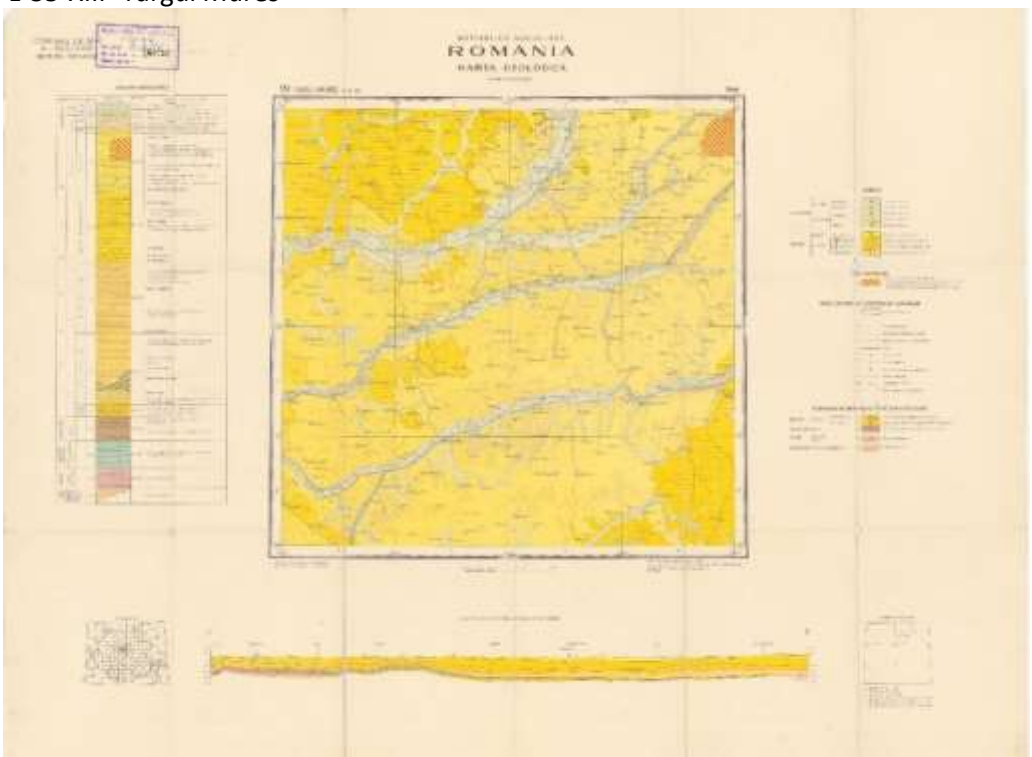


Figure 5.31. The geological map and description of section L-35-XIII- Targul Mures

20. L-35-XIV- Odorhei

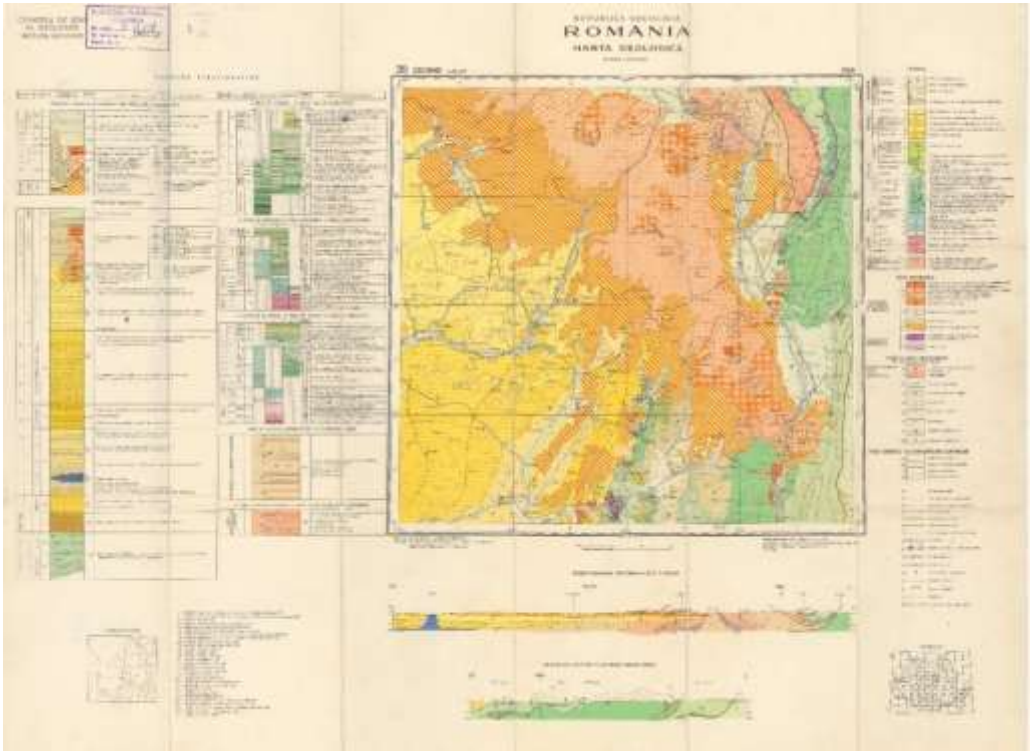


Figure 5.32. The geological map and description of section L-35-XIV- Odorhei

21. L-35-XV- Bacau

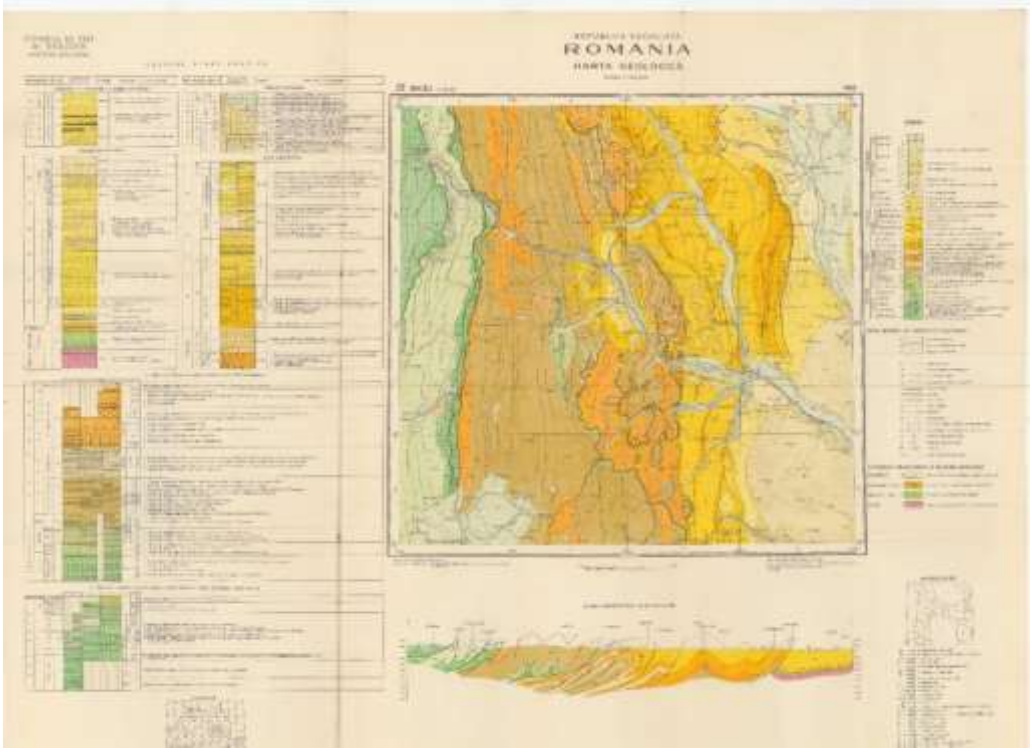


Figure 5.33. The geological map and description of section L-35-XV- Bacau

22. L-35-XVI- Birlad

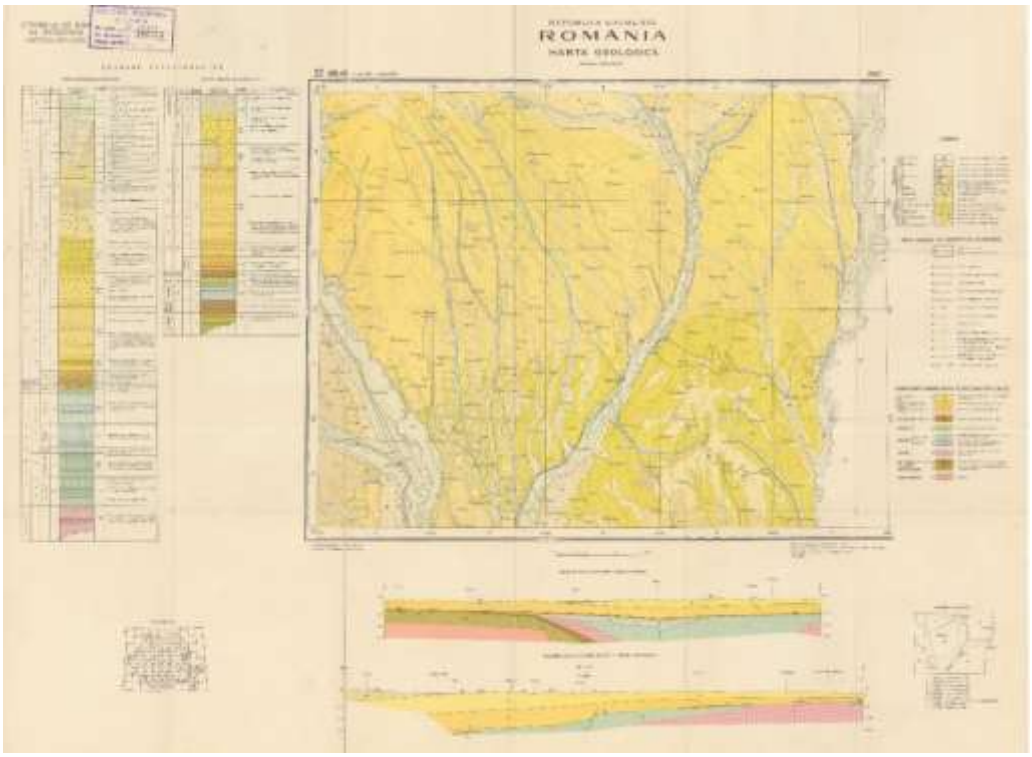


Figure 5.34. The geological map and description of section L-35-XVI- Birlad

23. L-34-XXI-Jimbolia

Figure 5.35. The geological map and description of section L-34-XXI-Jimbolia

24. L-34-XXII-Timisoara

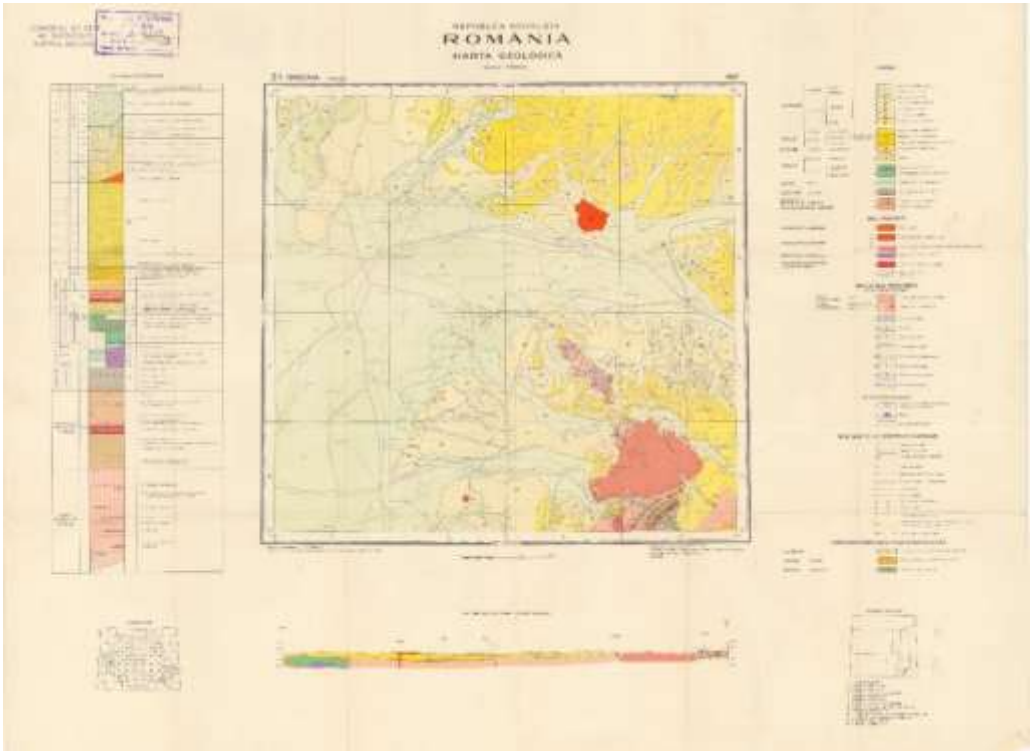


Figure 5.36. The geological map and description of section L-34-XXII-Timisoara

25. L-34-XIII-Deva

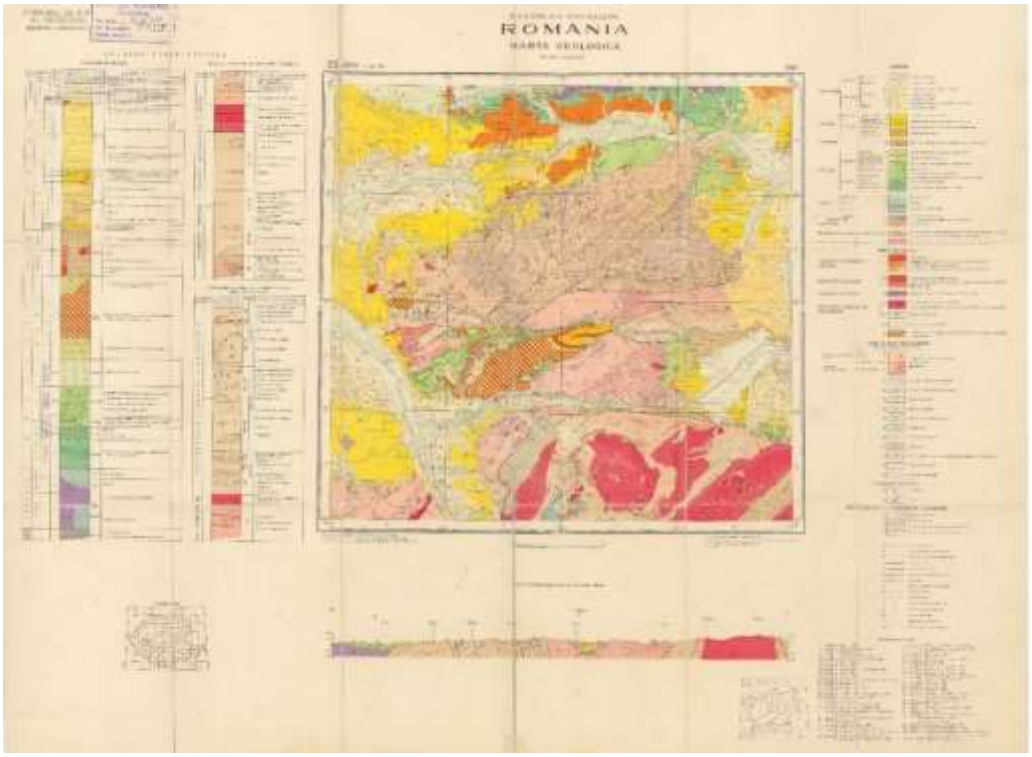


Figure 5.37. The geological map and description of section L-34-XIII-Deva

26. L-34-XIV-Orastie

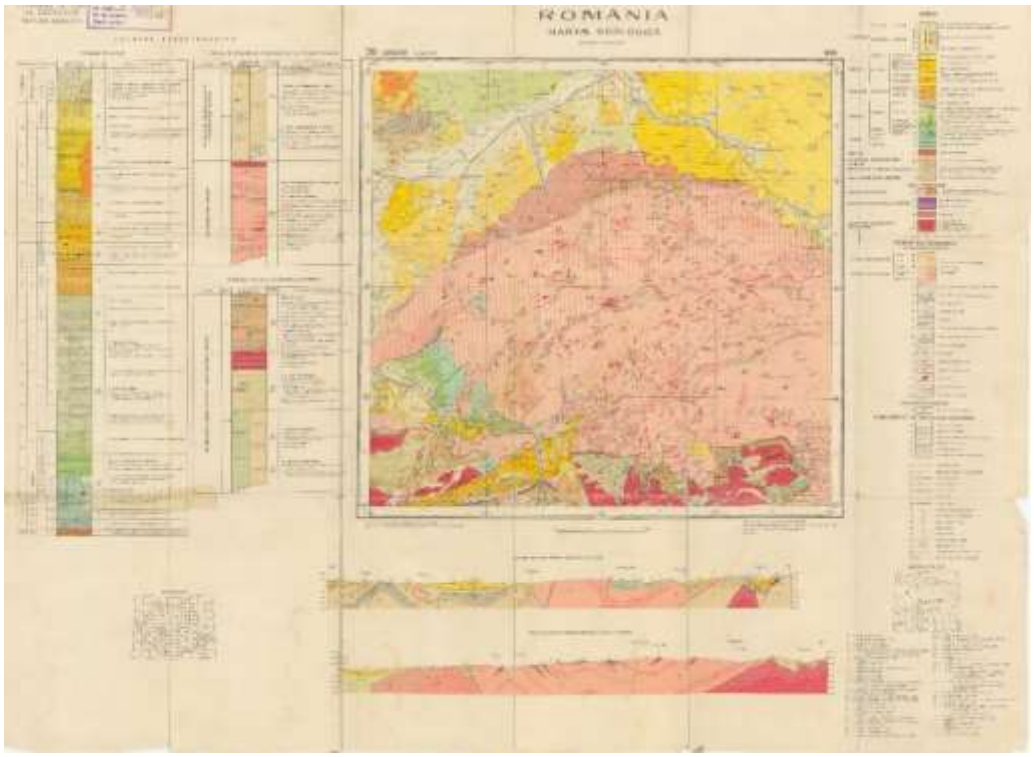


Figure 5.38. The geological map and description of section L-34-XIV-Orastie

27. L-35-XIX- Sibiu

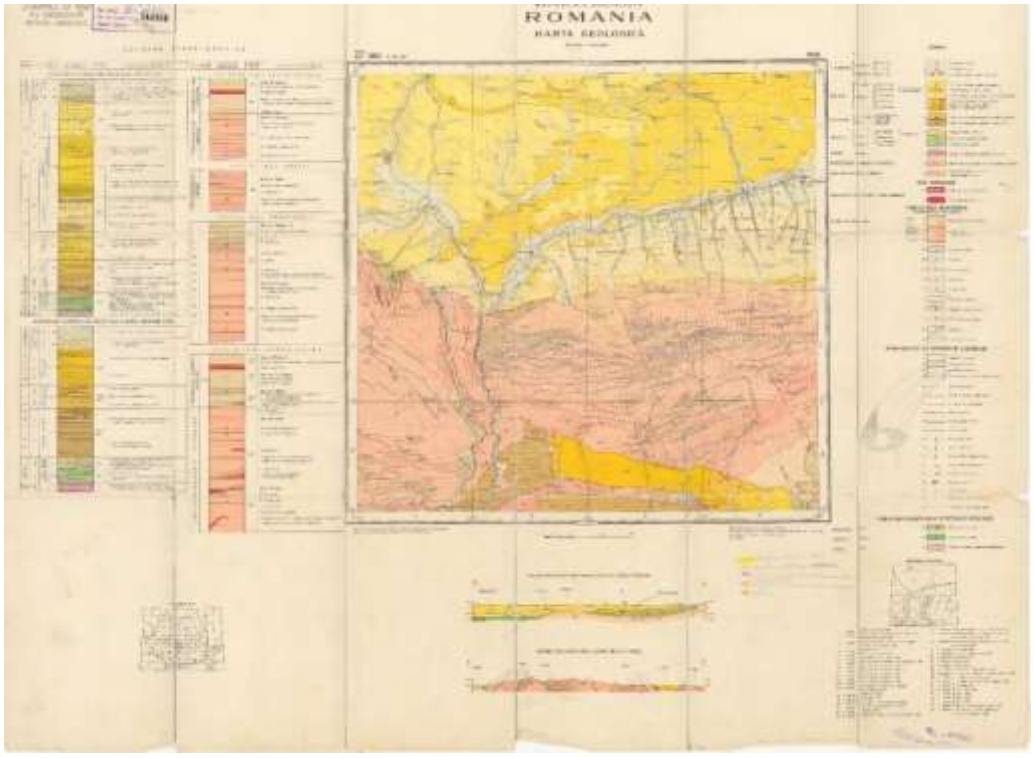


Figure 5.39. The geological map and description of section L-35-XIX- Sibiu

28. L-35-XX-Brasov

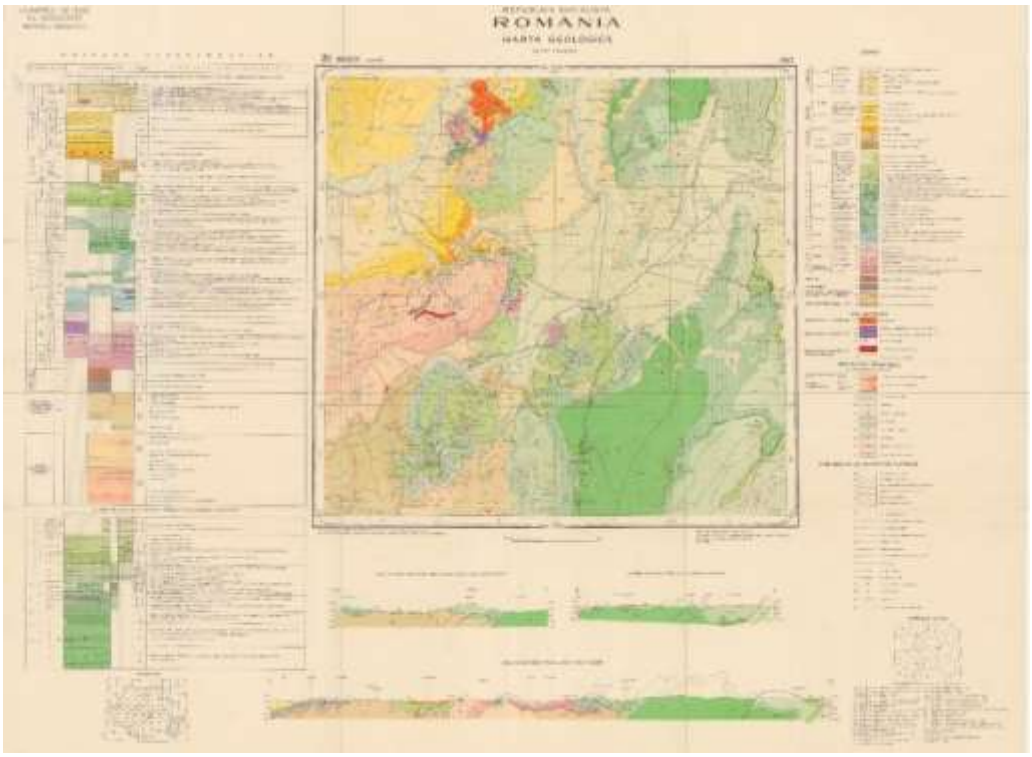


Figure 5.40. The geological map and description of section L-35-XX-Brasov

29. L-35-XXI- Covasna

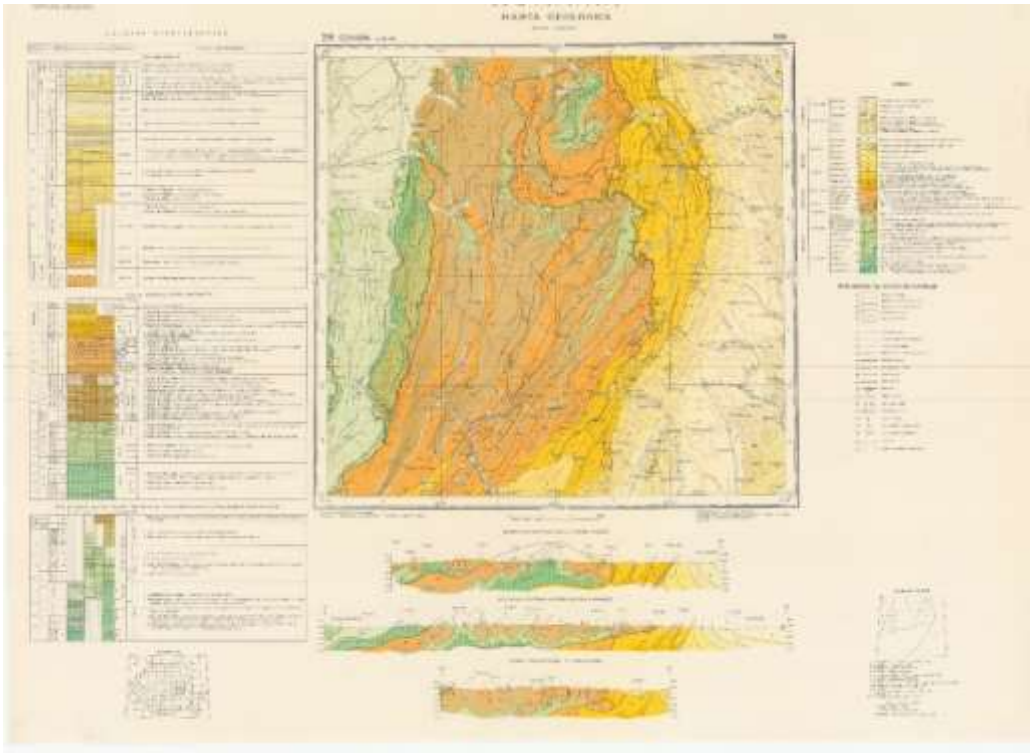


Figure 5.41. The geological map and description of section L-35-XXI- Covasna

30. L-35-XXII-Focsani

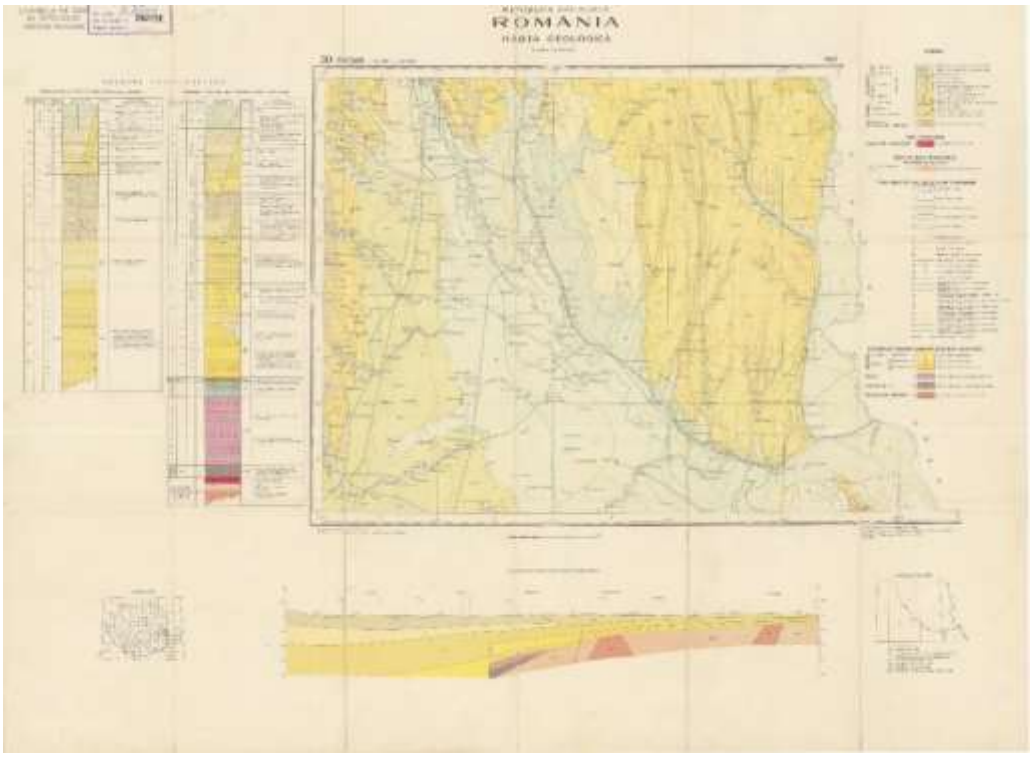


Figure 5.42. The geological map and description of section L-35-XXII-Focsani

31. L-34-XXVIII-Resita

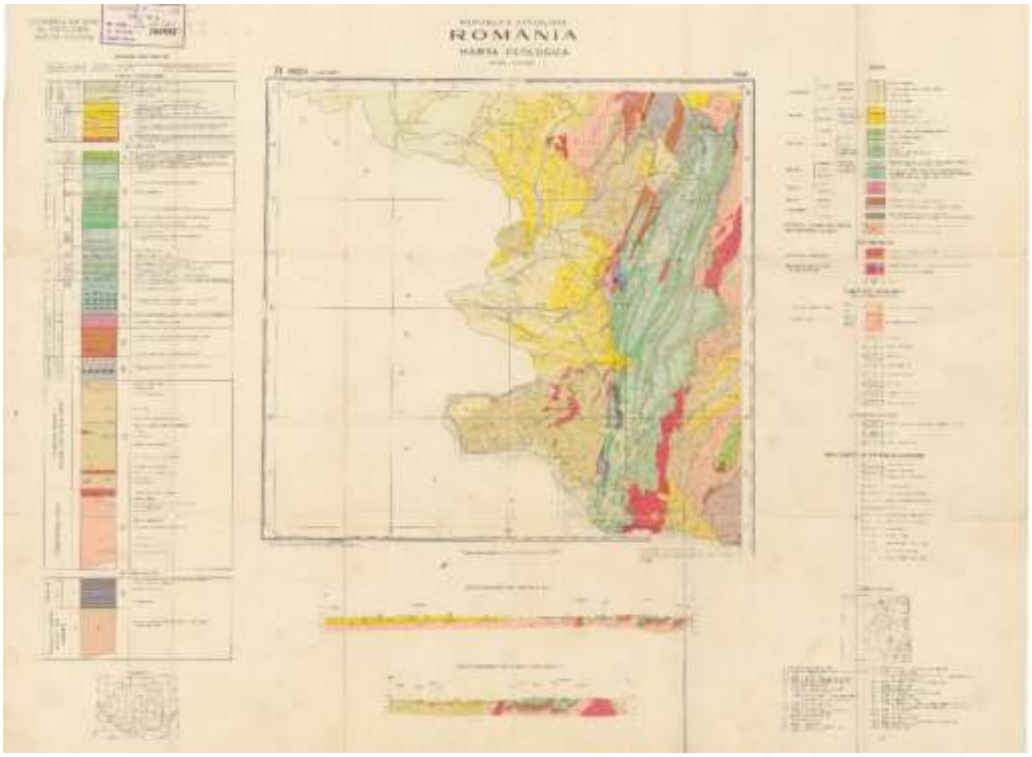


Figure 5.43. The geological map and description of section L-34-XXVIII-Resita

32. L-34-XXIX-Baia de Arama

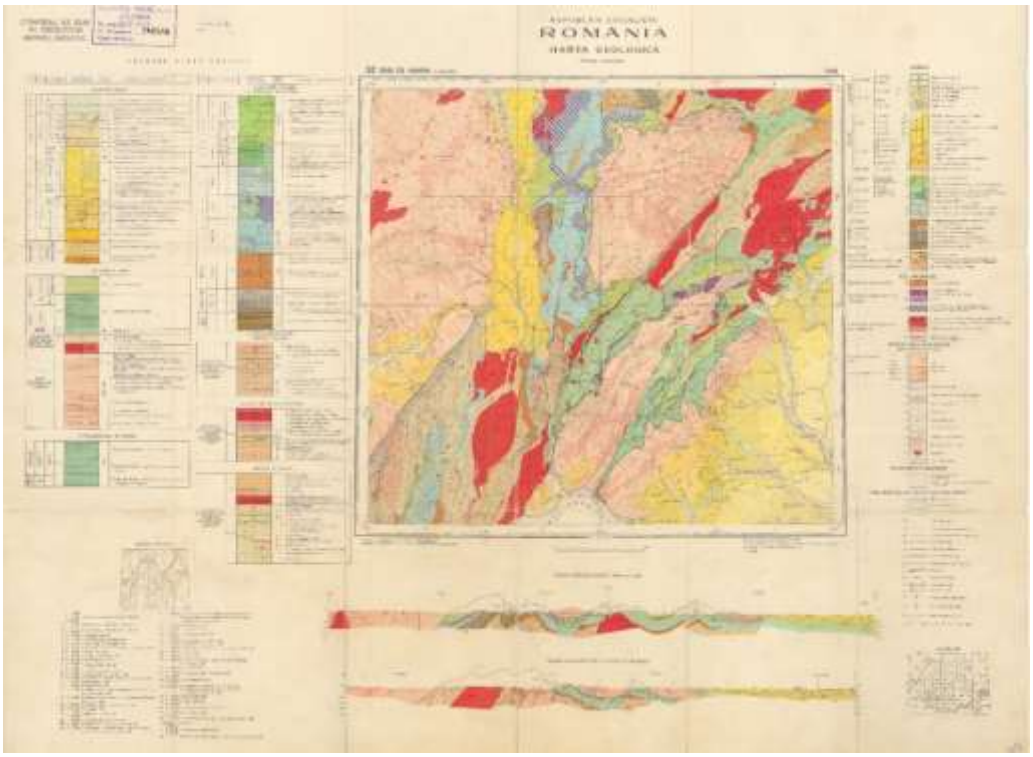


Figure 5.44. The geological map and description of section L-34-XXIX-Baia de Arama

33. L-34-XXX-Targul Jiu

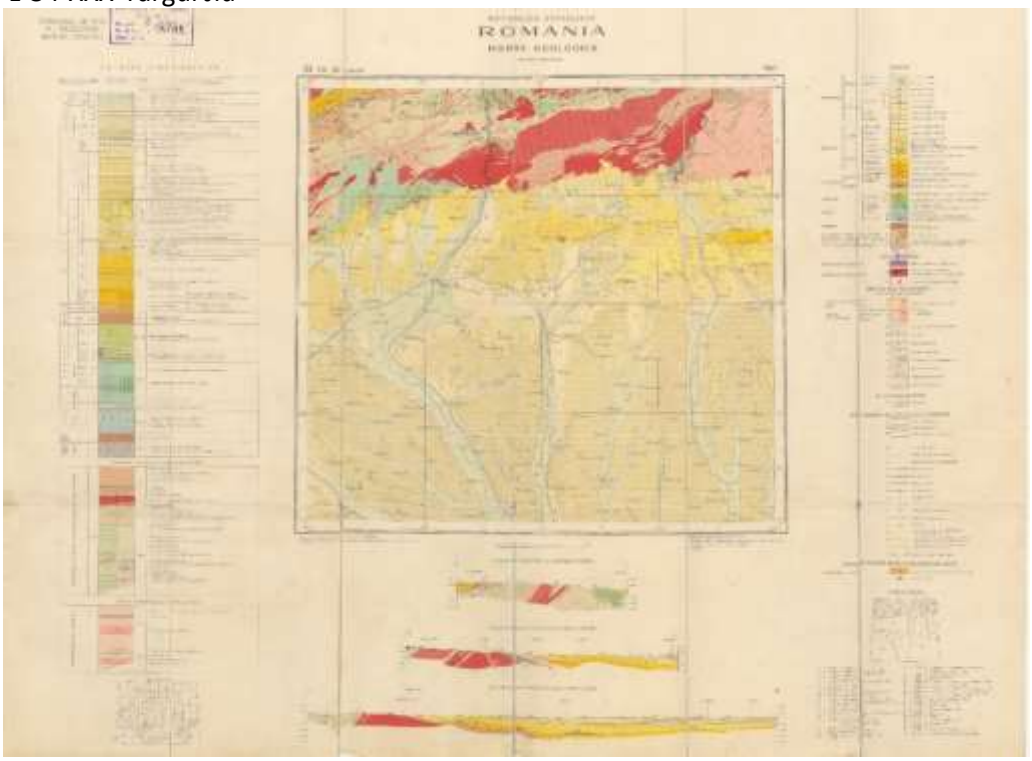


Figure 5.45. The geological map and description of section L-34-XXX-Targul Jiu

34. L-35-XXV-Pitesti

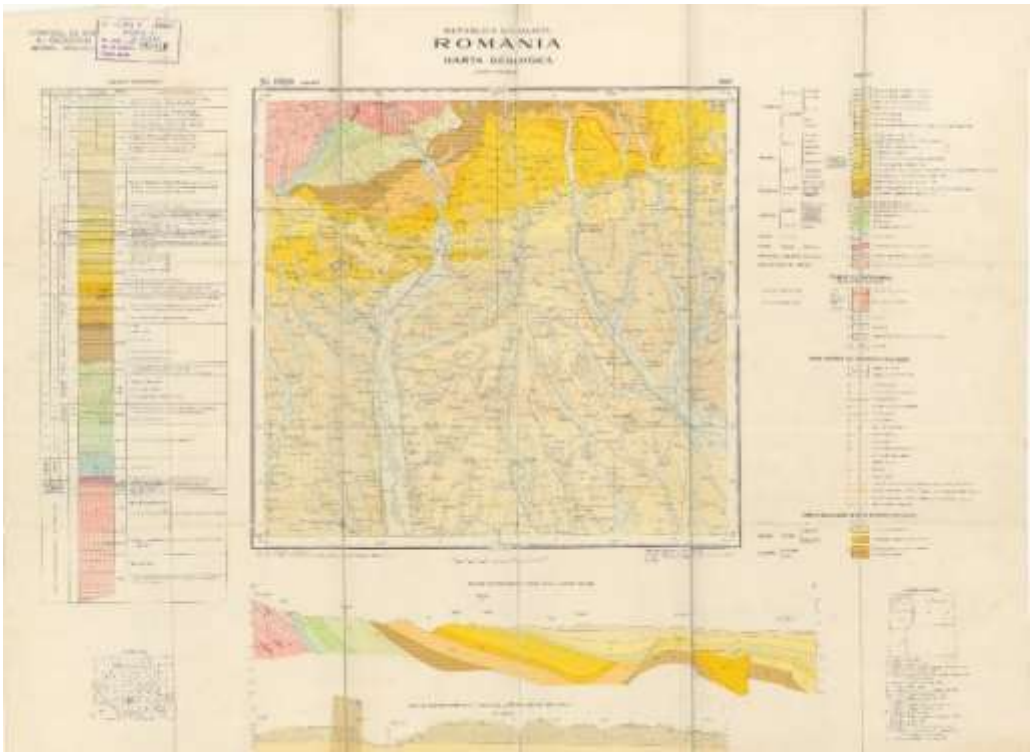


Figure 5.46. The geological map and description of section L-35-XXV-Pitesti

35. L-35-XXVI-Targoviste

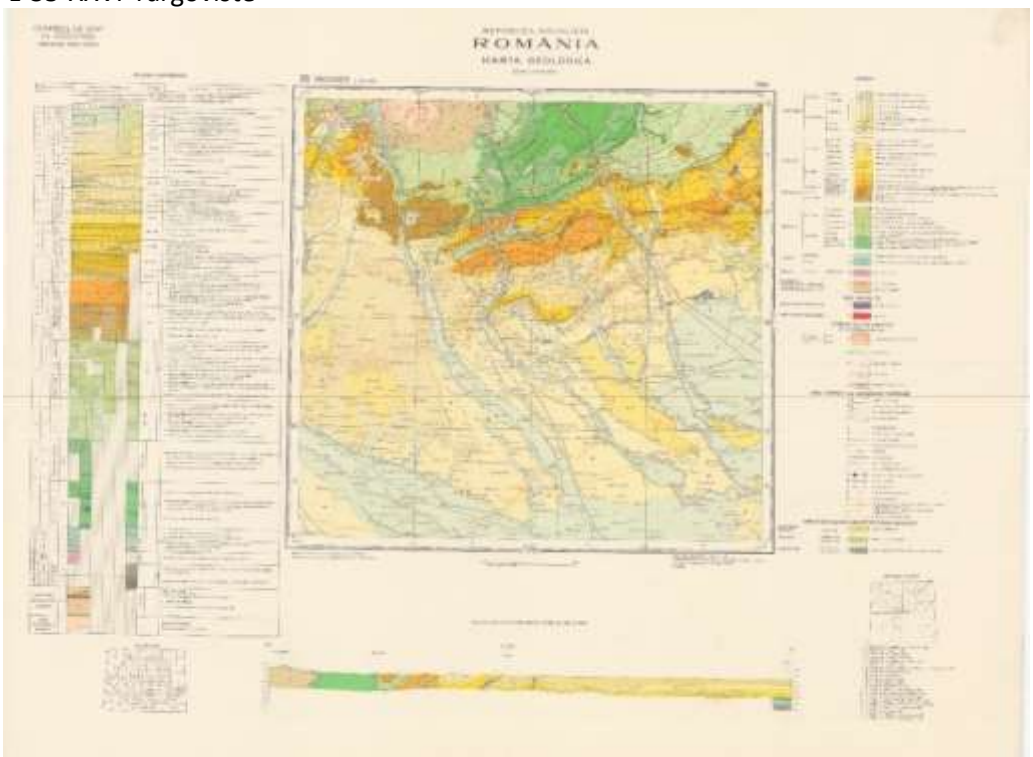


Figure 5.47. The geological map and description of section L-35-XXVI-Targoviste

36. L-35-XXVII-Ploiesti

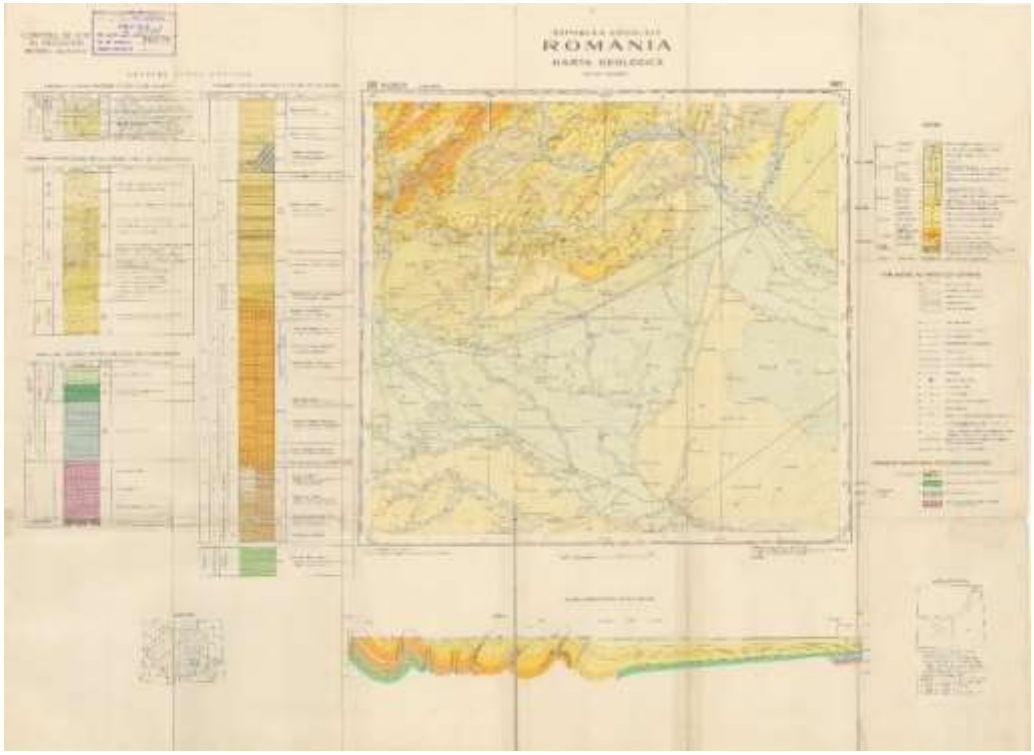


Figure 5.48. The geological map and description of section L-35-XXVII-Ploiesti

37. L-35-XXVIII-Braila

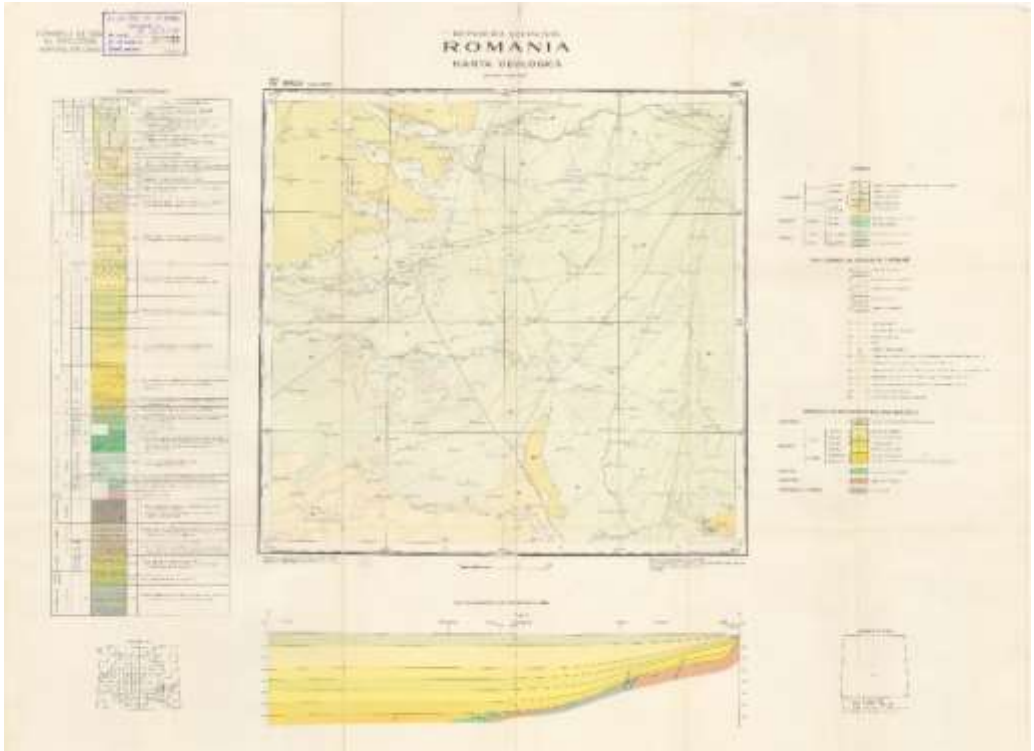


Figure 5.49. The geological map and description of section L-35-XXVIII-Braila

38. L-35-XXIX-Tulcea

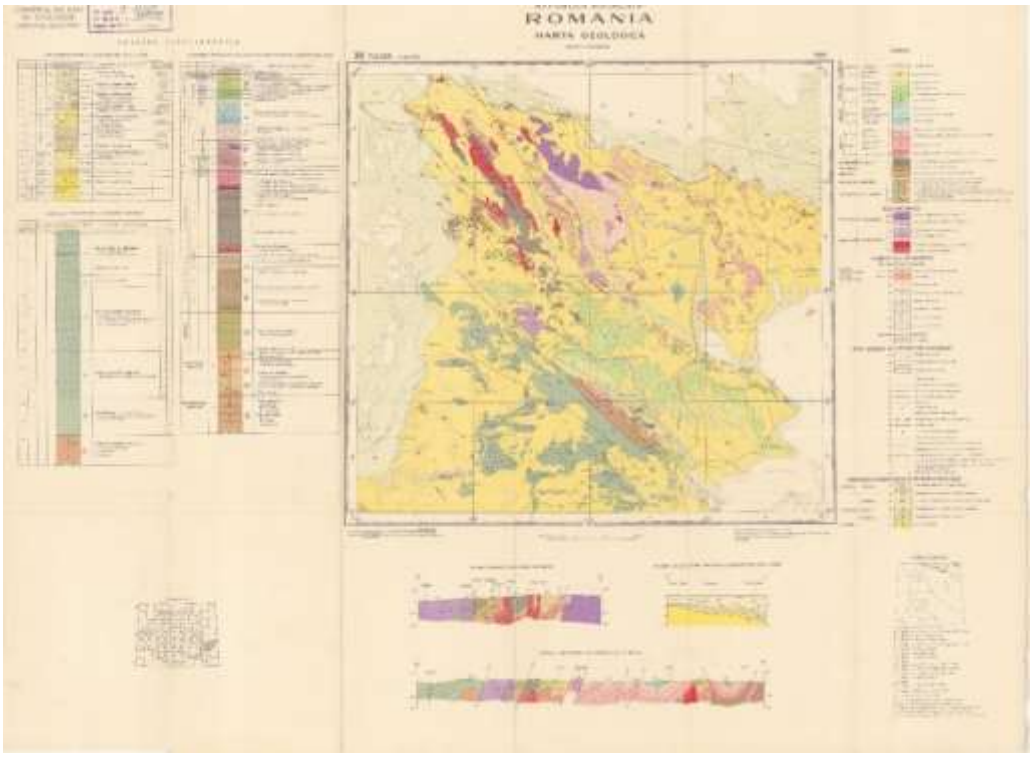


Figure 5.50. The geological map and description of section L-35-XXIX-Tulcea

39. L-35-XXX-Sulina

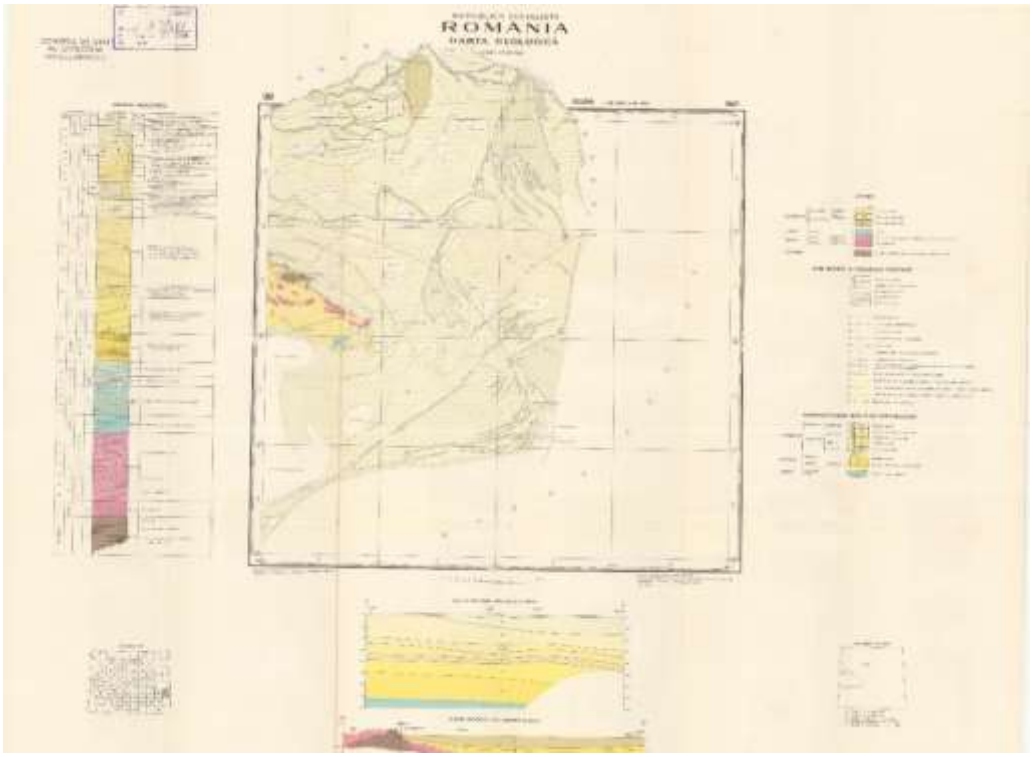


Figure 5.51. The geological map and description of section L-35-XXX-Sulina

40. L-34-XXXV-Turnu-Severin

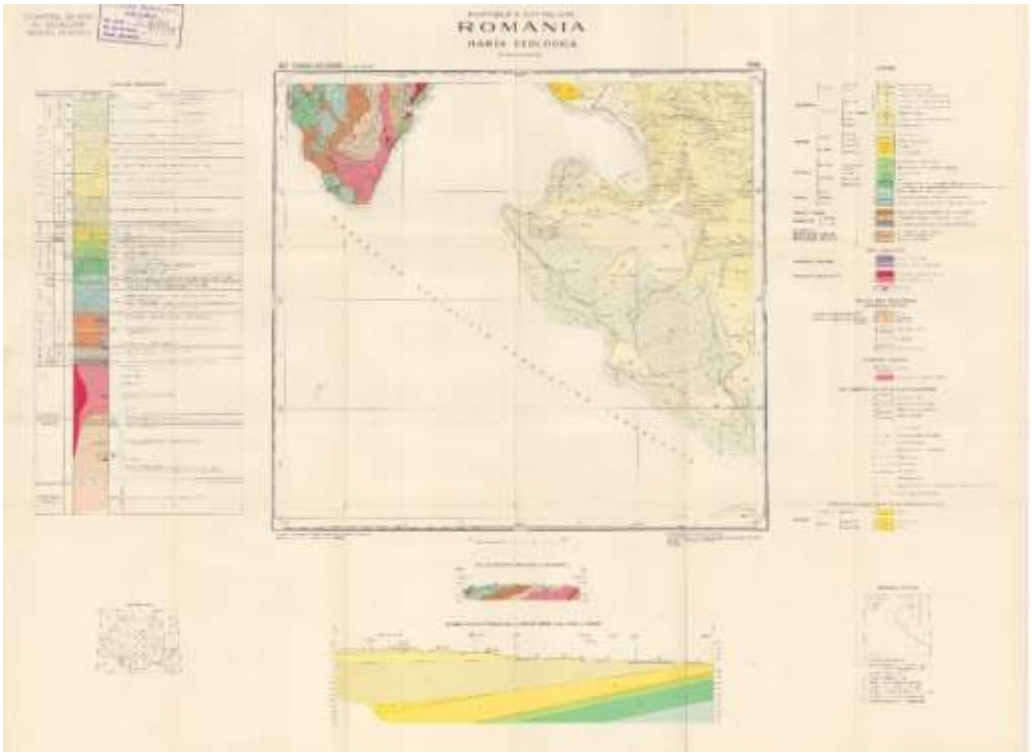


Figure 5.52. The geological map and description of section L-34-XXXV-Turnu-Severin

41. L-34-XXXVI-Craiova

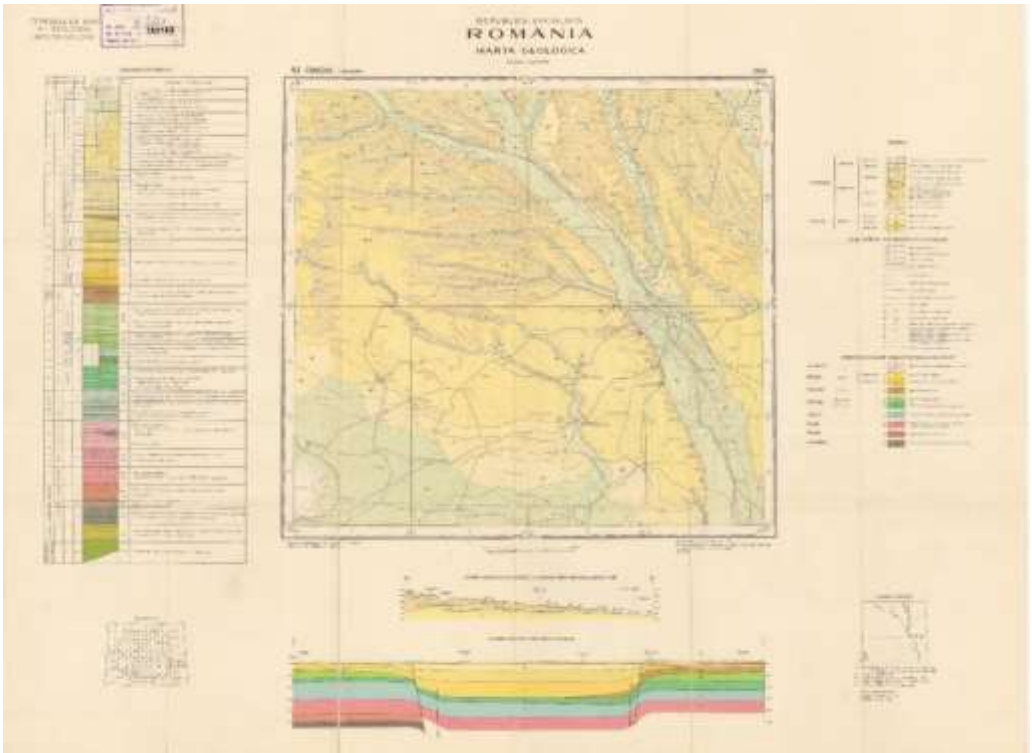


Figure 5.53. The geological map and description of section L-34-XXXVI-Craiova

42. L-35-XXXI-Slatina

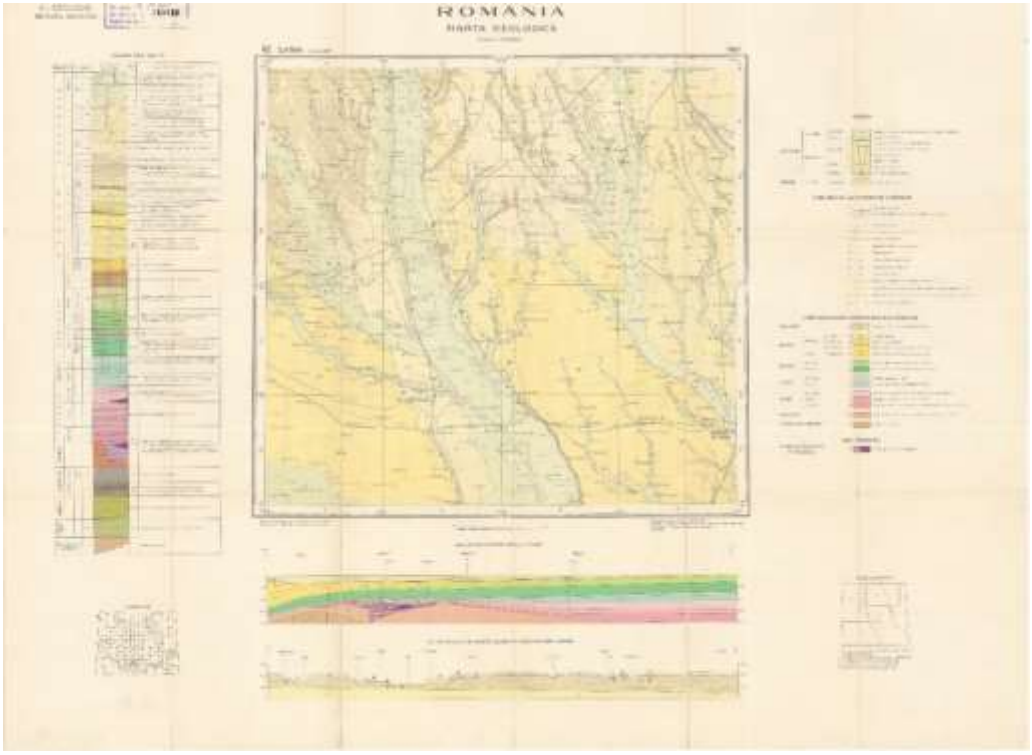


Figure 5.54. The geological map and description of section L-35-XXXI-Slatina

43. L-35-XXXII-Neajlov

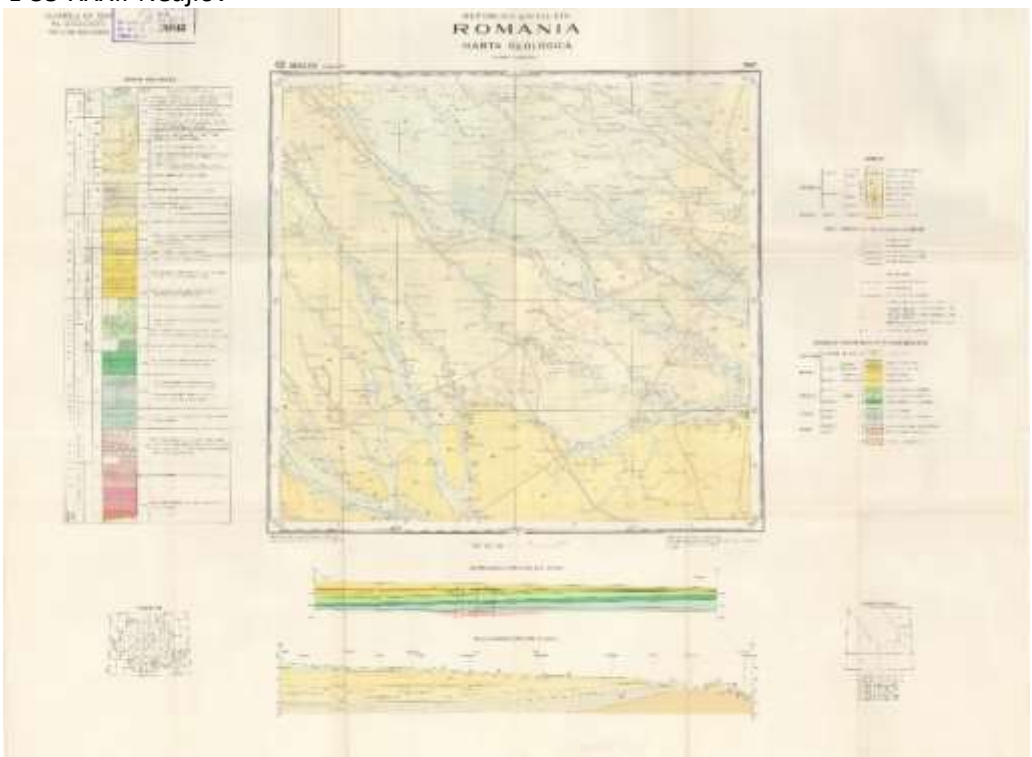


Figure 5.55. The geological map and description of section L-35-XXXII-Neajlov

44. L-35-XXXIII-Bucuresti

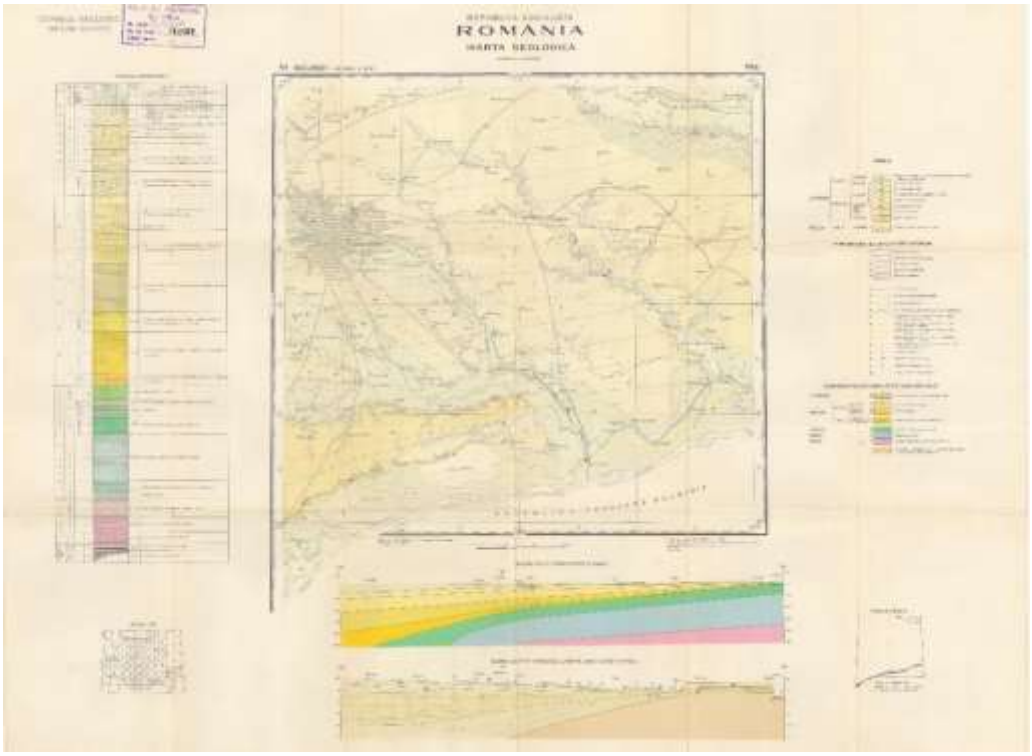


Figure 5.56. The geological map and description of section L-35-XXXIII-Bucuresti

45. L-35-XXXIV-Calarasi

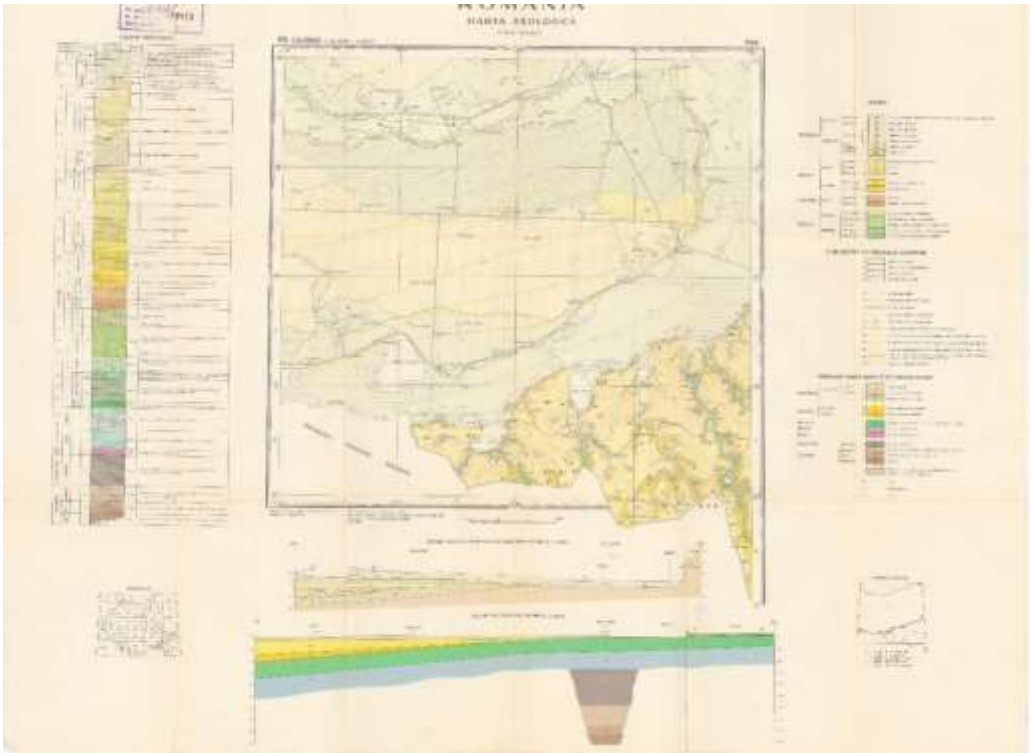


Figure 5.57. The geological map and description of section L-35-XXXIV-Calarasi

46. L-35-XXXV-Constanta

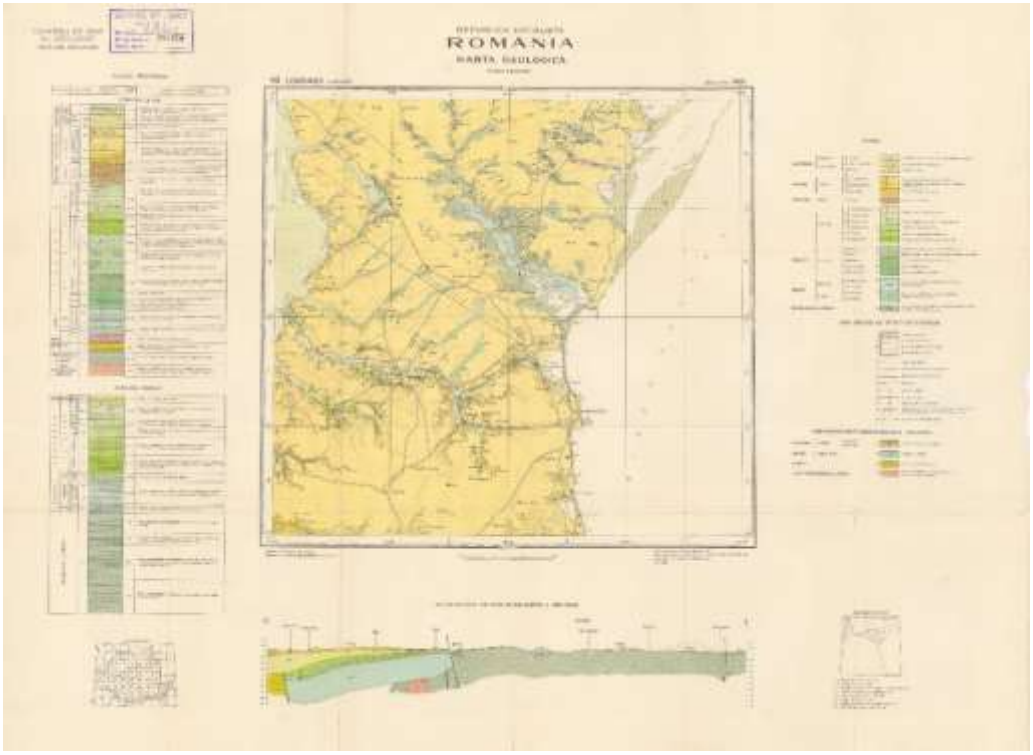


Figure 5.58. The geological map and description of section L-35-XXXV-Constanta

47. K-34-VI-Calafat-Bechet

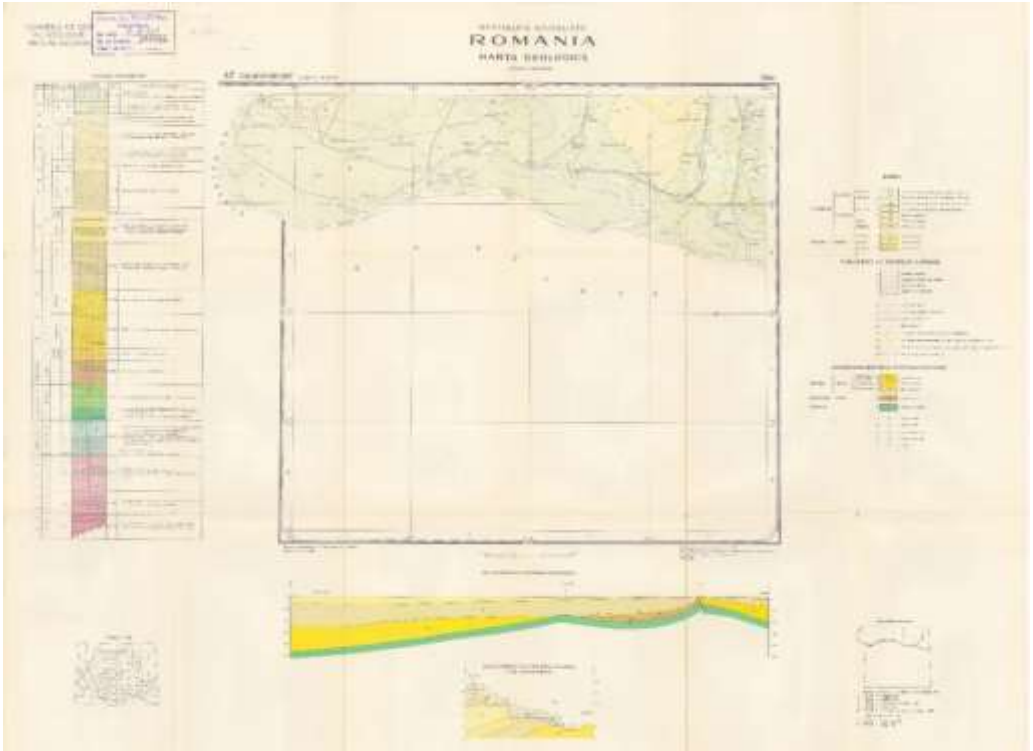


Figure 5.59. The geological map and description of section K-34-VI-Calafat-Bechet

48. K-35-I-Turnu-Marugele

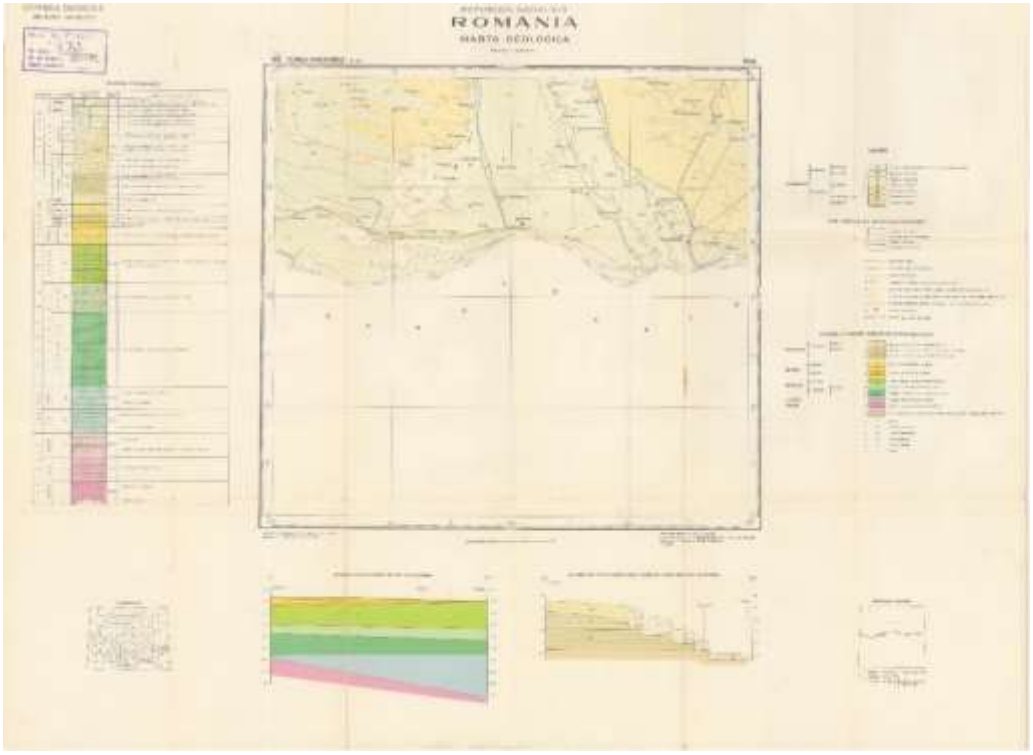


Figure 5.60. The geological map and description of section K-35-I-Turnu-Marugele

49. K-35-II-Girgiu

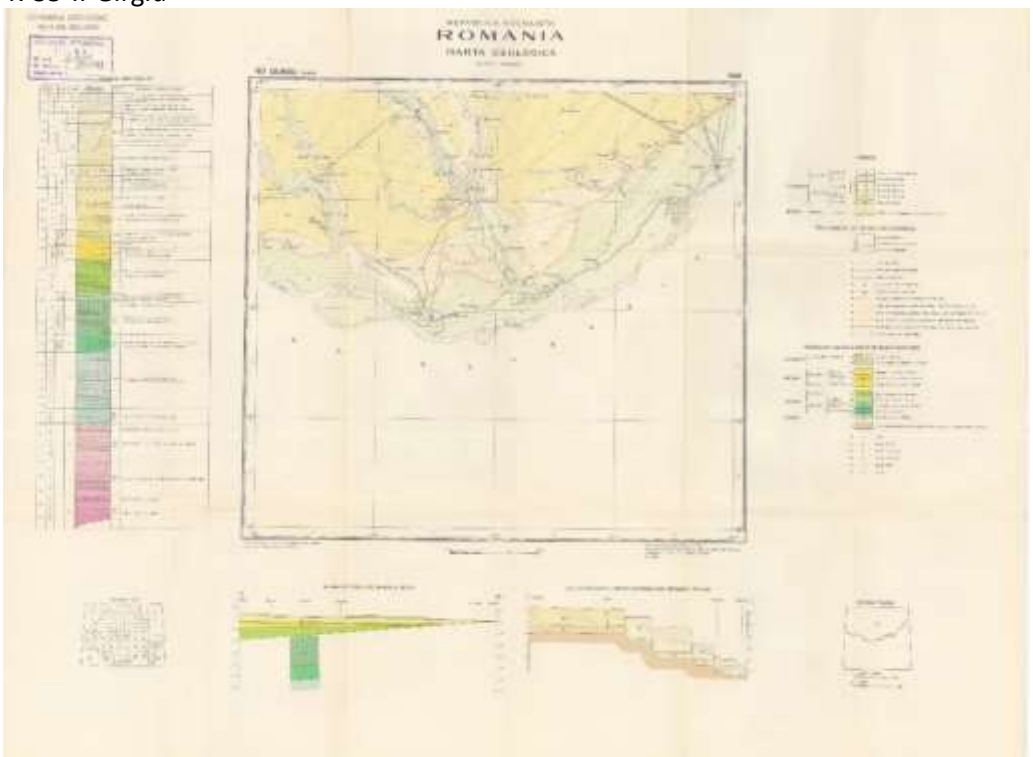


Figure 5.61. The geological map and description of section K-35-II-Girgiu

50. K-35-V-Mangalia

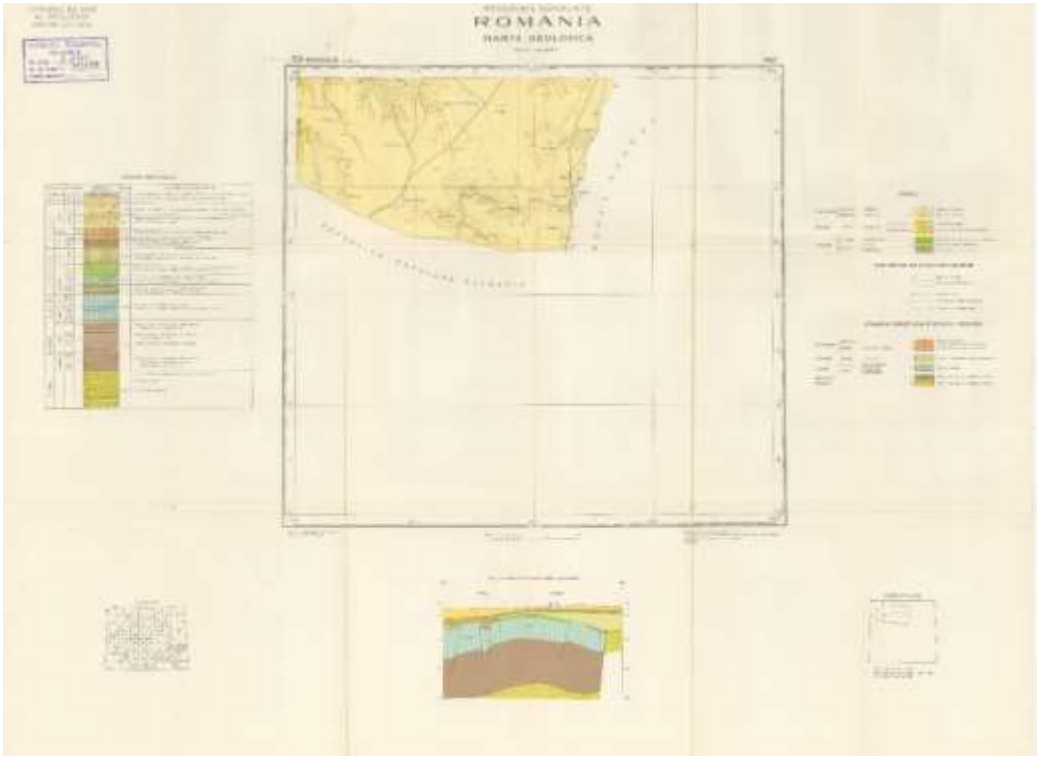


Figure 5.62. The geological map and description of section K-35-V-Mangalia

Also a more up to date version of the previous sheets can be found in the following publications:

1. Ștefănescu M., Polonic P., Alexandrescu G., Popescu I., Peltz S., Ionescu F., Niculin M., Popescu-Brădet L., Constantinescu P. (2018) A13: Secțiune geologică Tăul Zăului-Voiniceni-Ocna de Sus-Frumoasa-Dărmănești-Capăta-Bârlad. Editura Institutului Geologic al României, București. ISBN 978-606-94718-0-7.

2. Ștefănescu M., Mirăuță E., Seghedi A., Polonic P., Popescu I., Peltz S., Ionescu F., Niculin M., Popescu-Brădet L., Constantinescu P. (2018) A15: Secțiune geologică Tăul Zăului-Crăciunești-Nicolești-Biborțeni-Cernatu-Nereju-Brăila-Lacul Razelm. Editura Institutului Geologic al României, București. ISBN 978-606-94718-1-4.

3. Ștefănescu M. Polonic P., Popescu I., Ionescu F., Niculin M., Popescu-Brădet L., Tudorescu V. (2018) A16:Secțiune geologică Tăul Zăului-Ungheni-Paloș-Aita Mare-Sfântu Gheorghe-Beceni-Horia-Spiru Haret.Editura Institutului Geologic al României, București. ISBN 978-606-94718-2-1

4. Ștefănescu M. Polonic P., Popescu I., Ionescu F., Niculin M., Popescu-Brădet L., Tudorescu V. (2018) A19:Secțiune geologică Tăul Zăului-Criș-Zărnești-Poiana Țapului-Brebu-Ploiești-Lipia-Belciugatele-Chiselet.Editura Institutului Geologic al României, București. ISBN 978-606-94718-3-8.

I. Hydrogeology information

Also from this point of view the maps are presented in a large scale, and also in sheets.

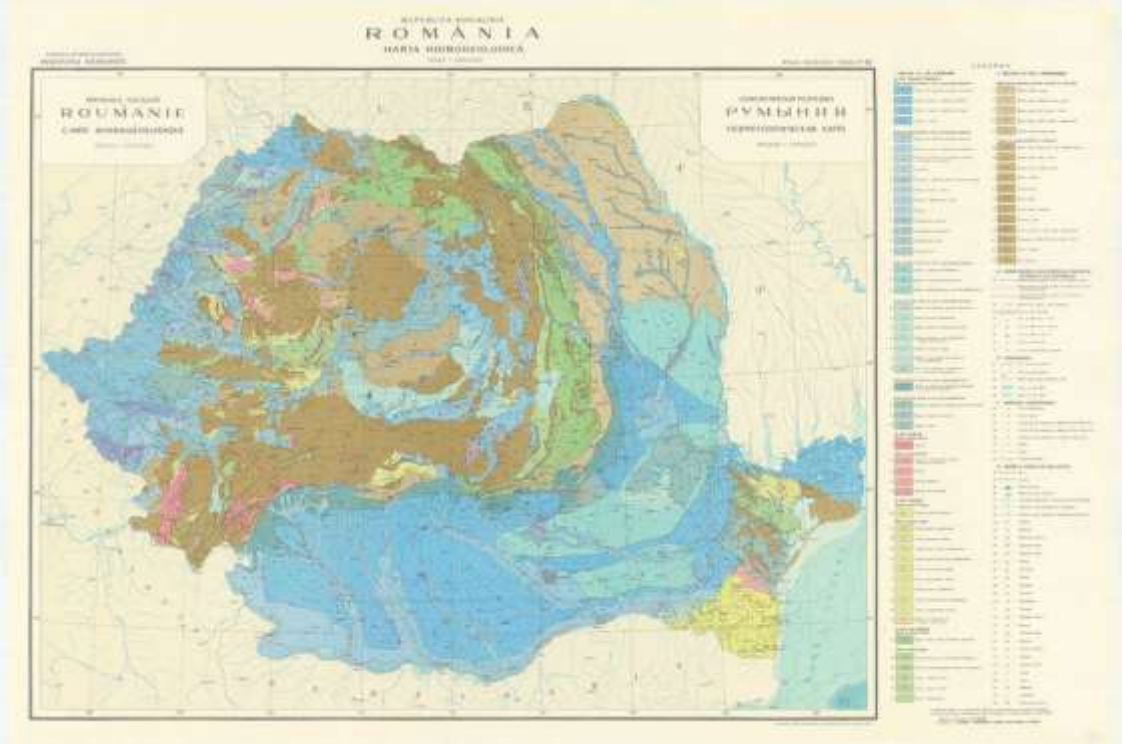


Figure 5.63. Hydrogeological map of Romania 1:1000000

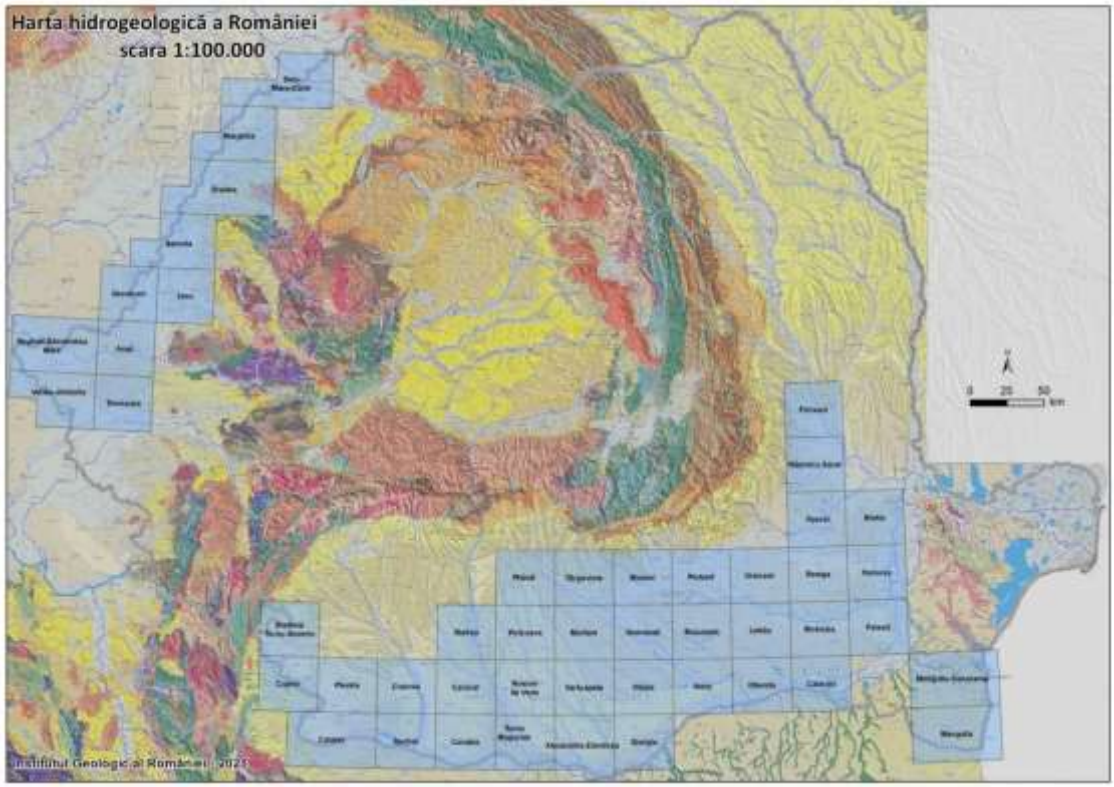


Figure 5.64. Hydrogeological map of Romania, and the sheets that are detailed.

Table 5.5. Table of published Hydrological sheets scale 1:100000

Nr. crt.	Sheet	I.G.R.	Year of edition	Authors
1	Bucureşti	44a	1966	Bandrabur T., Mihăilă N., Ghenea Ana
2	Olteniţa	44d	1966	Bandrabur T., Ghenea C., Ghenea Ana, Giurgea P.
3	Urziceni	36d	1968	Bandrabur T., Ghenea C., Giurgea P.
4	Brăila	37b	1968	Bandrabur T., Mihaila N., Giurgea P.
5	Reviga	37c	1968	Bandrabur T., Ghenea Ana, Mihaila N, Giurgea P.
6	Hârşova	37d	1968	Bandrabur T., Mihăilă N., Giurgea P.
7	Vidra	44c	1970	Bandrabur T.
8	Carei - Satu Mare	2a, 2b	1972	Bandrabur T.
9	Corabia	48a	1974	Bandrabur T.
10	Caracal	42c	1975	Bandrabur T.
11	Poiana Mare, Bechet	47b	1977	Bandrabur T.
12	Giurgiu	49b	1978	Bandrabur T.
13	Turnu Măgurele	48b	1980	Bandrabur T.
14	Râmnicu Sărat	30c	1982	Bandrabur T.
15	Craiova	41d	1985	Enciu P., Diaconu A., Giurgea P.
16	Moreni	35d	1970	Ghenea Ana, Ghenea C.
17	Domneşti	43b	1970	Ghenea C., Ghenea Ana
18	Mangalia	50a, 50b	1970	Ghenea C., Ghenea Ana
19	Medgidia, Constanţa	46c, 46d	1973	Ghenea C., Ghenea Ana
20	Târgovişte	35c	1974	Ghenea C., Ghenea Ana
21	Videle	43d	1976	Ghenea C., Ghenea Ana
22	Ploieşti	36c	1979	Ghenea C., Ghenea Ana
23	Focşani	30a	1980	Ghenea C., Bandrabur T., Ghenea Ana
24	Turnu Severin	40b	1981	Ghenea C., Ghenea Ana
25	Cujmir	40d	1981	Ghenea C., Ghenea Ana
26	Grăniceri	16a	1984	Ghenea C., Ghenea Ana
27	Galaţi	30d*	1990	Ghenea C., Ghenea Ana, Munteanu T., Munteanu E.
28	Slatina	42a	1970	Giurgea P.
29	Potcoava	42b	1970	Giurgea P.
30	Marghita	2c	1972	Giurgea P.
31	Morteni	43a	1973	Giurgea P., Mihăilă N.
32	Lehliu	44b	1966	Liteanu E., Bandrabur T., Ghenea Ana, Mihăilă N., GheneaC.
33	Slobozia	45a	1966	Liteanu E., Bandrabur T., Ghenea C., Mihăilă N., Ghenea Ana
34	Călăraşi	45c	1966	Liteanu E., Bandrabur T., Mihăilă N., Ghenea C., Ghenea Ana
35	Făurei	37a	1968	Liteanu E., Ghenea C., Ghenea Ana, Bandrabur T.
36	Feteşti	45b	1968	Liteanu E., Bandrabur T., Ghenea C., Ghenea Ana

37	Roşiori de Vede	42d	1970	Mihăilă N.
38	Oradea	8b, 9a	1970	Mihăilă N.
39	Salonta	8c, 8d	1972	Mihăilă N.
40	Vârtoapele	43c	1975	Mihăilă N., Giurgea P.
41	Alexandria, Zimnicea	49a, 49c	1977	Mihăilă N., Giurgea P.
42	Calafat	47a	1978	Mihăilă N.
43	Pleniţa	41c	1979	Mihăilă N., Giurgea P.
44	Piteşti	34d	1980	Mihăilă N., Giurgea P.
45	Ineu	16b	1981	Mihăilă N., Giurgea P.
46	Sânnicolau Mare	15c, 15d	1982	Mihăilă N., Giurgea P.
47	Jimbolia	23a, 23b	1983	Mihăilă N., Giurgea P.
48	Arad	16c	1985	Mihăilă N., Giurgea P.
49	Timişoara	24a	1987	Mihăilă N., Giurgea P.
50	Gătaia	24c*	1989	Mihăilă N., Giurgea P.

Table 5.6. Table of published Hydrological sheets scale 1:50000

Nr. crt.	Sheet	I.G.R.	Year of edition	Authors
1	Blăjani	131b	1987	Bandrabur T., Ghenea C., Ghenea Ana
2	Pogoanele *	149b	1987	Bandrabur T., Ghenea C., Ghenea Ana
3	Buzău *	131d	1987	Bandrabur T., Ghenea C., Ghenea Ana
4	Ruşeţu *	150a	1989	Bandrabur T., Ghenea C., Ghenea Ana
5	Zavoaia *		1989	Bandrabur T., Ghenea C, Ghenea Ana
6	Terpeziţa *	172a	1995	Enciu P., Enciu Mariana
7	Bălăciţa *	158c	1997	Enciu P., Enciu Mariana
8	Jirlău *	132c	1987	Ghenea C., Ghenea Ana, Bandrabur T.
9	Bălăceanu	132a	1987	Ghenea C., Ghenea Ana, Bandrabur T.
10	Zece Hotare*	40b	1987	Ponta G.
11	Zăvoaia *	150b	1988	Ghenea C., Bandrabur T.
12	Bărăganul *	151c	1989	Ghenea C., Ghenea A.
13	Filimon Sârbu *	132d	1990	Ghenea C., Munteanu T., Ghenea A., Munteanu E.
14	Padina *	150c	1991	Ghenea C., Ghenea A., Munteanu M., Munteanu E.
15	Traian *	150d	1991	Ghenea C.
16	Gârbovi *	149d	1992	Ghenea C., Ghenea A., Munteanu M., Munteanu E.
17	Viziru*	133c	1989	Giurgea P.
18	Glodeanu Sărat *	149a	1992	Giurgea P.
19	Fundulea *	165c	1996	Giurgea P.
20	Vaşilaţi *	177b	1997	Giurgea P.

21	Urziceni *	149c	1993	Giurgea P.
22	Bărcăneşti	165a	1994	Giurgea P.
23	Brăneşti	164d	1995	Giurgea P.
24	Şuţeşti *	132b	1990	Mihăilă N.
25	Slobozia *	166b	1991	Mihăilă N., Giurgea P.
26	Gheorghe Doja *	166a	1993	Mihăilă N.
27	Movila Miresii*	133a	1994	Mihăilă N.
28	Ţăndărei *	167a	1994	Mihăilă N.
29	Otopeni *	164a	1996	Mihăilă N.
30	Poenari Burchii *	148c	1997	Mihăilă N.
31	Afumaţi *	164b	1995	Mihăilă N.
32	Tărtăşeşti *	163b	1997	Mihăilă N.
33	Însurăţei *	151a	1990	Munteanu T., Giurgea P.
34	Munteni–Buzău *	165b	1994	Munteanu T., Munteanu E.
35	Brăila*	133b	1995	Munteanu T., Munteanu E.
36	Cioranii de Sus *	148b	1997	Munteanu T., Munteanu E.
37	Tufeşti *	151b	1997	Munteanu M., Munteanu E.
38	Istriţa *	131c	1998	Munteanu T.
39	Cioranii de Jos *	148d	1999	Munteanu T., Munteanu E., Mihăilă N.
40	Tichileşti *	133d	1996	Munteanu T., Munteanu E.
41	Vaşcău	55d	1986	Ponta G., Bleahu M., Panin Ş., Orăseanu I.
42	Pui *	107a	1988	Ponta G.
43	Pietroasa *	56a	1991	Ponta G.
44	Poiana Horea *	56b	1992	Ponta G.

II. Geothermal information

The formation of geothermal deposits on the territory of our country is the result of the presence of areas with high thermal flow, as can be seen from figure 1.4.8. [Negoita 1970, Cadere 1985, Milcoveanu 1984, Veliciu 1987, 1998]. The excess heat manifested by an increased thermal flow has its origin in magmatic subcrustal processes and is manifested due to regional characteristics related to the structure of the lithosphere. The presence of this thermal flow is mainly due to the thinning of the earth's crust in the intracarpathian basin, which caused the Mohorovicic discontinuity to be located at a depth of 20-25 km in the area of the Pannonian Depression, compared to the 30-35 km - the average depth at which this discontinuity is located in Europe [Paal 1975, Paraschiv 1975]. In figure 1.4.9 we have the geothermal map of exploration and geothermal perspectives. The main exploration In these areas, more than 200 completed wells were executed at depths between 800-3500 m, which demonstrated the existence of low (25-60°C) and medium enthalpy (60-120°C) geothermal resources [Airinei 1981]. But the antecedents are much older. The first geothermal well in Romania was drilled in 1885, in the resort of Felix, near Oradea. The well had a depth of 51 m, a flow rate of 195 l/s and a temperature at the mouth of the well of 490C. Then came the probes from Căciulata (1893 - 370C),

Oradea (1897 - 290C), Timişoara (1902 - 310C), etc. Geothermal deposits available to Romania are mainly located in the western part of the country [Negoiţă 1970, Bandrabur et al. 1982, Cadere 1985, Burchiu et al. 1998, Cohut and Bendea 2000]

PDF TABLICA

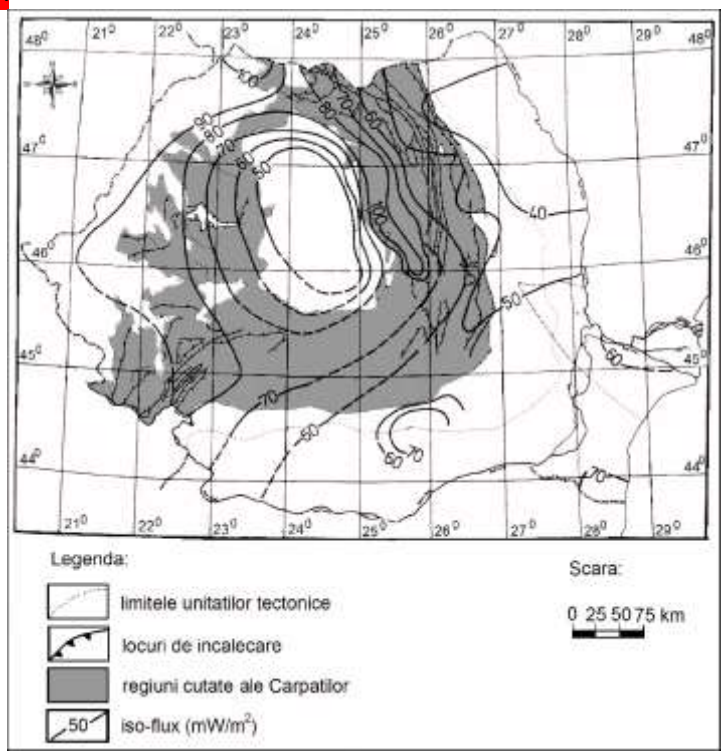


Figure 5.65. Distribution of geothermal flux in Romania [Negoita 1970, Cadere 1985, Milcoveanu 1984, Veliciu 1987, 1998]

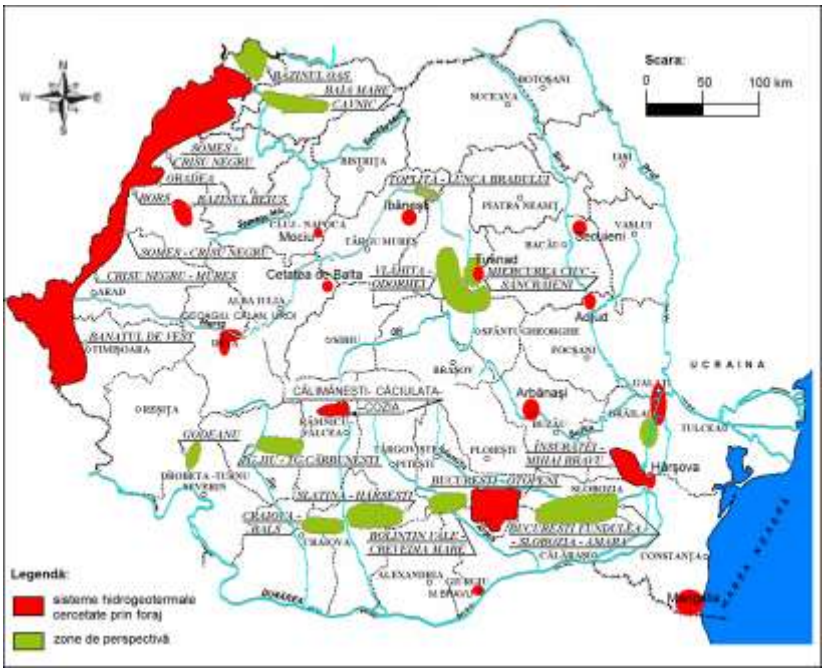


Figure 5.66. Geothermal drilling exploration and perspective zone [Negoiţă 1970, Bandrabur et al. 1982, Cadere 1985, Burchiu et al. 1998, Cohut and Bendea 2000]

5.4. Current energy cost comparison for residential and non-residential sector with estimated capital cost of drilling and equipment for shallow geothermal

In Romania, there are quite many companies that are energy suppliers (electricity and gas- the most used energy sources by residential and commercial customers). The list of electric energy producers and electricity suppliers can be found at https://arhiva.anre.ro/ro/info-consumatori/operatori-economici/energie-electrica1391006213/furnizare-catre-consumatori1391006442. The list of natural gas suppliers on the retail market can be found at https://arhiva.anre.ro/ro/info-consumatori/operatori-economici/gaze-naturale1391006232/lista-furnizorilor-de-gaze-naturale-pe-piata-cu-amanuntul. An analysis of the different fuel cost comparison for Romania is presented below.

Electricity
Residential: between 0,13 – 0,2 Euro (0,68 -1 RON) /kWh
Non-residential (commercial): between 0,2-0,261 Euro (1 -1,3 RON) /kWh

Gas
Residential: 0,062 Euro (0,31 RON) /kWh
Non-residential (commercial): 0,074 Euro (0,37 RON) /kWh
Conversion efficiency = 0,95 (condensing plant)
Residential real cost = 0,0652 Euro/kWh
Non-residential (commercial) real cost = 0,077 Euro/kWh

LPG
- $Density_{LPG}$ =0,508 kg / liter
- Caloric power = 45500 kJ / kg = 23114 kJ / liter
- Residential / Industrial: 0,7 Euro (3,5 RON) / liter
- Residential / Industrial: 0,108 Euro (0,54 RON) / kWh
- Conversion efficiency =0,9
- Residential / Industrial real cost: 0,12 Euro / kWh

Wood pellets
- Caloric power = 19000 kJ / kg
- Residential / Industrial: 0,24 – 0,266 EURO (1,2-1,33 RON) / kg
- Residential / Industrial: 0,054 Euro (0,266 RON) / kWh
- Conversion efficiency = 0,8
- Residential / Industrial real cost = 0,0675 Euro / kWh

Wood
- Cost = 100 – 120 Euro (500 – 600 RON) / m^3 = 0,1428 – 0,1714 Euro (0,714-0,857 RON) / kg
- $Density_{wood}$ = 700 kg / m3
- Caloric power = 15,000 kJ / kg
- Residential / Industrial cost: 0,034 – 0,042 Euro (0,171-0,205 RON) / kWh
- Conversion efficiency =0,75
- Residential / Industrial real cost = 0,045 – 0,056 Euro (0,225 – 0,28 RON) / kWh

Heat Pump

- **Soil-Water** - COP = 4; 0,25 kWh electric to produce 1 kWh thermic
- Residential cost = 0,0325 – 0,05 Euro (0,17 -0,25 RON) / kWh
- Industrial cost = 0,05 – 0,065 Euro (0,25 -0,325 RON) / kWh

- **Water-Water** - COP = 5; 0,2 kWh electric to produce 1 kWh thermic
- Residential cost = 0,026-0,04 Euro (0,136 -0,2 RON) /kWh
- Industrial cost = 0,04-0,0522 Euro (0,2 -0,26 RON) / kWh

Current Energy Cost Comparison for Residential and Non-Residential Sector

Analysis of up-to-date different fuel cost comparison in partner country for residential and commercial customers relevant to project development (electricity, natural gas, fuel oil, LPG) and installation of hybrid geothermal systems.

- **Electrical energy** (Figure 5.., Figure 5.., Figure 5.., Table 5.7.)

Source:https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics&oldid=629427#Electricity_prices_for_household_consumers

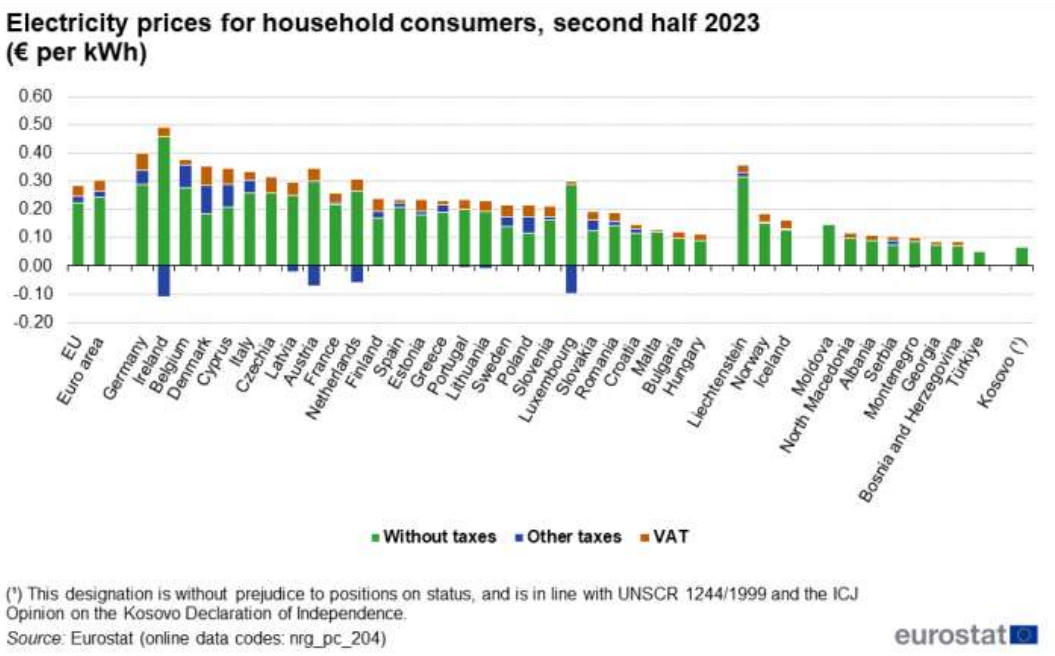


Figure 5.67. Electricity prices for household consumers, second half 2023

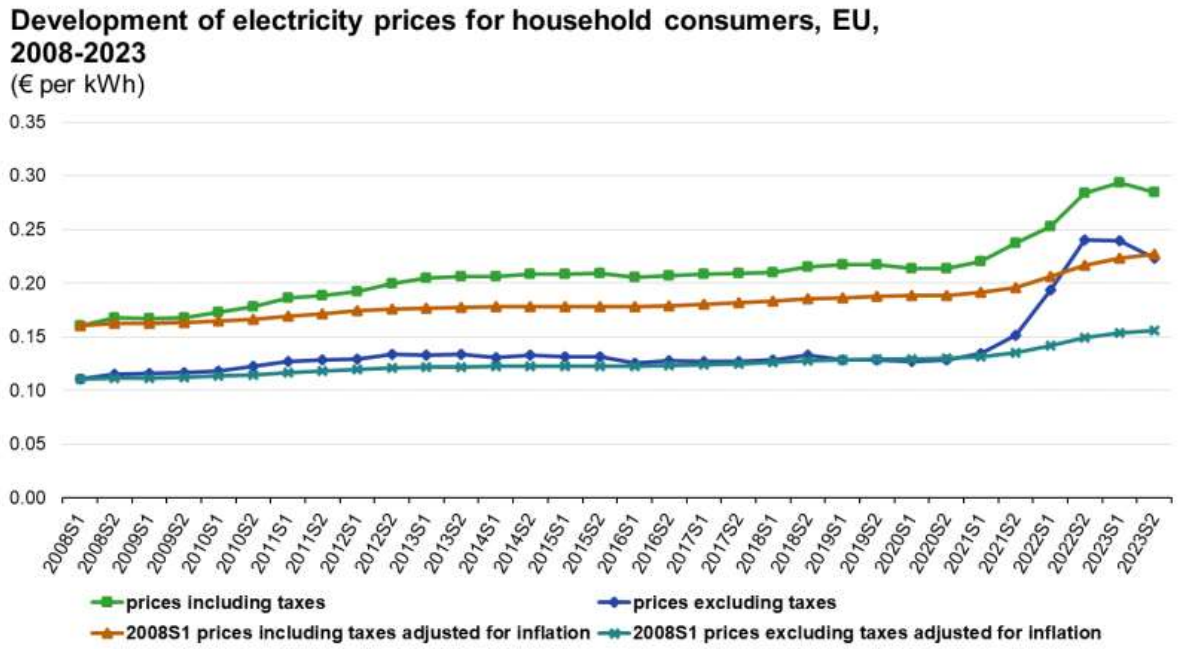
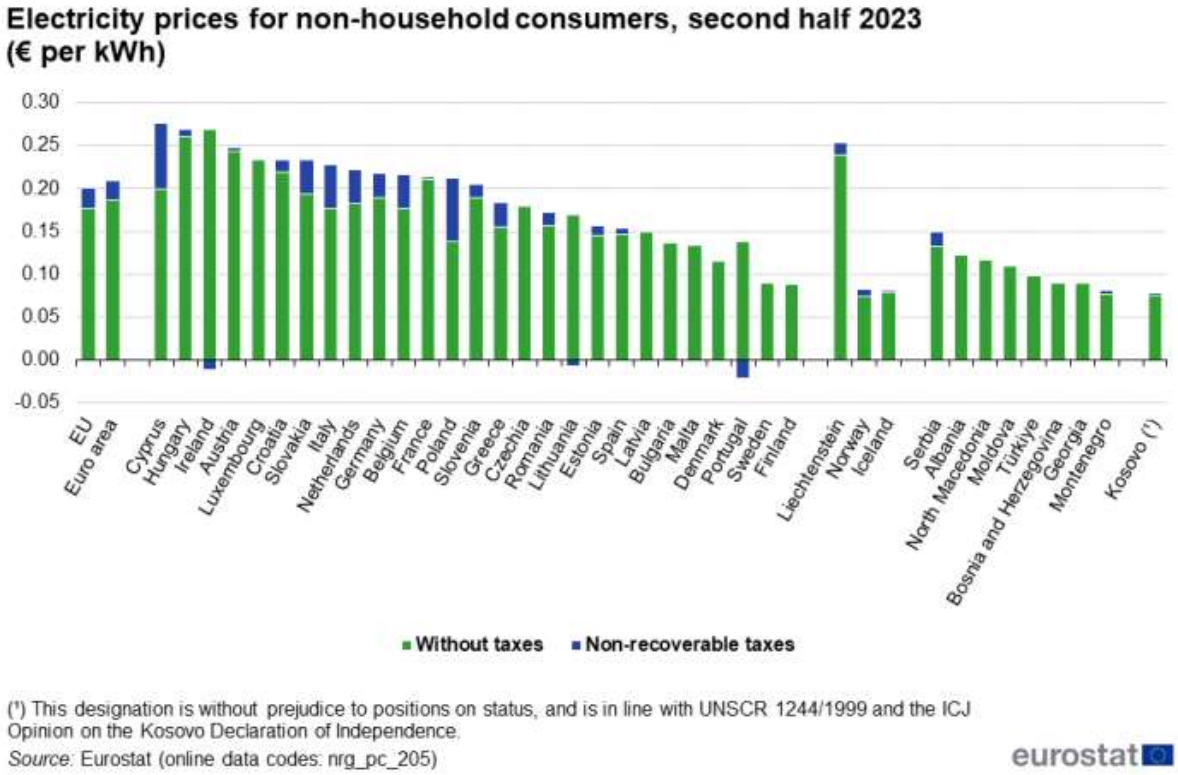


Figure 5.68. Development of electricity prices for households consumers, EU, 2008-2023



(*) This designation is without prejudice to positions on status, and is in line with UNSCR 1244/1999 and the ICJ Opinion on the Kosovo Declaration of Independence.

Source: Eurostat (online data codes: nrg_pc_205)

eurostat

Figure 5.69. Electricity prices for non-household consumers, second half 2023

Source: Emergency Ordinance 27/2022 with subsequent amendments (Ordonanta de urgenta 27/2022 cu modificarile ulterioare)

Table 5.7. Household and non-household prices

No.	Consumer/consumption category	Consumption period	Cost EURO/ (RON) / kWh (VAT included)
HOUSEHOLD CUSTOMERS			
1.	0-100 kWh	1.01.2023-31.03.2025	Max 0,136 (0,68)
2.	100-255 kWh	1.01.2023-31.03.2025	Max 0,16 (0,8)
3.	255-300 kWh	1.01.2023-31.03.2025	Max 0,26 (1,3)
NON-HOUSEHOLD CUSTOMERS AND PUBLIC INSTITUTIONS			
4.	85% from monthly consumption	1.01.2023-31.03.2025	0,2 (1,0)
5.	15% from monthly consumption	1.01.2023-31.03.2025	0,26 (1,3)

- **Natural Gas** (Figure 5.., Figure 5.., Figure 5.., Figure 5.., Table 5.8.)

Source: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Natural_gas_price_statistics

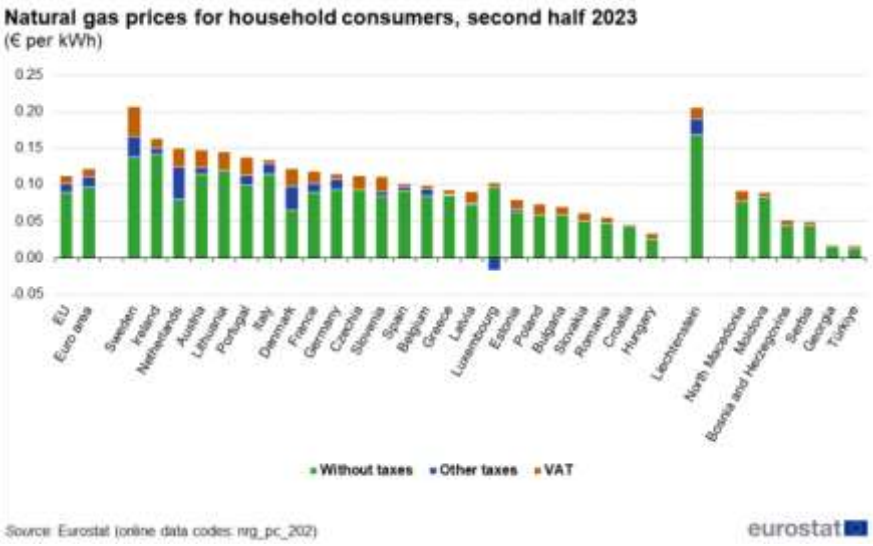


Figure 5.70. Natural gas prices for household consumers, second half 2023

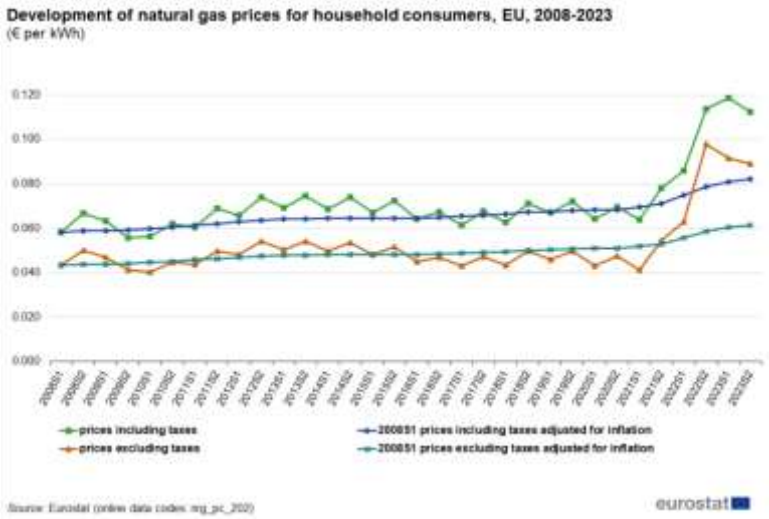


Figure 5.71. Development of natural gas prices for household consumers, EU, 2008-2023

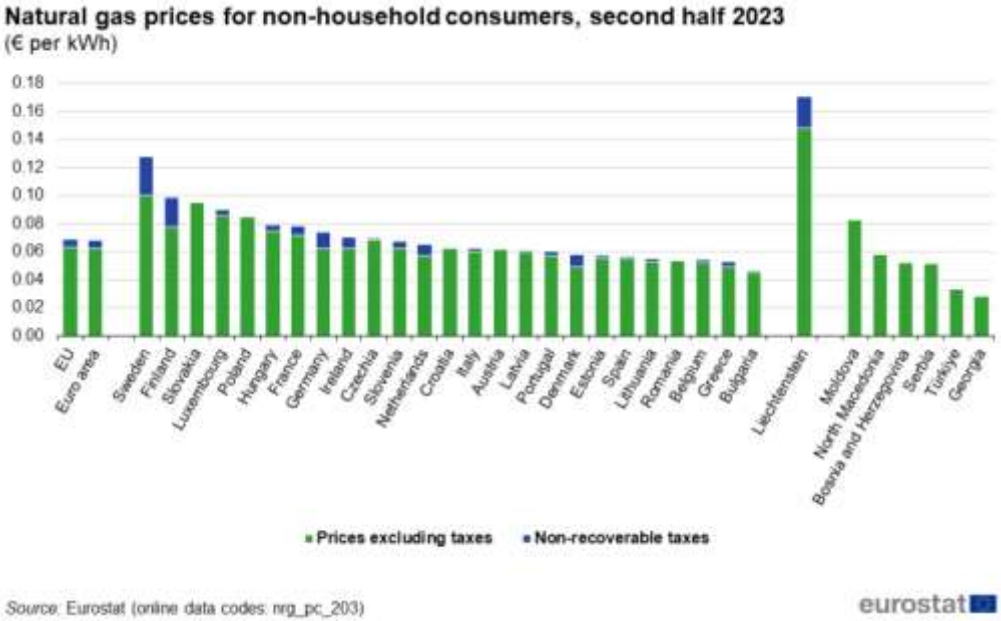


Figure 5.72. Natural gas prices for non-household consumers, second half 2023

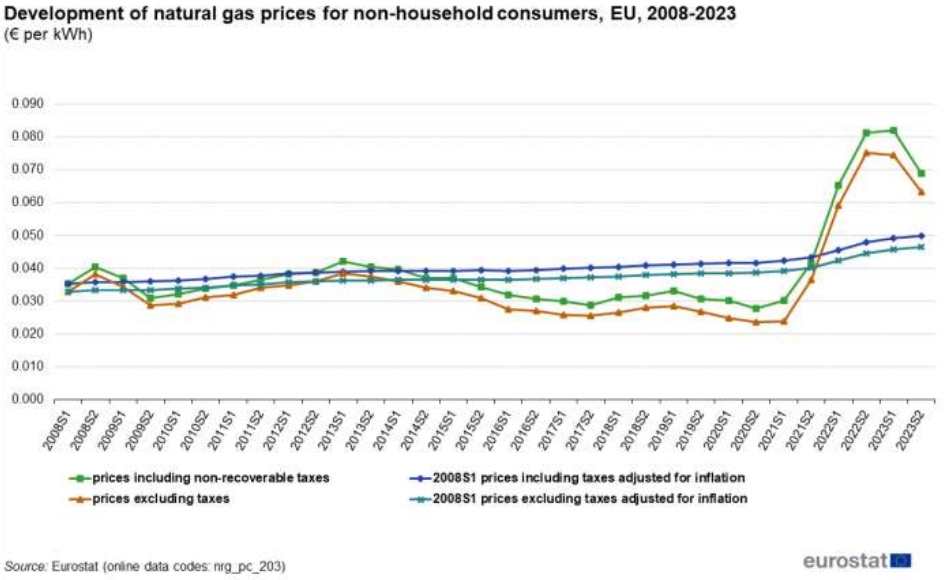


Figure 5.73. Development of natural gas prices for non-household consumers, EU, 2008-2023

Table 5.8. Natural gas prices for households and non-household consumers

No.	Consumer/consumption category	Consumption period	Cost EURO/ (RON) / kWh (VAT included)
HOUSEHOLD CUSTOMERS			
1.	0-100 kWh	1.04.2022-31.03.2025	0,062 (0,31)
NON-HOUSEHOLD CUSTOMERS AND PUBLIC INSTITUTIONS			
2.	50000 MWh	1.04.2023-31.05.2025	0,074 (0,37)

- **LPG** (Figure 5..)

Source: https://www.mylpg.eu/stations/romania/prices/
Medium Cost = 0,7 EUR (3,5 RON) / litre

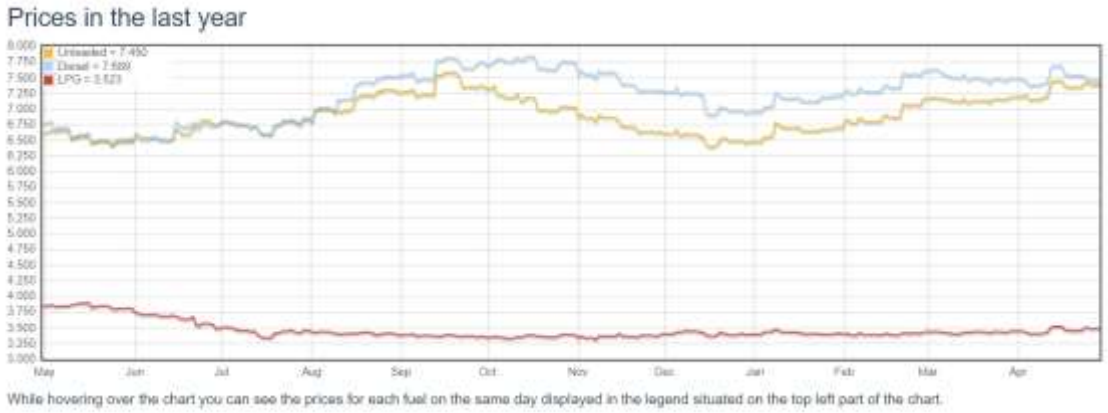


Figure 5.74. Prices of LPG in Romania

- **Wood pellets**

Cost = 0,24-0,266 EURO (1,2-1,33 RON) / kg
Sources: https://www.ameco.ro/produse/peletii-premium-ai-firmei-ameco
https://www.bio-combustibil.ro/pret-peleti-brichete/

- **Wood**

Cost = 12 - 80 EURO (60 - 400 RON) / m^3
Source: http://anunturi.rosilva.ro/disponibillemn

Estimated Capital Cost of Drilling, Completion and Equipment per meter for Shallow Geothermal Cost (BHE, water wells)

- Cost of drilling (water) = max 70 EURO (350 RON) / linear meter
- Cost of drilling (soil) = 30 EURO (150 RON) / linear meter

Source: https://www.trust-expert.ro/rezultate-configurator-pompa-caldura-220-250mp/

Connection with relevant up-to-date project examples with investment costs into shallow geothermal drilling and completion: http://ubeg.de/Regeocities/D2.2-EN%20overview%20shallow%20geothermal%20regulation%20Europe.pdf

Estimated range of capital equipment costs for typical residential and non-residential projects (mainly costs of heat pumps, boilers/furnaces in a typical household range cca. 10kW, and commercial cca. 100kW):

Heat pump between 8 kW – 128 kW
Costs: = 1800 – 27400 EURO (9000 – 137000 RON)
Source 1: https://www.trust-expert.ro/rezultate-configurator-pompa-caldura-220-250mp/
Source 2: https://termocasa.ro/

Source 3: https://www.nucleum.ro/pompe-de-caldura-sol-apa-apa-idm-austria-3727/Pompa-de-caldura-iDM-SW-Twin-TERRA-42-SOL-APA-APA-incalzire-racire-cu-doua-compresoare-Aplusplusplus.html

Boiler between 6 kW – 24 kW
Cost:= 640 – 1000 EURO (3200 – 5000 RON)
https://www.roinstalatii.ro/centrale-termice-pe-gaz-c75-p1?filtru=7[29]

Boiler 100 kW
Cost:= 4000 – 7000 EURO (20000 - 35000 RON)
https://www.arenainstalatiilor.ro/centrale-termice-pe-gaz-100-kw-c572-p1?filtru=26[501]

5.5. Environmental regulations and restrictions related to shallow geothermal development

The legislation that regulates the execution and exploitation of underground water:
Notification for the start of execution/Notification for commissioning, according to ORD. no. 873 of 21.02.2012 issued by M.M.P.;

- Water management approval according to ORD. no. 799 of 06.02.2012 issued by M.M.P.; ORDER. 662 of 28.06.2006 issued by M.M.G.A.;
- Technical consultancy, according to ORD. 662 of 28.06.2006 issued by M.M.G.A., CAP. II, art. 4.; - regarding natural persons, we will discuss whether TECHNICAL CONSULTATIONS will be issued for shallow drilling execution;
- Model of the well inventory sheet according to ORD. no. 799 of 06.02.2012 issued by M.M.P., APPENDIX.

For the execution of each borehole, it is necessary to obtain the following from the Water Basin Administration (A.B.A.) to which the area belongs to:

- a hydrogeological study prepared by companies accredited by the Ministry of Environment and Forests that will be expertized by I.N.H.G.A. Bucharest, and which will be the basis for obtaining the Approval of water management or the Notice of commencement of execution;
- for independent persons who request shallow drilling (phreatic) as a temporary source for household needs, until the expansion of the centralized water supply system in area, will be issued by A.B.A. an acceptance (consultancy) without requesting a hydrogeological study;
- the regulatory acts that are the basis for the execution of drillings, respectively their regulation, will be obtained in accordance with the legislation in force: Water Law 10711996 with the amendments and subsequent additions, Order 873/2012 for the approval of the Notification Procedure, Order 799/2012 for the approval of the Normative for the content of technical documentation substantiation necessary to obtain the water management approval and the water management authorization;
- at the completion of the drilling, you will have to draw up the Drilling Inventory Sheet drawn up in accordance with Order Tgg/2012, Annex T to the normative content.
- for exceptional situations, through the public relations office at A.B.A. you will receive necessary/additional information.

Phase 1 Projection :

- Preliminary hydrogeological study
- Expertise of the study by INHGA
  - Technical documentation for obtaining the drilling execution notification
- Obtaining the enforcement notice from the SGA

Phase II:

- Technical documentation for obtaining the Water Management Authorization
- Obtaining authorization from SGA
- Hydrogeological study regarding the dimensioning of the sanitary protection zones and the hydrogeological protection perimeter, according to H.G. no. 930/2005 and Order no. 1278/20,04.2011 for water supply drilling
- Expertise of the perimeter study Preparation of the technical book of the drilling

Town planning certificate / Construction permit

For the preparation of hydrogeological studies, the contact is:

- Romanian Waters: https://www.rowater.ro/default.aspx
- https://apepaduri.gov.ro/lista-institutiilor-publiceprivate-specializate-in-elaborarea-documentatiilor-pentru-fundamentarea-solicitarii-avizului-de-gospodarire-a-apelor-si-a-autorizatiei-de-gospodarire- of-certificated-waters-conf/

From the point of view of (underground) waters, Romania is divided into 11 Water Basin Administrations (Figure 5..).

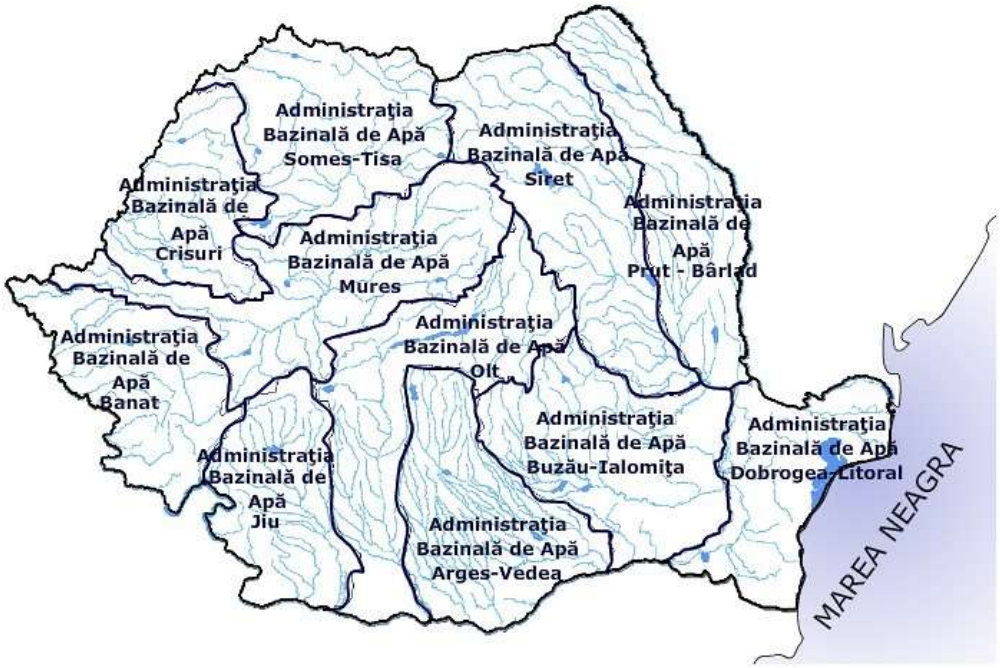


Figure 5.75. Water Basin Administrations of Romania

Regarding the area where the investment / drilling is located, one of the institutions stated on the Figure 5.75. is to be contacted.

6 Country status report for Serbia

6.1. Introduction to shallow geothermal energy utilization

Serbia is a landlocked country located in Southeast Europe, on the Balkan Penninsula (Figure 6.1.). Total country area is 8 499 km^2, in 2022 Serbia had a population of 6.65 millions (excluding Kosovo).

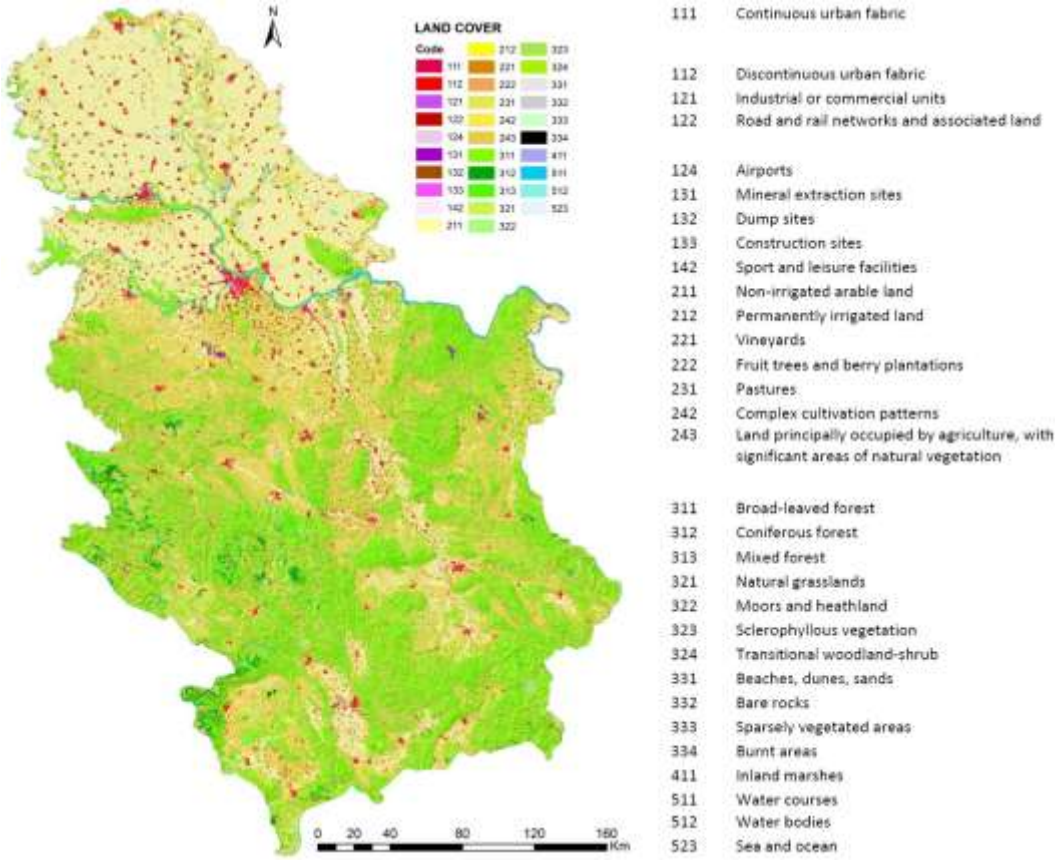


Figure 6.1. Land cover map of Serbia [1]

Serbia has a continental climate, which is to the extent changing from the north to the south. The north is characterized as continental with cold, dry winters and hot, humid summers. Central Serbia is the warmest and most humid part of the country (Figure 6.2.). The south is closer to Mediterranean climate, with warm, dry summers and autumns (Figure 6.3.), and wetter winters often with high snow. Also, regardless of location, the climate in Serbia is not marked by extreme weather conditions.

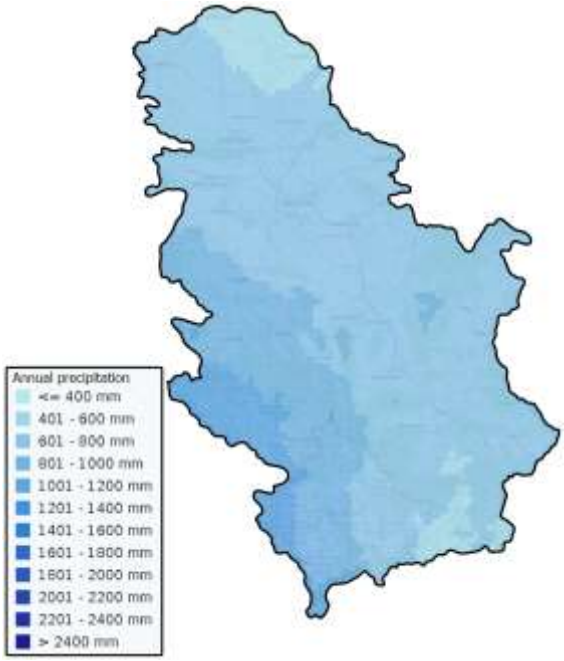


Figure 6.2. Annual precipitation [2]

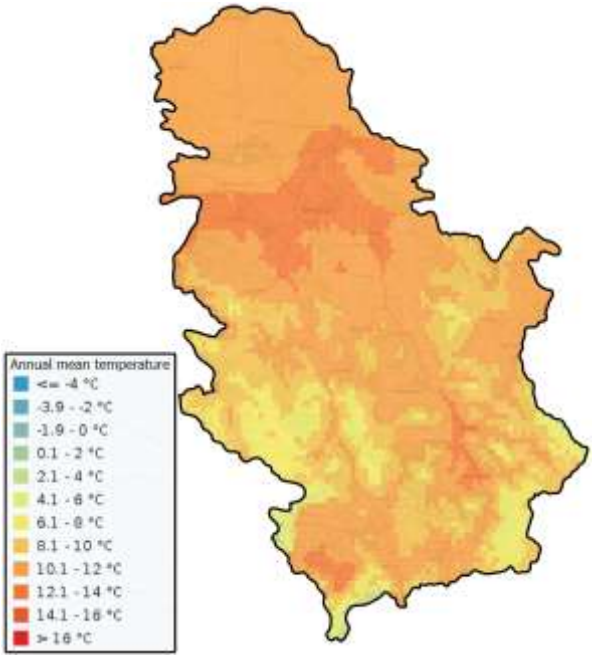


Figure 6.3. Annual mean temperature [2]

As stated in [3], the exploration of the geothermal potential in Serbia dates back to the first half of the 19th century. Modern research of geothermal energy started between the two world wars in spas, but the first systematic evaluation was conducted in 1975.

Figure 6.4. Pedological maps of Yugoslavia

The same authors noted that the "golden age" of geothermal research occurred between 1975 and 1988, marked by the construction and operation of numerous geothermal wells. However, this progress stalled during the economic crisis caused by political instability in the 1990s. Despite this, many geothermal energy projects and studies have continued. Through these efforts, the geothermal potential for heating in the Srem and Mačva districts (including Sremska Mitrovica, Loznica, Šabac and

Bogatić), Jošaničká Banja in the Municipality of Raška and Vranjska Banja were utilised. Also, a register of geothermal resources for Belgrade was created and the Geothermal Atlas of AP Vojvodina was published.

Golusin et al. [4] gave similar historical review, authors noted that significant knowledge of geothermal potential began to accumulate since 1949. Between 1969 and 1996, 73 wells were drilled, with a total depth of 62,678.60 meters. The most intensive exploration was in the 1980s, with 45 wells reaching a combined depth of 34,840 meters, representing about 56% of all drilling efforts during this period.

It is important to note that the term "geothermal energy" in the previous paragraphs refers to "deep geothermal" energy, a resource that Serbia is relatively rich in. "Shallow geothermal" or "subgeothermal" or "low enthalpy geothermal energy" has not received much attention from the scientific community or the industrial/commercial sector during the period under review. Only in the last 20 years has shallow geothermal energy begun to attract significant attention from professionals and the public.

State of the field of deep geothermal energy in Serbia

Geological structures of the territory of Serbia are based on geotectonic units (Figure 6.5.). Generally, the following units are identified: Pannonian Basin in the north, Carpatho-Balkanides from east to west, Serbo-Macedonian Massif, Vardar Zone, and the Dinarides. Based on the terrain concept, the central part of the Balkan peninsula and the central part of Serbia are further subdivided into different units [5].

Figure 6.5. Geotectonic units of Serbia [3]

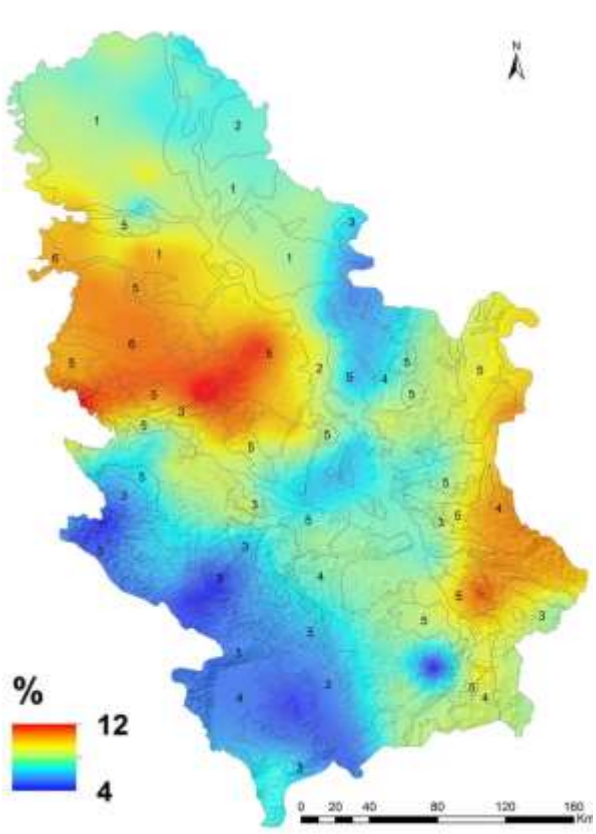


Figure 6.6. Relative mean annual moisture content in the topsoil (0-40 cm) for period 2021 - 2050 [1]

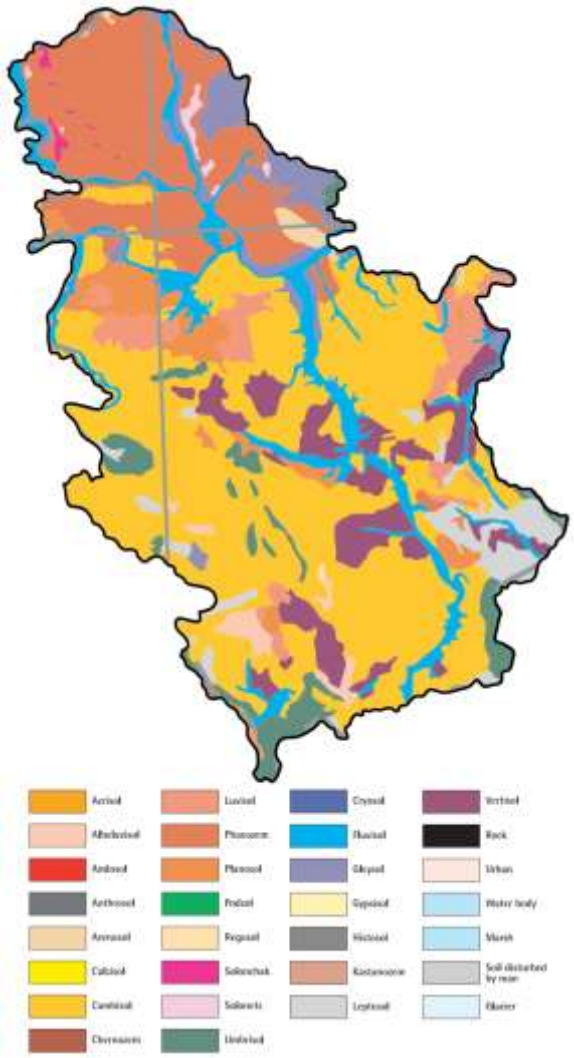


Figure 6.7. Soil map of Serbia [5]

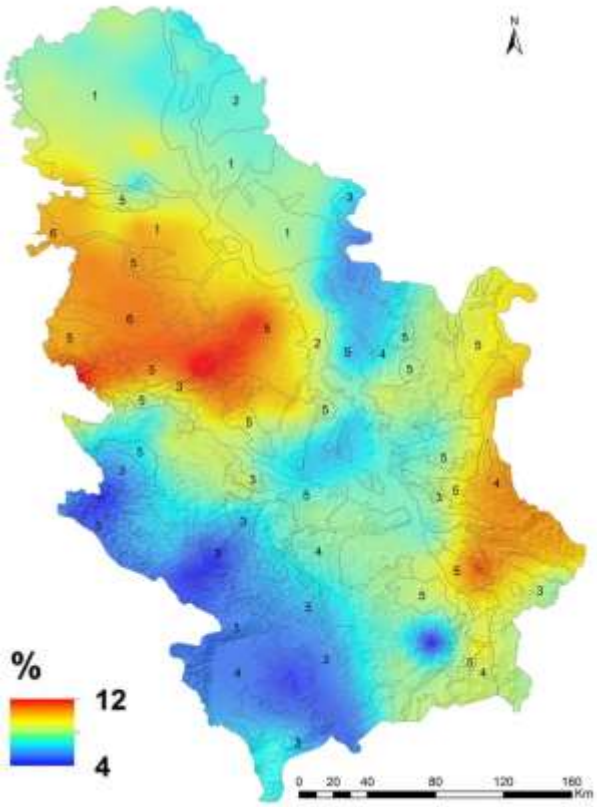


Figure 6.8. Relative mean annual moisture content in the topsoil (0-40 cm) for period 2021 - 2050 [1]

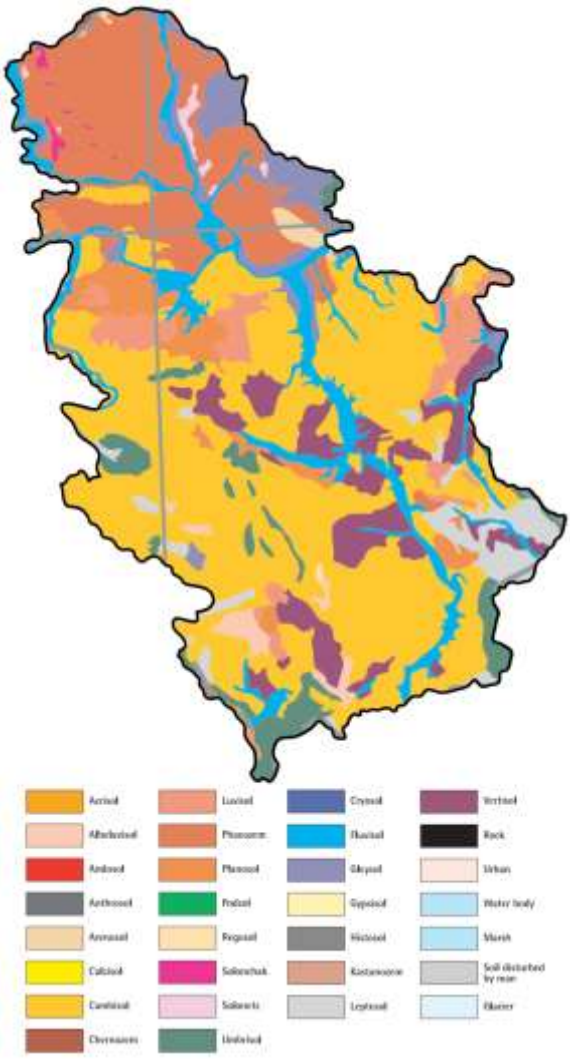


Figure 6.9. Soil map of Serbia [6]

Hydrogeological regions of Serbia [5 - 7] are following geotectonic units: Pannonian Basin on the north, then from east to west: Dacian basin region, the Carpatho-Balkanides, the Serbian crystalline core region, the Šumadija-Kopaonik-Kosovo region, and the Internal Dinarides region.

The Province of Vojvodina has significant geothermal potential as part of the Pannonian Basin. Geothermal potential of Pannonian basin is well known [8 – 12]. In some parts of the Pannonian Basin, the Neogene complex is composed of sandstone, shale, marls, limestone, clay, sand, and gravel with depth over 3 km. Magmatic and volcanic rocks can be found here as well, alongside their pyroclastic equivalents [13].

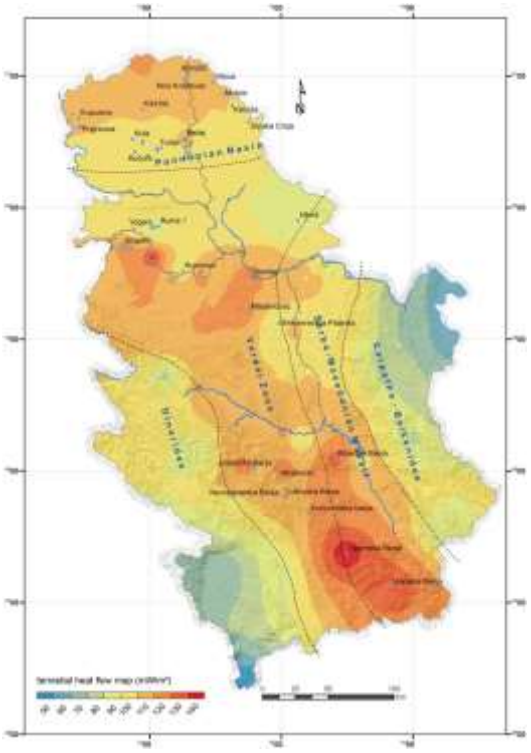


Figure 6.10. Terrestrial Heat Flow Density map of Serbia [13, 14] with boreholes/springs with water temperature higher than 50 °C [15]

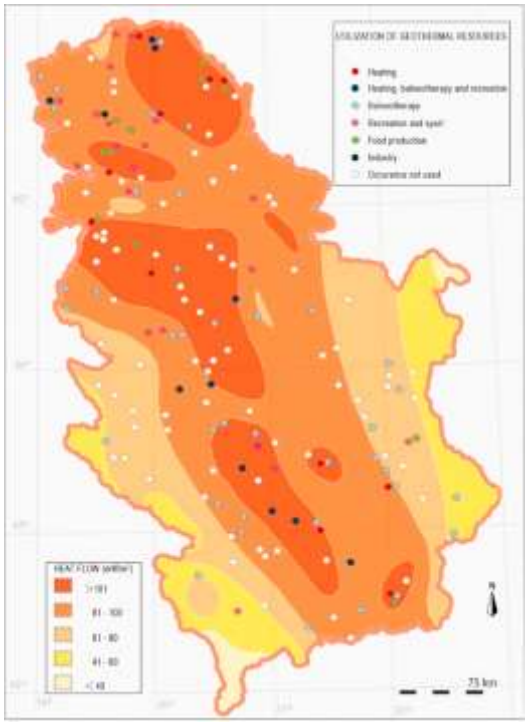


Figure 6.11. Map of heat flow density and locations of major geothermal resources of Serbia [3]

Geothermal resources are also present in other Neogene basins in Serbia. A particularly productive aquifer is located in Mačva (western Serbia) [16], where highly karstified Triassic limestone (karst aquifer) is located under deep Neogene and Quaternary sediments, with a maximum thickness of up to 1500 meters. The paleo relief is composed of paleogranite, which explains the thermal anomaly in this area. The heat flow in Mačva reaches up to 120 mW/m² [16, 17], which makes this part of Serbia very productive for the exploitation of geothermal energy (**Error! Reference source not found.**12.). The highest recorded temperature is in Bogatić (80°C). In addition to high temperatures, a significant amount of groundwater can be extracted in this region (245 l/s from five wells) [16].

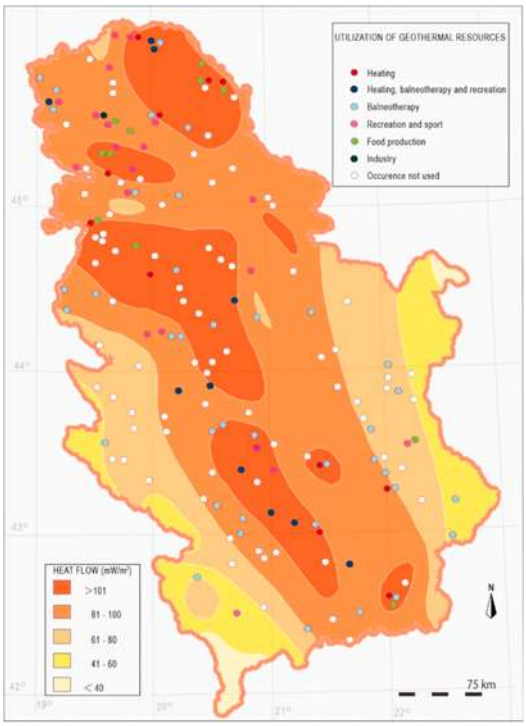


Figure 6.12. Map of heat flow density and locations of major geothermal resources of Serbia [3]

According to the classification of geothermal resources [18], thermal waters in Serbia are of low-enthalpy resources water (<90°C); however, water in Vranjska Banja is the only intermediate-enthalpy resource (90-150°C), and possibly suitable for the production of electricity.

Based on the available measurement data, the average geothermal heat flow density in Serbia ranges from 80 mW/m^2 to 120 mW/m^2, which is above Europe's average (60 mW/m^2) [34]. The highest values have been observed in the Pannonian Basin (>100 mW/m^2), Vardar Zone and in the Serbian-Macedonian Massif, while the lowest values have been recorded in the Mesian Platform and the southwestern part of Serbia (**Error! Reference source not found.**.).

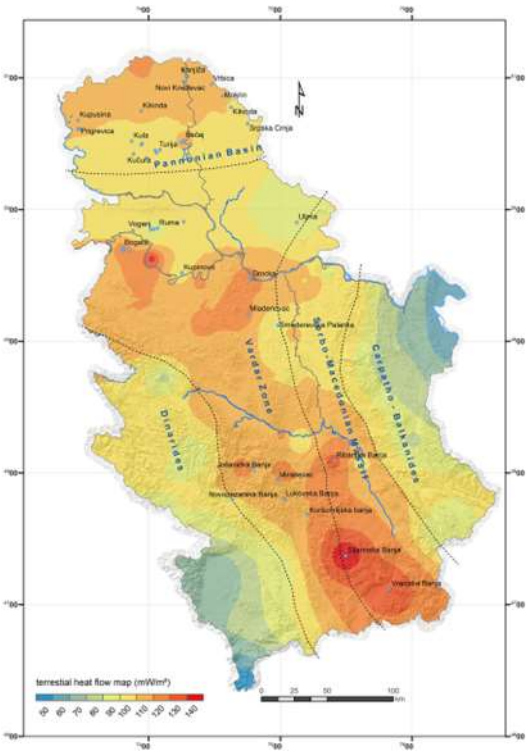


Figure 6.13. Terrestrial Heat Flow Density map of Serbia [13, 14] with boreholes/springs with water temperature higher than 50 °C. [5]

Geothermal resources are mostly of traditional use in Serbia, for balneotherapy and in swimming pools. Water with positive balneological effect is classified as healing water based on its physical and chemical properties. In addition, geothermal resources are used for heating the spa objects, medical centres, and hotels. However, many of these systems are worn-out and work partially.

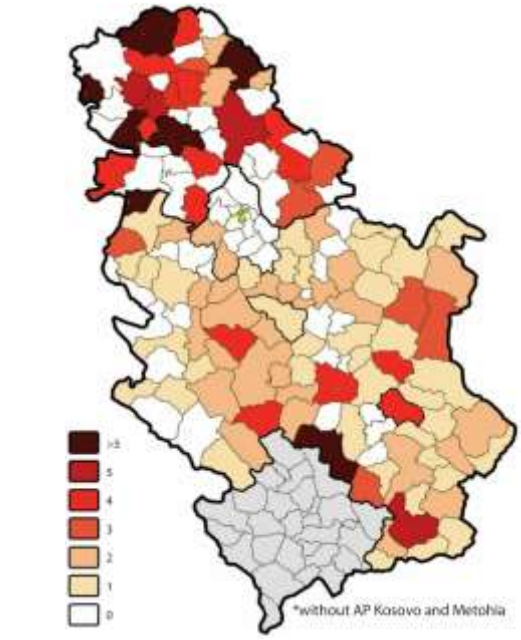


Figure 6.14. Number of installed geothermal wells [19]

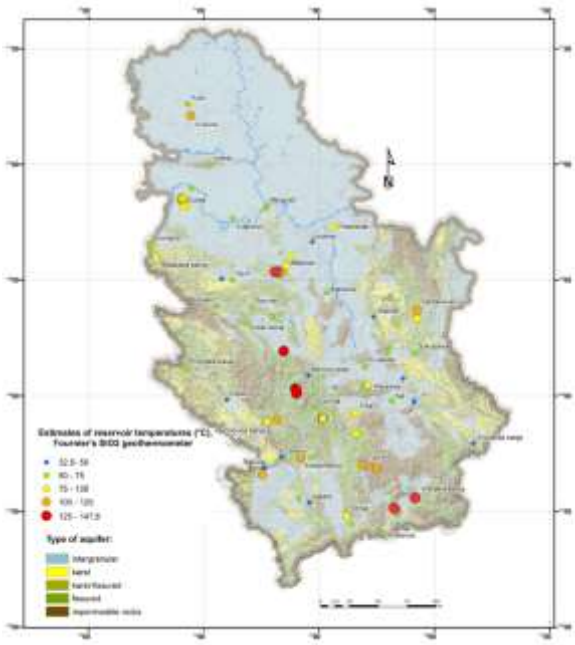


Figure 6.15. Estimated reservoir temperatures

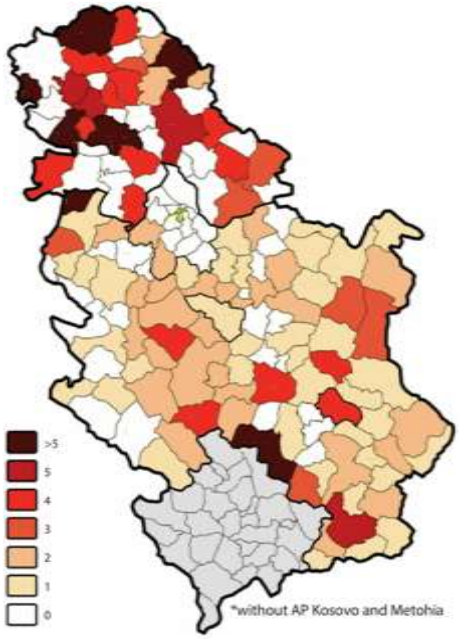


Figure 6.16 Number of installed geothermal wells [19]

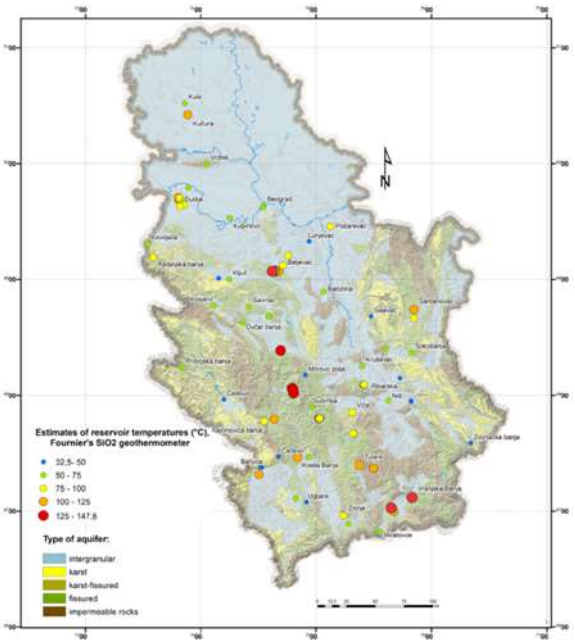


Figure 6.17. Estimated reservoir temperatures

Analyzing the use of geothermal energy in Serbia, the total installed heat capacity in 2010 was 100.8 MW, with an annual use of geothermal energy of 1410 TJ/year and a capacity factor of 0.44 [16]. By 2015, the total installed capacity had increased to 104.55 MW, with an annual consumption of 1714 TJ/year and a capacity factor of 0.52 [20]. As of 2019, the total installed thermal capacity reached 111

MW, and the energy consumption was 1507 TJ/year, with a capacity factor of 0.53. The flow of all wells and springs is up to 911 l/s, and the most promising locations are Vranjska Banja (approx. 100 l/s), Bogatić (84 l/s), Debrc (75 l/s), Sokobanja (75 l/s), and Pribojska (58 l/s).

Pešić and others. [3] state that the available borehole studies up to 3 km deep revealed 60 convective hydrogeothermal systems in Serbia: 30 in the Dinarides (Inner Dinarides and Vardar zone), 20 in the Carpatho-Balkanid area, five in the Serbian-Macedonian massif, and five in the Pannonian basin.

The same authors continue: Natural and artificial sources of thermal water have been identified in more than 60 municipalities, with water temperature above 60°C in six municipalities (Vranje, Šabac, Kuršumlija, Raška, Medveđa, Apatin). The highest temperature was measured at the springs of Vranjska Banja (96°C), which are among the hottest in Europe. In addition, other sources with high temperatures are Jošanička Banja (78.5°C), Sijarinska Banja (71°C), Kuršumlijska Banja (59°C) and Novopazarska Banja (54°C).

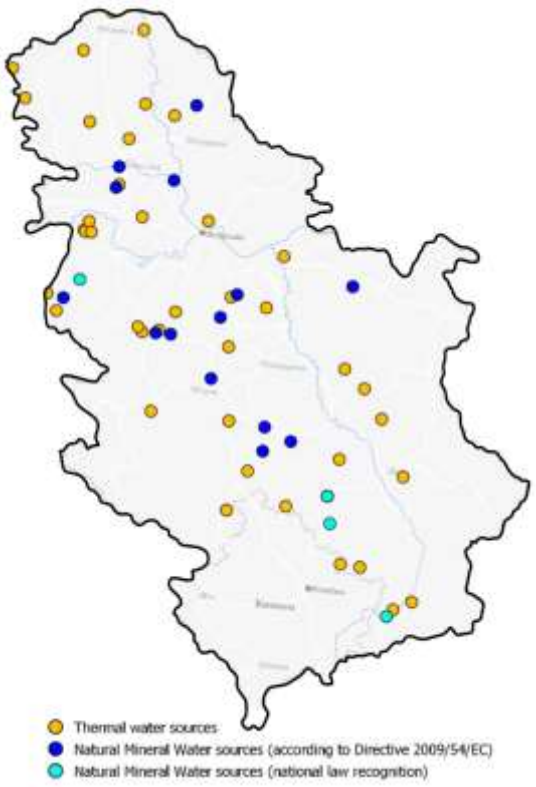


Figure 6.18. Thermal waters and natural mineral waters wells according to EU HOVER Project [21]

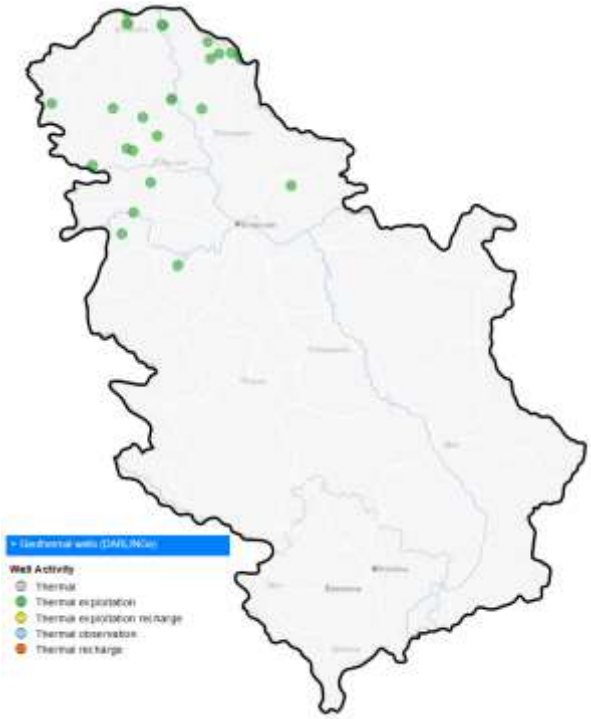


Figure 6.19. Geothermal wells according to [22]

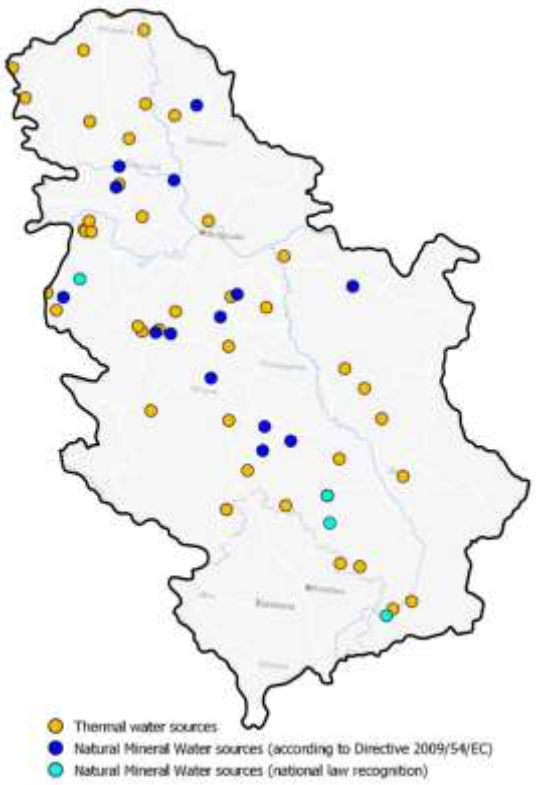


Figure 6.20. Thermal waters and natural mineral waters wells according to EU HOVER Project [21]

Figure 6.21. Geothermal wells according to [22]

All natural springs have a flowing well yield of around 4000 l/s, while 62 drill holes in Vojvodina Province have a yield of 550 l/s. The average flowing well yield from the existing springs and wells is up to 20 l/s. At several sites, the well yield exceeds 50 l/s (Bogatić, Kuršumlija, Pribojska Banja and Niška Banja), and only at one site it is over 100 l/s (Banja Koviljača).

As far as primary energy production is concerned, Serbia is known for decades-long domination of energy obtained by burning coal, mostly of poor quality (lignite). Regardless of the potential, the share of GTE from geothermal springs in primary energy production is negligible. Also, the average share of RES usage in Serbia for period 2010-2019 was 9,18%.

Table 6.1. Utilization of geothermal energy in Serbia in 2019 [20]

Purpose	Number of locations or units	Installed thermal power (MWt)	Produced heat (TJ/year)
Individual space heating	-	12.818	245.119
District heating	21	41.484	503.053
Greenhouse heating	8	5.06	89.329
Fish farming	1	1.653	22.854
Animal farming	3	3.947	85.854
Agricultural drying	1	0.967	26.868
Bathing and swimming	49	33.773	628.581
Geothermal heat pumps	771 units	15.6	124.413
Total	1005 units	115.302	1726.141

According to the data from 2009 [4] there are 160 long holes that are exploiting the water at a temperature around 60°C (140 F) and their heat power reaches 160 MJ/s. It was stated that adequate exploitation of existing and new geothermal sources yearly would save about 500,000 tons of fossil fuels which is proportional to the 10% of today's heating system.
The database [5] contains 293 geothermal records (springs, boreholes) registered at 160 locations, with groundwater temperatures in the range between 20°C and 111°C. The maximum expected temperature of the reservoir is 146°C according to the use of a SiO_2 geothermometer.

State of the field of shallow geothermal energy in Serbia

As shown in [23] the ground waters of modest temperature levels, between 10 and 30 °C are frequently found in the diverse regions of Serbia as well throughout Balkan Peninsula. Such, sub-geothermal ground waters obviously have certain energy potential but, due to their low temperatures, cannot be used for direct heating purposes.

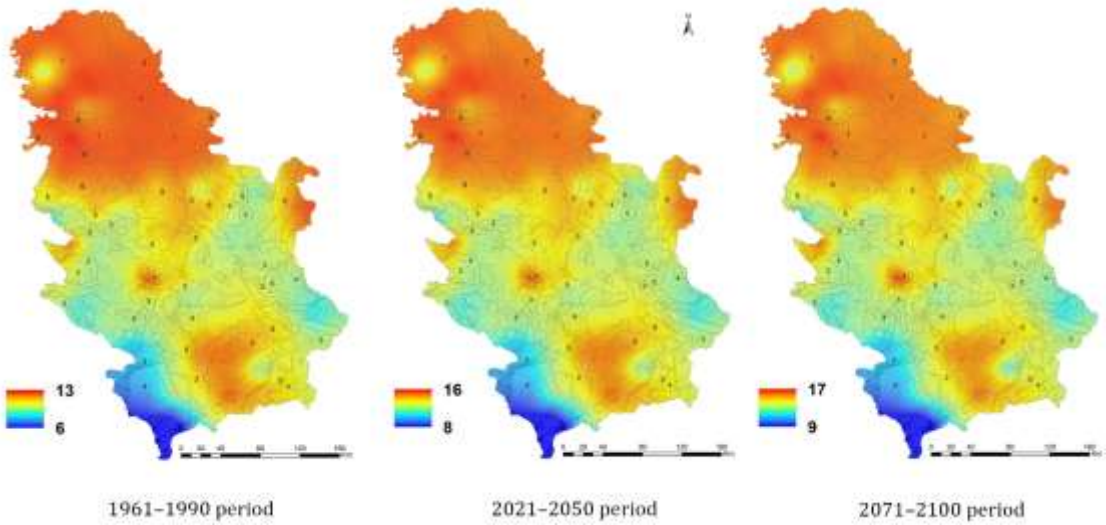


Figure 6.22. Soil temperature in the topsoil (0 - 40 cm) with predictions for the future considering climate changes [1]

The main parameter for defining the geothermal potential of an area is the heat flow density. The average heat flow density of the Earth is 82 mW/m² [24]. In Serbia, the heat flux density exceeds 100 mW/m² [25] in the Pannonian Basin, the Serbian-Macedonian Massif and the Vardar Zone. Furthermore, the Pannonian Basin has a mean heat flow value of about 100 mW/m², in the range of 50 to 130 mW/m² [8]. These values in Serbia are higher than the average in continental Europe [25].

The use of heat pumps has been increasing in recent years, most often for heating and cooling buildings, residential complexes and business premises. These systems use low underground water temperatures, up to 30°C, for their work. In 2018, 100 heat pumps were installed in Serbia, with a total capacity of 15.59 MW, which produce 34.37 GWth/year [20].

According to the data from 2022 [3] there are:

- 66 projects in Serbia with direct use of geothermal energy;
- and 1005 geothermal heat pump units.

Their power varies between 10 kW and 40 kW and they operate on average 2860 full load hours per year.

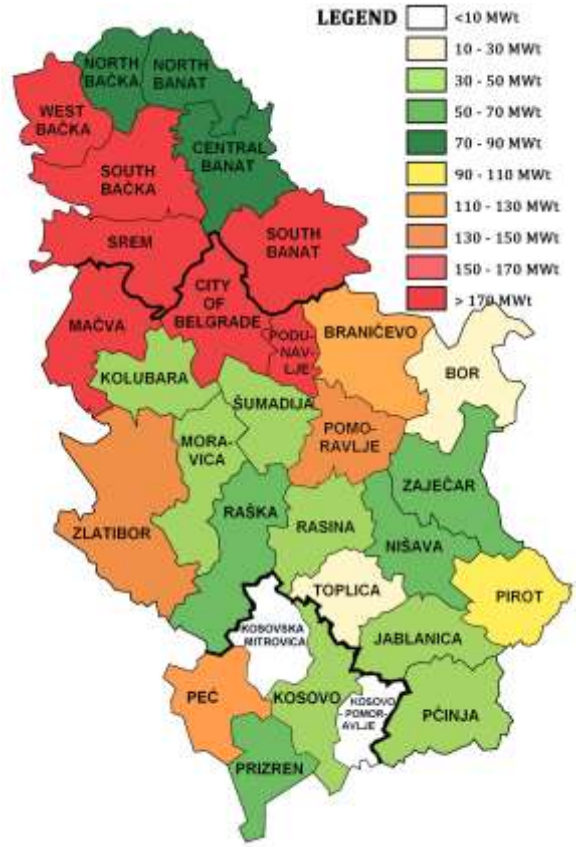


Figure 6.23. Division of Serbia into districts with estimated district capacities in the field of shallow geothermal (sub-geothermal) energy

[26]

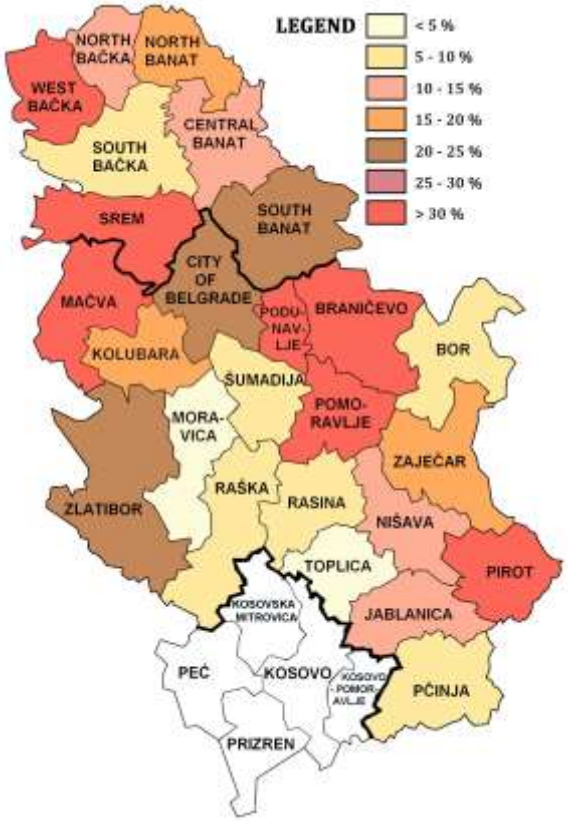


Figure 6.24. The percentage of the total area of residential units at the district level that could be heated by shallow geothermal energy

[26]

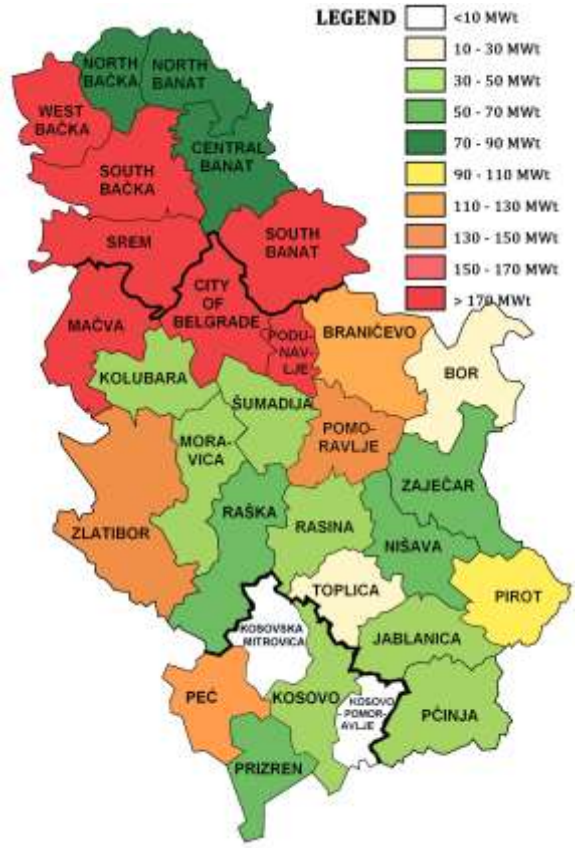


Figure 6.25. Division of Serbia into districts with estimated district capacities in the field of shallow geothermal (sub-geothermal) [26]

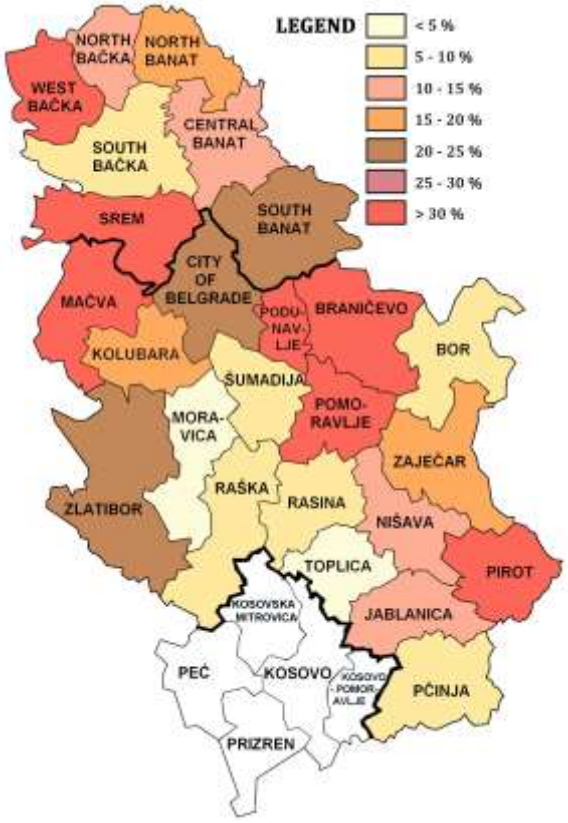


Figure 6.26. The percentage of the total area of residential units at the district level that could be heated by shallow geothermal energy [26]

Table 6.2. Expected capacities in the field of shallow geothermal (sub-geothermal) energy per district in Serbia [26] updated with 2022 Census of Population numbers [27]

NORTH BAČKA DISTRICT	
Area	1 784 km^2
The capital of the district	Subotica
Number of municipalities	3
Population	160 163
Population density	89.7 per km^2
Number of cities / number of apartments / total area of apartments	3 / 53 406 / 3 979 633
Number of rural settlements / number of residential buildings / total area	42 / 30 977 / 2456 008

	Source	Flow Q (l/s)	Temperature T °C	Temperature difference ΔT °C	Potential thermal power MWt
In the water supply system	Basic aquifer complex	755	15	11	37.4
	Total				**37.4**
Outside of the water supply system	Basic aquifer complex	995	15	11	45.9
	Total				**45.9**
	Total				**83.3**

SOUTH BAČKA DISTRICT	
Area	4 016 km^2
The capital of the district	Novi Sad
Number of municipalities	11
Population	607 178
Population density	151.2 per km^2
Number of cities / number of apartments / total area of apartments	16 / 199 833 / 13 654 540
Number of rural settlements / number of residential buildings / total area	61 / 73 490 / 6429 082

	Source	Flow Q (l/s)	Temperature T °C	Temperature difference ΔT °C	Potential thermal power MWt
In the water supply system	Alluvium	908	12	8	30.5
	Basic aquifer complex	537	15	11	24.8
	Neogene	189	17	13	10.3
	Total				**65.6**
Outside of the water supply system	Alluvium	2724	12	8	91.5
	Basic aquifer complex	698	15	11	32.2
	Neogene	280	17	13	15.3
	Total				**139**
	Total				**204.6**

NORTH BANAT DISTRICT	
Area	2 329 km^2
The capital of the district	Kikinda
Number of municipalities	6
Population	117 896
Population density	50.6 per km^2
Number of cities / number of apartments / total area of apartments	7 / 41 954 / 3 331 633
Number of rural settlements / number of residential buildings / total area	43 / 25 694 / 2 063 592

		Flow	Temperature	Temperature difference	Potential thermal power
	Source	**Q (l/s)**	**T °C**	**ΔT °C**	**MWt**
In the water supply system	Basic aquifer complex	779	15	11	35.9
	Neogene	8	17	13	0.4
	Total				**36.3**
Outside of the water supply system	Basic aquifer complex	991	15	11	45.8
	Neogene	8	17	13	0.44
	Total				**46.2**
	Total				**82.5**

CENTRAL BANAT DISTRICT	
Area	3 256 km^2
The capital of the district	Zrenjanin
Number of municipalities	5
Population	157 711
Population density	48.4 per km^2
Number of cities / number of apartments / total area of apartments	4 / 40 325 / 3 195 115
Number of rural settlements / number of residential buildings / total area	51 / 43 122 / 3 576 784

		Flow	Temperature	Temperature difference	Potential thermal power
	Source	**Q (l/s)**	**T °C**	**ΔT °C**	**MWt**
In the water supply system	Basic aquifer complex	648	15	11	29.9
	Total				**29.9**
Outside of the water supply system	Alluvium	400	12	8	13.4
	Basic aquifer complex	950	15	11	43.9
	Total				**57.3**
	Total				**87.2**

SOUTH BANAT DISTRICT	
Area	4 245 km^2
The capital of the district	Pančevo
Number of municipalities	8
Population	260 244
Population density	61.3 per km^2
Number of cities / number of apartments / total area of apartments	10 / 71 950 / 5 429 216
Number of rural settlements / number of residential buildings / total area	84 / 54 410 / 4 648 298

		Flow	Temperature	Temperature difference	Potential thermal power
	Source	**Q (l/s)**	**T °C**	**ΔT °C**	**MWt**
In the water supply system	Alluvium	396	12	8	13.3
	Basic aquifer complex	557	15	11	25.7
	Neogene	51	17	13	2.8
	Total				**41.8**
Outside of the water supply system	Alluvium	2 516	12	8	84.5
	Basic aquifer complex	822	15	11	37.9
	Neogene	76	17	13	4.0
	Total				**126.4**
	Total				**168.2**

SREM DISTRICT	
Area	3486 km^2
The capital of the district	Sremska Mitrovica
Number of municipalities	7
Population	282 547
Population density	81 per km^2
Number of cities / number of apartments / total area of apartments	7 / 53 136 / 4 205 704
Number of rural settlements / number of residential buildings / total area	102 / 79 270 / 6 058 744

		Flow	Temperature	Temperature difference	Potential thermal power
	Source	**Q (l/s)**	**T °C**	**ΔT °C**	**MWt**
In the water supply system	Alluvium	160	12	8	5.4
	Basic aquifer complex	340	15	11	15.7
	Neogene	296	17	13	16.2
	Total				**37.3**
Outside of the water supply system	Alluvium				209.0
	Basic aquifer complex				25.4
	Neogene				16.2
	Total				**250.6**
	Total				**287.9**

MAČVA DISTRICT	
Area	3 268 km^2
The capital of the district	Šabac
Number of municipalities	8
Population	265 377
Population density	81.2 per km^2
Number of cities / number of apartments / total area of apartments	2 / 39 015 / 2 588 457
Number of rural settlements / number of residential buildings / total area	223 / 95 682 / 6 808 986

		Flow	Temperature	Temperature difference	Potential thermal power
	Source	**Q (l/s)**	**T °C**	**ΔT °C**	**MWt**
In the water supply system	Alluvium	1078	12	8	36.2
	Karst	30	11	7	0.9
	Total				**37.1**
Outside of the water supply system	Alluvium	6798	12	8	228.4
	Karst	180	11	7	5.3
	Total				**233.7**
	Total				**270.8**

KOLUBARA DISTRICT	
Area	2 474 km^2
The capital of the district	Valjevo
Number of municipalities	6
Population	154 497
Population density	62.4 per km^2
Number of cities / number of apartments / total area of apartments	
Number of rural settlements / number of residential buildings / total area	

		Flow	Temperature	Temperature difference	Potential thermal power
	Source	**Q (l/s)**	**T °C**	**ΔT °C**	**MWt**
In the water supply system	Alluvium	85	11	7	2.5
	Karst	267	10	6	6.7
	Total				**9.2**
Outside of the water supply system	Alluvium	130	11	7	2.8
	Karst	1 050	10	6	26.5
	Karst fissures	100	10	6	2.5
	Total				**32.8**
	Total				**42.0**

ZLATIBOR DISTRICT	
Area	6 140 km^2
The capital of the district	Užice
Number of municipalities	10
Population	254 659
Population density	41.5 per km^2
Number of cities / number of apartments / total area of apartments	11 / 61 353 / 3 943 813
Number of rural settlements / number of residential buildings / total area	427 / 71 925 / 4 415 077

		Flow	Temperature	Temperature difference	Potential thermal power
	Source	**Q (l/s)**	**T °C**	**ΔT °C**	**MWt**
In the water supply system	Alluvium	212	11	7	6.2
	Karst	379	10	6	9.5
	Total				**15.7**
Outside of the water supply system	Alluvium	272	11	7	8
	Karst	4 380	10	6	110.4
	Karst fissures	100	10	6	2.5
	Total				**120.9**
	Total				**136.6**

MORAVICA DISTRICT	
Area	3 016 km^2
The capital of the district	Čačak
Number of municipalities	5
Population	189 281
Population density	62.8 per km^2
Number of cities / number of apartments / total area of apartments	5 / 45 407 / 3 164 100
Number of rural settlements / number of residential buildings / total area	206 / 52 250 / 3 308 769

		Flow	Temperature	Temperature difference	Potential thermal power
	Source	**Q (l/s)**	**T °C**	**ΔT °C**	**MWt**
In the water supply system	Alluvium	380	11	7	11.2
	Total				**11.5**
Outside of the water supply system	Alluvium	240	11	7	7.1
	Karst	580	10	6	14.6
	Total				**21.7**
	Total				**32.9**

ŠUMADIJA DISTRICT	
Area	2 387 km^2
The capital of the district	Kragujevac
Number of municipalities	7
Population	269 728
Population density	113 per km^2
Number of cities / number of apartments / total area of apartments	5 / 78 594 / 5 461 820
Number of rural settlements / number of residential buildings / total area	169 / 53 393 / 3 778 808

		Flow	Temperature	Temperature difference	Potential thermal power
	Source	**Q (l/s)**	**T °C**	**ΔT °C**	**MWt**
In the water supply system	Alluvium	320	12	8	10.7
	Neogene	15	17	13	0.8
	Karst	26	10	6	0.65
	Total				**12.2**
Outside of the water supply system	Alluvium	470	12	8	15.8
	Neogene	200	17	13	10.9
	Karst	86	10	6	2.2
	Total				**28.9**
	Total				**41.1**

RASINA DISTRICT	
Area	2 667 km^2
The capital of the district	Kruševac
Number of municipalities	5
Population	207 197
Population density	77.7 per km^2
Number of cities / number of apartments / total area of apartments	5 / 36 950 / 2 544 536
Number of rural settlements / number of residential buildings / total area	291 / 63 372 / 5 003 036

		Flow	Temperature	Temperature difference	Potential thermal power
	Source	**Q (l/s)**	**T °C**	**ΔT °C**	**MWt**
In the water supply system	Alluvium	290	11	7	8.5
	Neogene	25	16	12	1.3
	Karst	50	10	6	1.3
	Total				**11.1**
Outside of the water supply system	Alluvium	240	11	7	7.1
	Neogene	185	16	12	9.3
	Karst	70	10	6	1.8
	Karst fissures	100	10	6	2.5
	Total				**20.7**
	Total				**31.8**

RAŠKA DISTRICT	
Area	3 918 km^2
The capital of the district	Kraljevo
Number of municipalities	5
Population	296 532
Population density	75.7 per km^2
Number of cities / number of apartments / total area of apartments	9 / 59 966 / 4 369 079
Number of rural settlements / number of residential buildings / total area	250 / 58 924 / 4 353 821

	Source	Flow Q (l/s)	Temperature T °C	Temperature difference ΔT °C	Potential thermal power MWt
In the water supply system	Alluvium	260	11	7	7.6
	Karst	100	10	6	2.5
	Karst fissures	17	10	6	0.4
	Total				**10.5**
Outside of the water supply system	Alluvium	600	11	7	17.6
	Karst	1 480	10	6	37.3
	Karst fissures	100	10	6	2.5
	Total				**57.4**
	Total				**67.9**

PODUNAVLJE DISTRICT	
Area	1 248 km^2
The capital of the district	Smederevo
Number of municipalities	3
Population	175 573
Population density	140.7 per km^2
Number of cities / number of apartments / total area of apartments	3 / 42 839 / 3 118 052
Number of rural settlements / number of residential buildings / total area	55 / 41 833 / 3 288 171

	Source	Flow Q (l/s)	Temperature T °C	Temperature difference ΔT °C	Potential thermal power MWt
In the water supply system	Alluvium	730	11	7	21.5
	Total				**21.5**
Outside of the water supply system	Alluvium	5 370	11	7	157.8
	Neogene	50	15	11	2.3
	Total				**160.1**
	Total				**181.3**

POMORAVLJE DISTRICT	
Area	2 614 km^2
The capital of the district	Jagodina
Number of municipalities	5
Population	182 047
Population density	69.6 per km^2
Number of cities / number of apartments / total area of apartments	6 / 45 556 / 3 345 901
Number of rural settlements / number of residential buildings / total area	185 / 55 680 / 4 584 262

		Flow	Temperature	Temperature difference	Potential thermal power
	Source	**Q (l/s)**	**T °C**	**ΔT °C**	**MWt**
In the water supply system	Alluvium	205	11	7	6.0
	Neogene	430	15	11	19.9
	Karst	150	10	6	3.8
	Total				29.7
Outside of the water supply system	Alluvium	525	11	7	15.4
	Neogene	720	15	11	33.3
	Karst	2 300	10	6	58.0
	Total				**106.7**
	Total				**136.4**

BRANIČEVO DISTRICT	
Area	3 865 km^2
The capital of the district	Požarevac
Number of municipalities	9
Population	156 367
Population density	40.5 per km^2
Number of cities / number of apartments / total area of apartments	7 / 33 230 / 2 646 787
Number of rural settlements / number of residential buildings / total area	182 / 57 184 / 4 972 328

		Flow	Temperature	Temperature difference	Potential thermal power
	Source	**Q (l/s)**	**T °C**	**ΔT °C**	**MWt**
In the water supply system	Alluvium	530	12	8	17.8
	Karst	90	10	6	2.3
	Total				**20.1**
Outside of the water supply system	Alluvium	2 530	12	8	85
	Neogene	80	15	11	3.7
	Karst	370	10	6	9.3
	Total				**98.0**
	Total				**118.1**

BOR DISTRICT	
Area	3 507 km^2
The capital of the district	Bor
Number of municipalities	4
Population	101 100
Population density	28.8 per km^2
Number of cities / number of apartments / total area of apartments	6 / 33 776 / 2 236 203
Number of rural settlements / number of residential buildings / total area	84 / 34 888 / 2 744 169

		Flow	Temperature	Temperature difference	Potential thermal power
	Source	**Q (l/s)**	**T °C**	**ΔT °C**	**MWt**
In the water supply system	Alluvium	65	12	8	2.2
	Neogene	60	15	11	2.7
	Karst	90	10	6	2.3
	Total				**7.2**
Outside of the water supply system	Alluvium	200	12	8	6.7
	Neogene	140	15	11	6.5
	Karst	220	10	6	5.5
	Total				**18.7**
	Total				**25.9**

ZAJEČAR DISTRICT	
Area	3 623 km^2
The capital of the district	Zaječar
Number of municipalities	4
Population	96 715
Population density	26.7 per km^2
Number of cities / number of apartments / total area of apartments	5 / 30 407 / 2 261 553
Number of rural settlements / number of residential buildings / total area	168 / 33 895 / 2 252 750

		Flow	Temperature	Temperature difference	Potential thermal power
	Source	**Q (l/s)**	**T °C**	**ΔT °C**	**MWt**
In the water supply system	Alluvium	110	12	8	3.7
	Karst	525	15	11	24.3
	Total				**28.0**
Outside of the water supply system	Alluvium	150	12	7	4.4
	Karst	610	15	11	28.2
	Total				**32.6**
	Total				**60.6**

NIŠAVA DISTRICT	
Area	2 729 km^2
The capital of the district	Niš
Number of municipalities	7
Population	343 950
Population density	126 per km^2
Number of cities / number of apartments / total area of apartments	8 / 96 177 / 6 029 633
Number of rural settlements / number of residential buildings / total area	277 / 80 158 / 5 442 740

		Flow	Temperature	Temperature difference	Potential thermal power
	Source	**Q (l/s)**	**T °C**	**ΔT °C**	**MWt**
In the water supply system	Alluvium	440	12	8	14.8
	Karst	381	10	6	9.6
	Total				**24.4**
Outside of the water supply system	Alluvium	690	12	8	23.2
	Neogene	60	15	11	2.7
	Karst	770	10	6	19.4
	Total				**45.3**
	Total				**69.7**

PIROT DISTRICT	
Area	2 761 km^2
The capital of the district	Pirot
Number of municipalities	4
Population	76 700
Population density	27.8 per km^2
Number of cities / number of apartments / total area of apartments	4 / 23 061 / 1 684 105
Number of rural settlements / number of residential buildings / total area	210 / 30 465 / 1 766 438

		Flow	Temperature	Temperature difference	Potential thermal power
	Source	**Q (l/s)**	**T °C**	**ΔT °C**	**MWt**
In the water supply system	Alluvium	5	12	8	0.2
	Karst	715	13	9	27
	Total				**27.2**
Outside of the water supply system	Alluvium	15	12	8	0.5
	Neogene	40	15	11	1.8
	Karst	1 960	13	9	74
	Total				**76.3**
	Total				**103.5**

TOPLICA DISTRICT	
Area	2 231 km^2
The capital of the district	Prokuplje
Number of municipalities	4
Population	77 341
Population density	34.7 per km^2
Number of cities / number of apartments / total area of apartments	4 / 18 593 / 1 312 265
Number of rural settlements / number of residential buildings / total area	263 / 29 630 / 2 006 662

		Flow	Temperature	Temperature difference	Potential thermal power
	Source	**Q (l/s)**	**T °C**	**ΔT °C**	**MWt**
In the water supply system	Neogene	25	15	11	1.2
	Karst	75	12	8	2.5
	Total				**3.7**
Outside of the water supply system	Alluvium	60	12	8	2.0
	Neogene	40	15	11	1.8
	Karst	115	12	8	3.8
	Karst fissures	100	10	6	2.5
	Total				**10.1**
	Total				**13.8**

JABLANICA DISTRICT	
Area	2 769 km^2
The capital of the district	Leskovac
Number of municipalities	6
Population	184 502
Population density	66.6 per km^2
Number of cities / number of apartments / total area of apartments	7 / 34 800 / 2 431 307
Number of rural settlements / number of residential buildings / total area	329 / 54 388 / 3 649 759

		Flow	Temperature	Temperature difference	Potential thermal power
	Source	**Q (l/s)**	**T °C**	**ΔT °C**	**MWt**
In the water supply system	Alluvium	55	11	7	1.6
	Neogene	350	15	11	16.2
	Total				**17.8**
Outside of the water supply system	Alluvium	180	11	7	5.3
	Neogene	450	15	11	20.8
	Karst fissures	100	10	6	2.5
	Total				**28.6**
	Total				**46.4**

PČINJA DISTRICT	
Area	3 520 km^2
The capital of the district	Vranje
Number of municipalities	7
Population	193 802
Population density	55.1 per km^2
Number of cities / number of apartments / total area of apartments	6 / 32 996 / 2 431 091
Number of rural settlements / number of residential buildings / total area	357 / 37 499 / 2 420 848

		Flow	Temperature	Temperature difference	Potential thermal power
	Source	**Q (l/s)**	**T °C**	**ΔT °C**	**MWt**
In the water supply system	Alluvium	455	11	7	13.4
	Karst	39	12	8	1.3
	Total				**14.7**
Outside of the water supply system	Alluvium	555	11	7	16.3
	Karst	84	12	8	2.8
	Karst fissures	150	10	6	3.8
	Total				**22.9**
	Total				**37.6**

KOSOVSKA MITROVICA DISTRICT	
Area	2 050 km^2
The capital of the district	Kosovska Mitrovica
Number of municipalities	7
Population	-
Population density	-
Number of cities / number of apartments / total area of apartments	-
Number of rural settlements / number of residential buildings / total area	-

		Flow	Temperature	Temperature difference	Potential thermal power
	Source	**Q (l/s)**	**T °C**	**ΔT °C**	**MWt**
In the water supply system	Alluvium	86	12	8	2.8
	Karst	30	10	6	0.8
	Total				**3.6**
Outside of the water supply system	Alluvium	100	12	8	3.4
	Karst	30	10	6	0.8
	Total				**4.2**
	Total				**7.8**

KOSOVO DISTRICT	
Area	3 117 km^2
The capital of the district	Priština
Number of municipalities	10
Population	-
Population density	-
Number of cities / number of apartments / total area of apartments	-
Number of rural settlements / number of residential buildings / total area	-

	Source	Flow Q (l/s)	Temperature T °C	Temperature difference ΔT °C	Potential thermal power MWt
In the water supply system	Alluvium	185	12	8	6.2
	Neogene	60	15	11	2.7
	Total				**8.9**
Outside of the water supply system	Alluvium	610	12	8	20.5
	Neogene	120	15	11	5.5
	Total				**26**
	Total				**34.9**

PEĆ DISTRICT	
Area	2 450 km^2
The capital of the district	Peć
Number of municipalities	5
Population	-
Population density	-
Number of cities / number of apartments / total area of apartments	-
Number of rural settlements / number of residential buildings / total area	-

	Source	Flow Q (l/s)	Temperature T °C	Temperature difference ΔT °C	Potential thermal power MWt
In the water supply system	Neogene	140	15	11	6.5
	Karst	860	10	6	21.7
	Total				**28.2**
Outside of the water supply system	Alluvium	150	12	8	5.0
	Neogene	180	15	11	8.3
	Karst	3 150	10	6	79.4
	Total				**92.7**
	Total				**120.9**

KOSOVO POMORAVLJE DISTRICT	
Area	1 412 km^2
The capital of the district	Gnjilane
Number of municipalities	5
Population	-
Population density	-
Number of cities / number of apartments / total area of apartments	-
Number of rural settlements / number of residential buildings / total area	-

	Source	Flow Q (l/s)	Temperature T °C	Temperature difference ΔT °C	Potential thermal power MWt
In the water supply system	Alluvium	55	12	8	1.8
	Total				**1.8**
Outside of the water supply system	Alluvium	55	12	8	1.8
	Total				**1.8**
	Total				**3.6**

PRIZREN DISTRICT	
Area	1 910 km^2
The capital of the district	Prizren
Number of municipalities	4
Population	-
Population density	-
Number of cities / number of apartments / total area of apartments	-
Number of rural settlements / number of residential buildings / total area	-

	Source	Flow Q (l/s)	Temperature T °C	Temperature difference ΔT °C	Potential thermal power MWt
In the water supply system	Alluvium	30	12	8	1.0
	Karst	375	10	6	9.5
	Total				**10.5**
Outside of the water supply system	Alluvium	150	12	8	5.0
	Neogene	150	15	11	6.9
	Karst	1 250	10	6	31.5
	Total				**43.4**
	Total				**53.9**

6.2. Country statistics of installed shallow geothermal systems and general energy balances

Although there is potential for geothermal energy exploitation, the usage of this type of renewable energy in Serbia is negligible [3]. According the data obtained from the market, the one supplier of geothermal probes has market share over 90%. The data from this supplier are showing a significant increase in the number of installed wells and/or buildings/objects that are using geothermal heat pumps. The Figure 6.27. illustrates this trend in geothermal probe sales from 2010 to 2023 according to mentioned supplier of equipment.

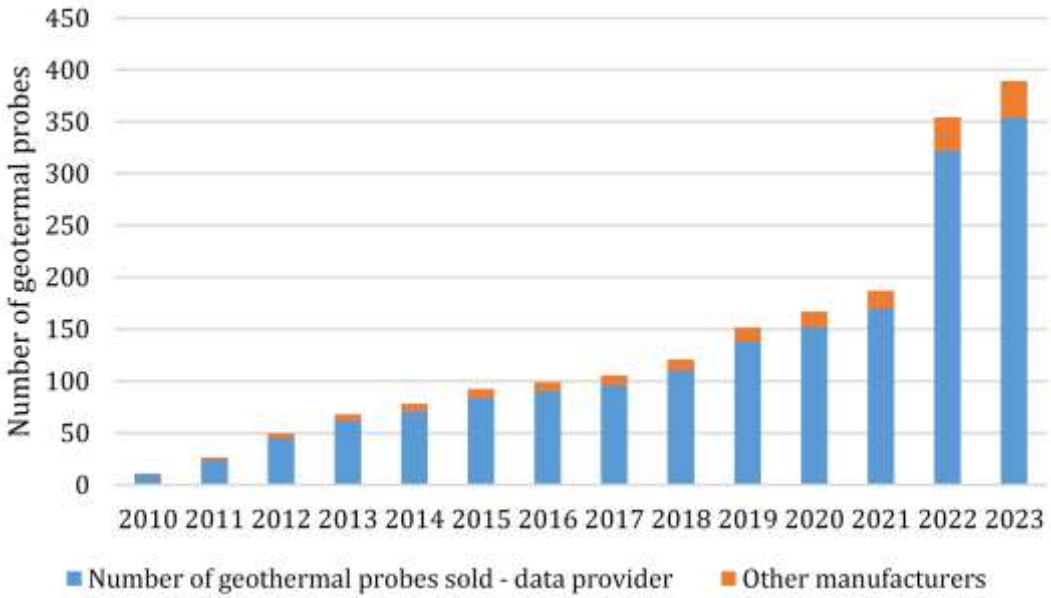


Figure 6.27. Number of geothermal sondes sold per year by equipment supplier that is dominant on the Serbian market

Total number of geothermal probes installed from 2010 - 2030 is estimated on 1700, while in the past two years (2022-2023) significant increase is recorded with around 720 installed probes or around 350 per year.

In the last two years, a total of 676 geo-probes have been sold by one, dominant manufacturer on the market. The total length of all installed boreholes is about 80 km, so if the average available power of geothermal potential in Serbia of 80 W/m is taken into account, the total installed power of exchangers (geothermal probes) is estimated at about 6 MW. Based on all of the above and the estimated value of COP=4 of ground/water type heat pumps, the thermal power delivered to the heating system in buildings is estimated to be 7,7 MW. Figure 6.28. shows the locations of installed geothermal probes in the period from 2022-2023.

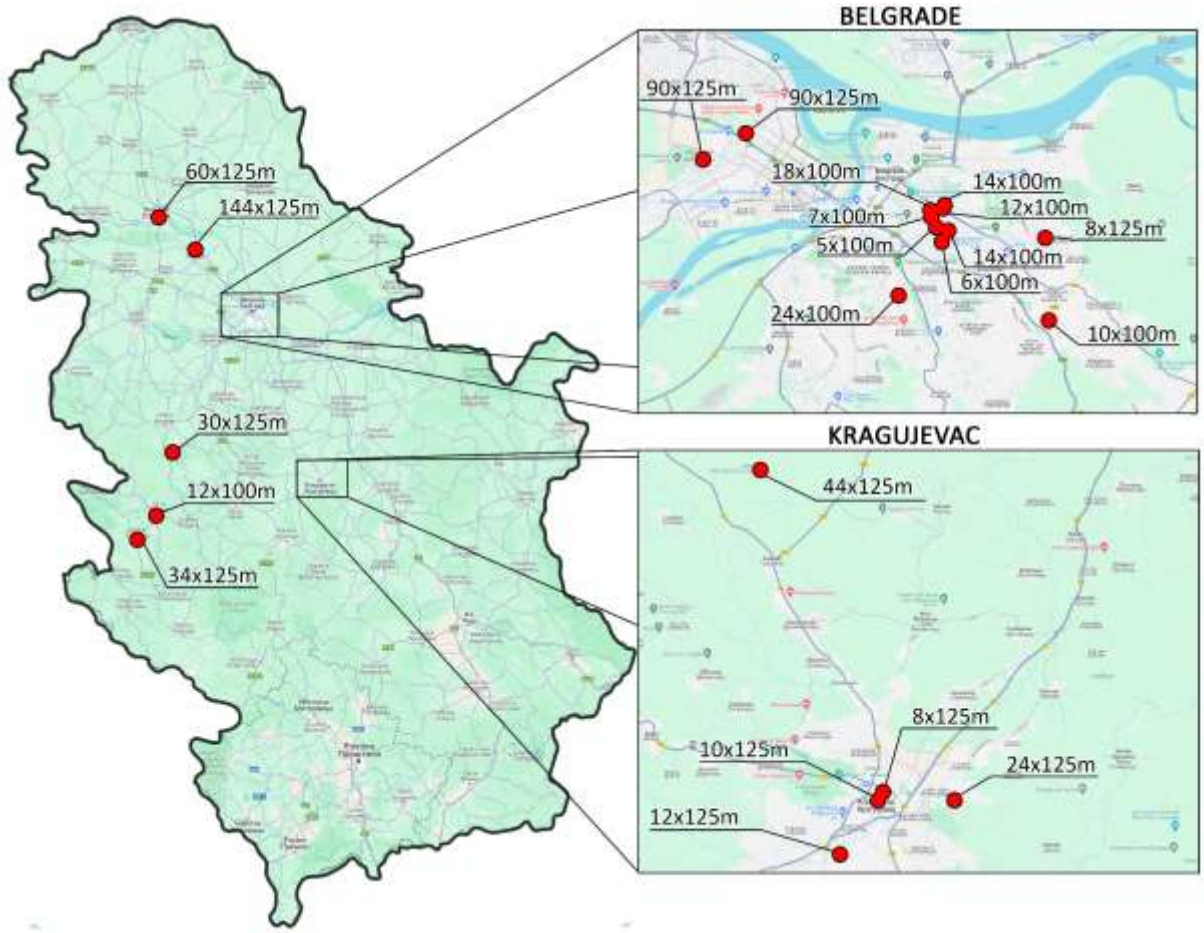


Figure 6.28. Map of major shallow geothermal projects executed in Serbia in 2022 and 2023 ("number of probes" x "depth in meters")

Depending on the location and diameter of the well, the price of drilling (hydraulic-rotary) ranges from 20-40 €/m. Drilling speed is about 20 m per day. The price of geothermal probes, depending on the manufacturer, ranges from 25-30 €/m. In total, the average cost of digging a well and installing probes with filling (Bentonite) is estimated at 60 €/m.

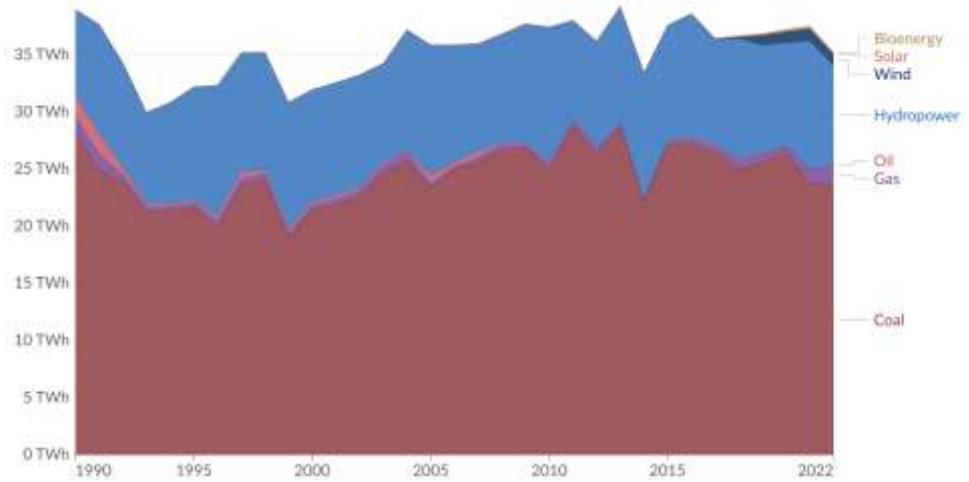


Figure 6.29. Electricity energy mix in Serbia [28]

Figure 6.30. 2021 - 2023 electricity emissions factors (gCO_2eq/kWh) [29]

6.3. Overview of current regulations, incentives and general policy related to shallow geothermal

Regulations

The main document considering the legal framework for RES utilization in the Republic of Serbia is the Energy Law. The present law includes regulations considering RES: conditions and incentives for energy production from RES and the combined production of heat and power, rights and responsibilities of government agencies; status, funding, activities, and other issues relevant to the work of the Energy Agency of the Republic of Serbia related to monitoring the implementation of this law. Another important document affecting geothermal energy utilization is the Law on Mining and Geological Exploration (RS Official Gazette 101/2015). This law includes regulations considering conditions and manners of execution of geological explorations of mineral and other geological resources, researching of geological environment, classification of resources and reserves of mineral raw materials and ground waters, etc. For instance, it defines the maximum size of the area for geological explorations of groundwater and geothermal resources (10 km^2). In 2021, the Republic of Serbia adopted the Law on the Use of Renewable Energy Sources (Official Gazette of the RS 40/2021) which regulates: i)

Utilization of energy from RES, ii) Targets for the use of energy from renewable sources, iii) Method for determination of the share of RES in the gross final energy consumption, iv) integration of RES into the energy market, v) incentive systems for the production of electricity from renewable sources, vi) guarantees of origin of electricity, vii) production of electricity from RES for own consumption, viii) use of RES in the field of thermal energy and traffic, ix) procedures related to the construction and connection of energy facilities using RES, x) basics of the mechanism of cooperation with other countries in the field of RES, xi) supervision over the implementation of this Law, and xii) other issues of importance for RES. According to Pešić et al. [3] and Tsagarakis et al. [30], the other documents directly affecting the utilization of geothermal resources are the Water Law (Official Gazette of the Republic of Serbia 30/2010, 93/2012 and 101/2016) the Law of Planning and Construction (Official Gazette of the Republic of Serbia 72/2009, 81/2009), the Law on Environmental Protection (Official Gazette of the Republic of Serbia 135/2004, 36/2009), the Law on Spas (Official Gazette of the Republic of Serbia 80/1992, 67/1993), the Law on Concessions (Official Gazette of the Republic of Serbia 55/2003), the Law on Efficient Use of Energy (Official Gazette of the Republic of Serbia 25/2013), and other legal documents.

The most recent strategic documents considering RES that affect the use of geothermal energy in Serbia are the Energy Sector Development Strategy of Serbia to 2025 with projections to 2030, the Strategy on the Sustainable Use of Natural Resources, the National Renewable Energy Action Plan, the Integrated National Energy and Climate Plan of the Republic of Serbia for the period 2030 with the projections up to 2050, and Low Carbon Development Strategy of the Republic of Serbia for the period 2023 - 2030 with projections until 2050.

Figure 6.31. describes the legal framework for geothermal heat generation plant construction in the Republic of Serbia. It is important to emphasize that after acquiring the right to construct the plant and getting permission to connect it to the power grid the plant can start with energy production with a temporary status. Afterward, after obtaining the right to perform the activity of heat production the plant status changes to permanent [31].

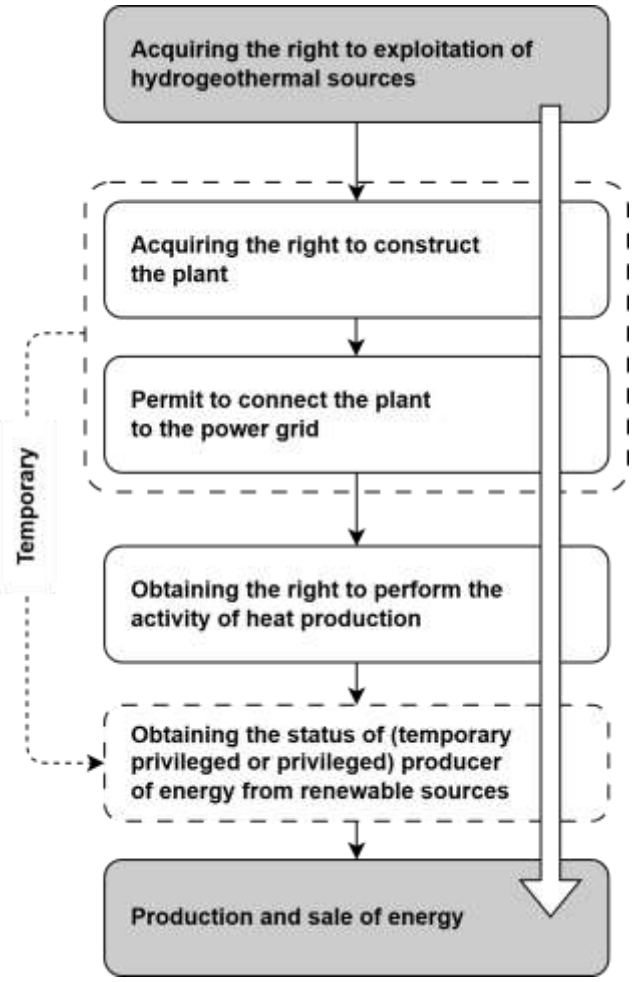


Figure 6.31. Legal framework for geothermal heat generation plant construction in Serbia [31]

Figure 6.32. shows the documentation needed to obtain the right to exploitation of hydrogeothermal sources. According to the Law on Mining and Geological Exploration, this permit shall be issued only when it refers to exploiting high-enthalpy geothermal sources (above 100°C) [31]. Figure 6.33. shows the documentation needed to acquire the right to construct the plant.

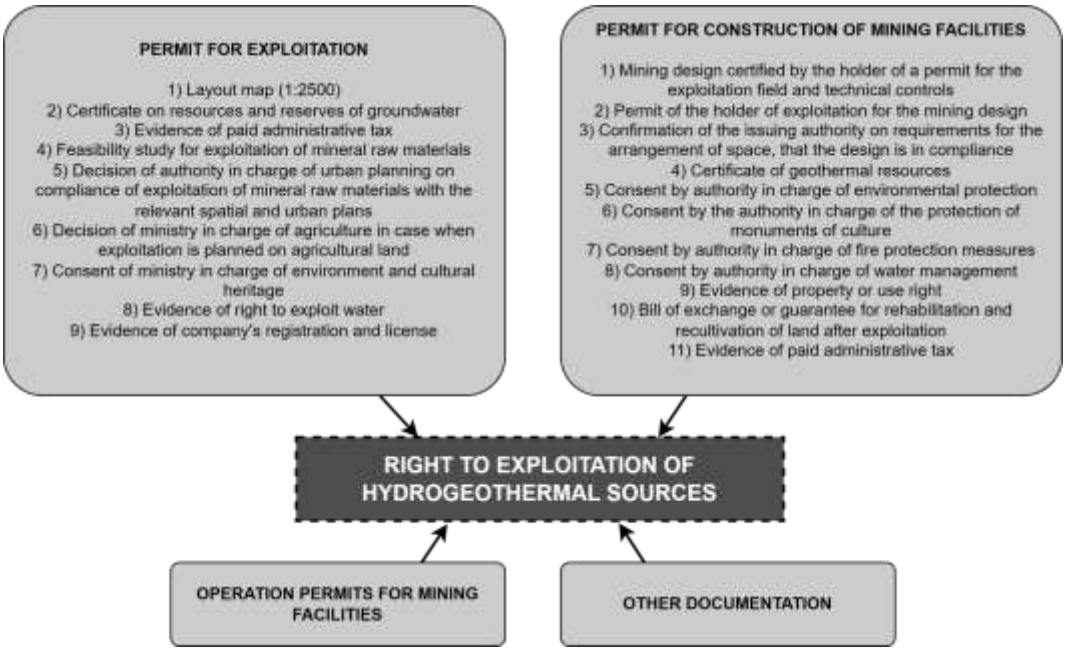


Figure 6.32. Documentation needed to obtain the right to exploitation of hydrogeothermal sources [31]

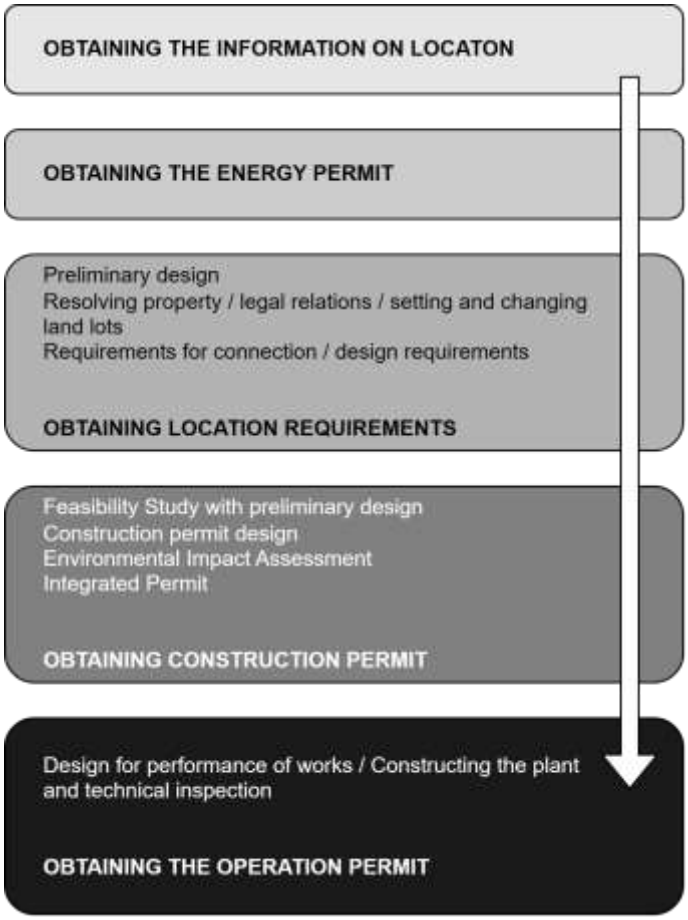


Figure 6.33. Documentation needed to acquire the right to construct the plant [31]

For facilities for heat generation of capacity below 1 MW, the energy permit is not required. The procedures of obtaining the location requirements and construction permits are issued for plants with a capacity of 10 MW and more, and facilities within the boundaries of cultural assets registered in the List of World Cultural and Natural Heritage, structures in protected environs of cultural assets of exceptional significance with determined boundaries of cadastre lots and structures in protected environs of cultural assets inscribed in the List of World Cultural and Natural Heritage, structures in protected environs by acts on the protection of cultural assets, and structures within the boundaries of national parks and structures within the boundaries of protection of protected natural assets of special significance, structures of structural span exceeding 50m, and structures of height exceeding 50 m. To obtain the construction permit, a Feasibility Study with preliminary design, Environmental Impact Assessment, and Integrated Permit are needed. Environmental impact assessment is mandatory for plants exceeding 50 MW, while for plants of capacity between 1 and 50 MW it can be required by the authorized delegate. An Integrated Permit is only required for hydrogeothermal plants with a capacity exceeding 50 MW [31]. Figure 6.34. shows the ways of acquiring the right to engage in the activity of heat production.

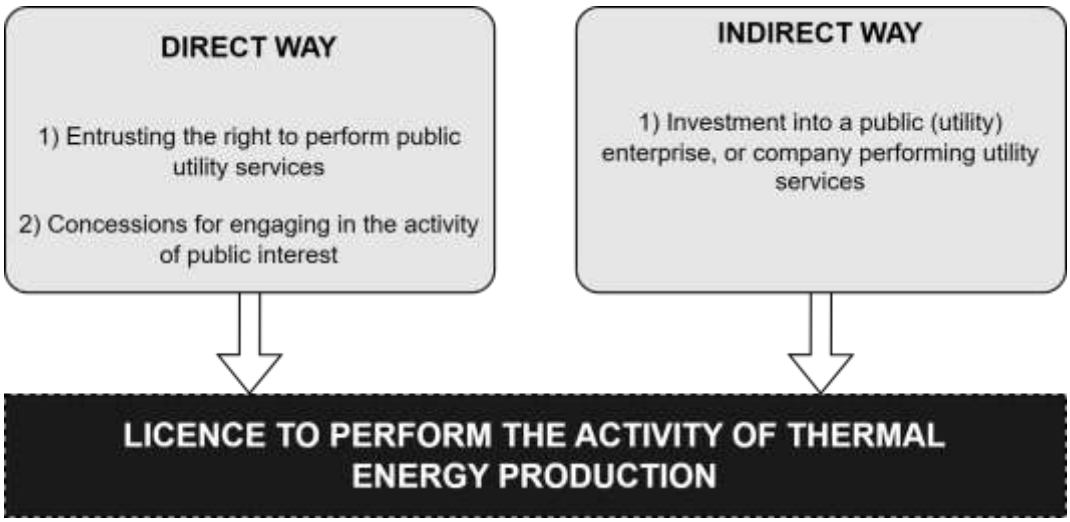


Figure 6.34. Ways of acquiring the right to engage in the activity of heat production [31]

Incentives

In the Republic of Serbia, two subsidy programs related to heat pumps/geothermal energy exploitation are currently active, one is provided by the Green Economy Financing Facility (GEFF), and the other by the Ministry of Mining and Energy of the Republic of Serbia. GEFF is a program introduced by the European Bank for Reconstruction and Development that funds green technology investments in the residential sector and businesses that provide these products and services to households. According to the GEFF, implemented and verified projects will be subsidized for: i) Individuals - up to 20% of eligible costs for projects implemented in individual apartments or households for acceptable technologies (including heat pumps), ii) Groups of individuals, housing cooperatives, service providers - up to 35% of eligible costs for projects implemented in multi-apartment buildings for acceptable technologies. The procedure of subsidizing includes:

1) Online registration via the verification system after the technology is successfully installed;
2) Verification of the installed technology done by authorized individuals from GEFF, which could be in the form of an on-site visit;

3) Payment of subsidies to the bank account after successful verification of the technology. The financial partners of the GEFF in the Republic of Serbia are Erste Bank, ProCredit Bank, Banca Intesa, and 3Bank [32].

The Ministry of Mining and Energy of the Republic of Serbia issued a public call for financing the energy rehabilitation program of households and apartments implemented by local self-government units. The goal of this project is to save energy, promote its rational use, support socially vulnerable groups, and achieve the goals of the project "Čista energija i energetska efikasnost za građane u Srbiji" (eng. Clean energy and energy efficiency for citizens in Serbia) which includes increasing the use of energy efficiency, sustainable heating and rooftop solar panels in households. This financing project targets all energy efficiency measures including the improvement of the building's termotechnical systems by replacing the whole or part of the old system with a new more efficient one:

i) the change of an existing with a new, more efficient boiler;
ii) the change or installation of a new pipe network, heating elements, and accompanying equipment;
iii) installation of heating pumps that use the energy of air, water, or ground;
iv) installation of electronically regulated circulation pumps, and;
v) installation of devices for regulation and measuring of used heating energy in the building.

This project includes two stages of applications. in the first stage, the local self-government units are obliged to submit the necessary documentation to the Ministry of Mining and Energy. If the local self-government unit meets all the requirements, the ministry will define the amount of subsidies that will be allocated to it. In the second stage, citizens are applying for subsidies to their local self-government unit. The commission determines the fulfillment of the conditions based on a review of the submitted documentation and a field visit to inspect the condition of the building and check the data filled in the application. The maximum share of subsidies for individual measures is up to 50% of the total project value (ЈП 1/24).

6.4. General country geology, hydrogeology and thermogeological parameters

Based on previous research, Serbia has significant geothermal potential and numerous resources that can be used. Despite this, the current exploitation of geothermal energy in Serbia is low. According to Pešić et al. [3], the geothermal heat flow density in Serbia ranges from 80 to 120 mW/m², which is higher than the European average of 60 mW/m². The highest values are in the Pannonian basin (>100 mW/m²), the Vardar zone and the Serbian-Macedonian massif, while the lowest are in the Mesian platform and southwestern Serbia.

The annual use of geothermal energy for direct heat is 1507 TJ/year, with an estimated capacity of 111 MW. The deepest groundwater well in the Pannonian basin is 2520 meters deep [4, 25].

The geological and tectonic structures of Serbia are complex. Serbia was shaped by the Alpine Orogeny, and includes the Dinarides, the Carpatho-Balkanides, the Moesian Platform, the Serbian-Macedonian Massif and the Pannonian Basin. The Dinarides are mainly Mesozoic rocks, separated from the Carpatho-Balkanides by the Serbian-Macedonian massif, which consists mainly of Proterozoic metamorphic rocks. The Carpatho-Balkanides are Mesozoic carbonate platforms, and the Pannonian Basin consists of Paleogene, Neogene and Quaternary sediments. This complex geology results in numerous mineral and thermomineral springs in Serbia.

Filipović et all [7] defined six hydrogeological regions based on geological and hydrological characteristics important for mineral waters: Dacian Basin, Carpatho-Balkan, Serbian Crystalline Core, Šumadija-Kopaonik-Kosovo, Dinarides of Western Serbia and Pannonian Basin. In Serbia, there are 159 thermal springs (t > 15°C) [14, 33] and 60 commercial spas [33, 34].

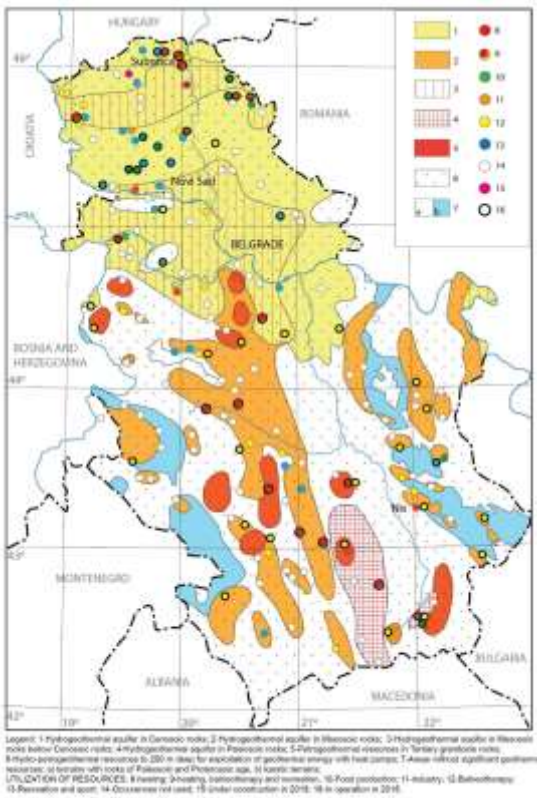


Figure 6.35. Map of geothermal resources of Serbia (background: Geothermal resources map, [35] [20]

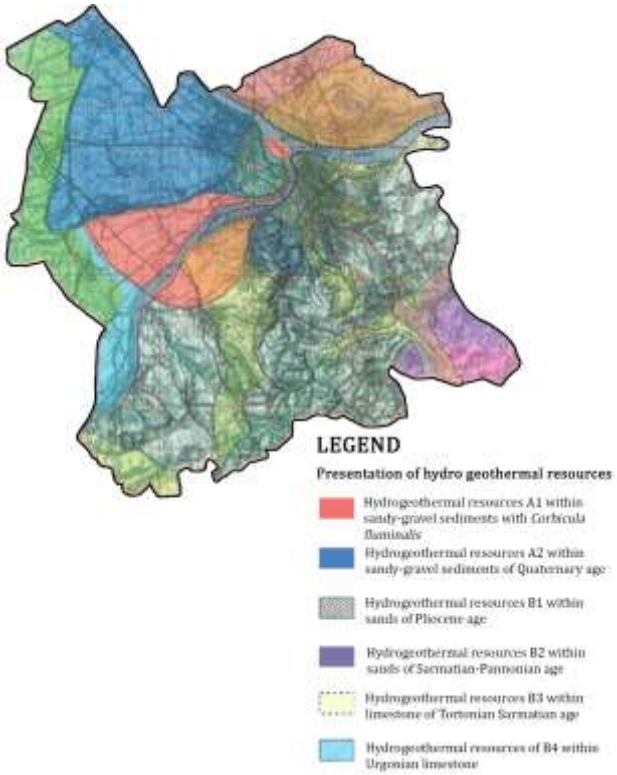


Figure 6.36. Distribution of hydro geothermal resources in Belgrade [26]

Geological structures in Serbia are classified into several geotectonic units [36]. The main units identified are: the Pannonian Basin in the north, the Carpatho-Balkanides extending from east to west, the Serbian-Macedonian Massif, the Vardar Zone and the Dinarides. The central part of the Balkan Peninsula and central Serbia are further divided into different units based on terrain concepts [37–39]. The hydrogeological regions in Serbia [5, 7] are closely related to these geotectonic units: the Pannonian Basin in the north, then the Dacian Basin region, the Carpatho-Balkanides, the Serbian crystalline core region, the Šumadija-Kopaonik-Kosovo region and the Inner Dinarides region.

From a hydrogeological point of view, based on the lithostratigraphic units, the following types of aquifers are present:

- Intergranular (porous): Quaternary and Tertiary;
- Karst;
- Karst-fissured;
- Fissured (fractured).

Intergranular (Porous):

- Mainly comprising Quaternary and Tertiary sediments.
- Thermal waters can be found in confined or semi-confined layers within the Neogene basins.

- Hydrochemical zonality is present, with increasing mineralization and temperature with depth.
- Temperatures range from 22°C to 82°C.
- Locations: Spread across Serbia, with significant presence in the Province of Vojvodina.

Karst:

- Composed of carbonate rocks, predominantly limestone and dolomite.
- Karst springs exhibit oscillations in yield and temperature.
- Thermal springs are linked with fold-thrust belts and magmatic intrusions.
- Temperatures vary from 13°C to 39°C.
- Locations: Found in eastern and western Serbia, particularly in regions such as Niška Banja, Carpatho-Balkanides, and Dinarides.

Karst-Fissured:

- Found in terrains with diverse rock compositions, including conglomerates, sandstones, marls, and dolomite.
- Thermal springs occur in areas with intensive rock changes.
- Temperature varies depending on location.
- Locations: Various locations with intensive rock changes, and specific sites may vary.

Fissured (Fractured):

Comprised of intrusive, effusive, metamorphic, and sedimentary rocks.

Dominant in the Serbian Crystalline Core region, with thermal water mainly originating from Tertiary volcanic and magmatic activity.

Geological structures like fractures and faults play a crucial role in heat flow and water dynamics.

Temperatures vary across different aquifers but can exceed 120°C.

Locations: Predominantly in the Serbian Crystalline Core region, including areas such as Vranjska Banja, Kuršumlijska, and Novopazarska.

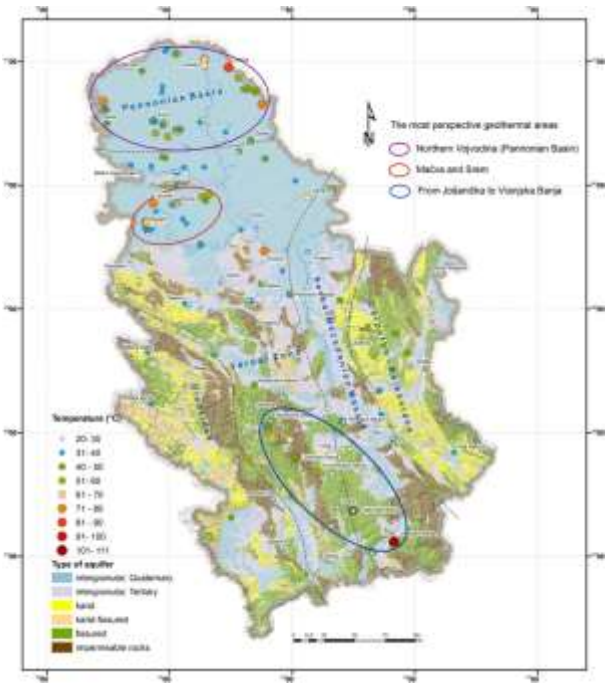


Figure 6.37. Hydrogeological map of Serbia with the most perspective geothermal areas and distribution of thermal waters [5]

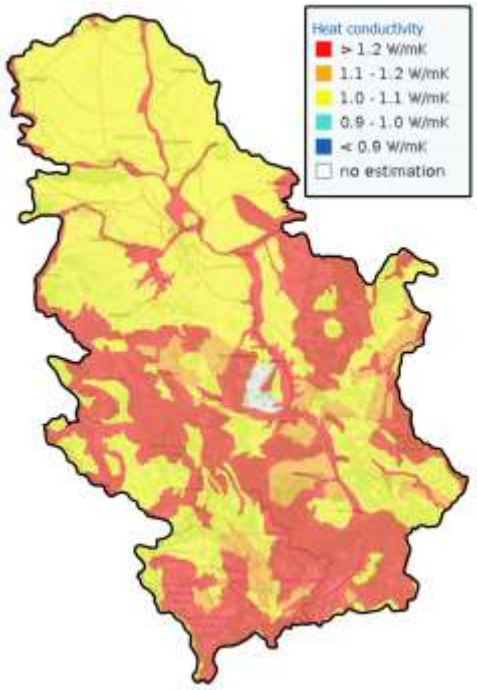


Figure 6.38. Heat conductivity (W/mK) [40]

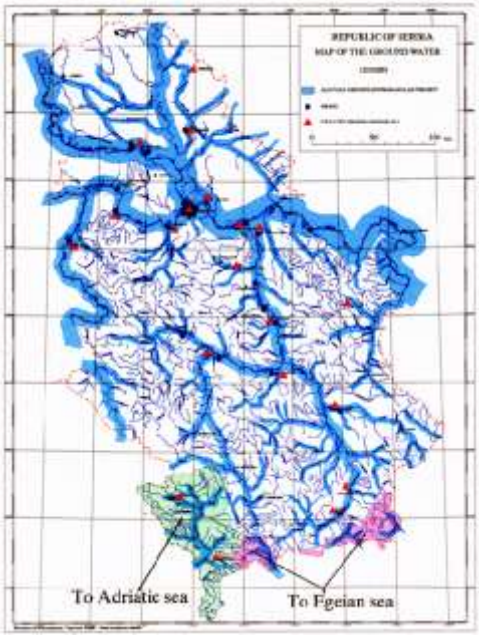


Figure 6.39. Map of alluvial aquifers [41]

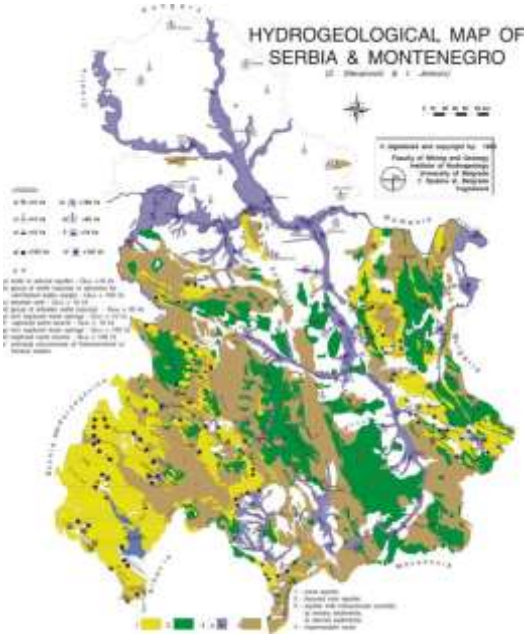


Figure 6.40. Hydrogeological map of Serbia and Montenegro

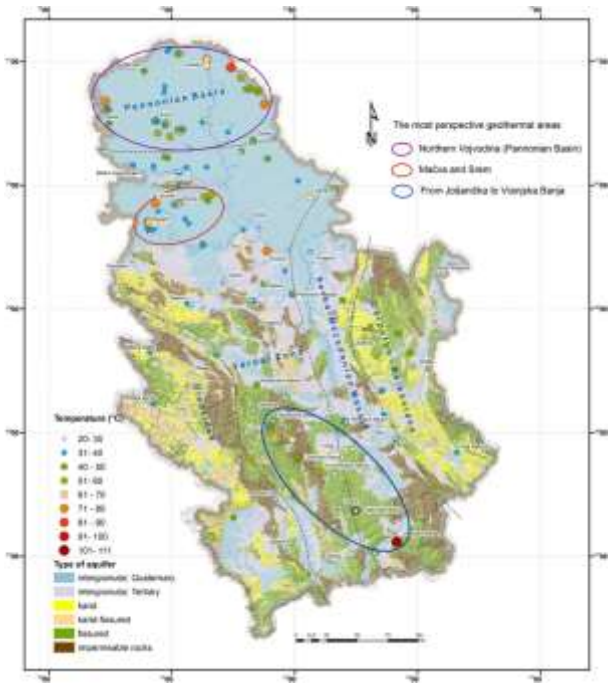


Figure 6.41. Hydrogeological map of Serbia with the most perspective geothermal areas and distribution of thermal waters [15]

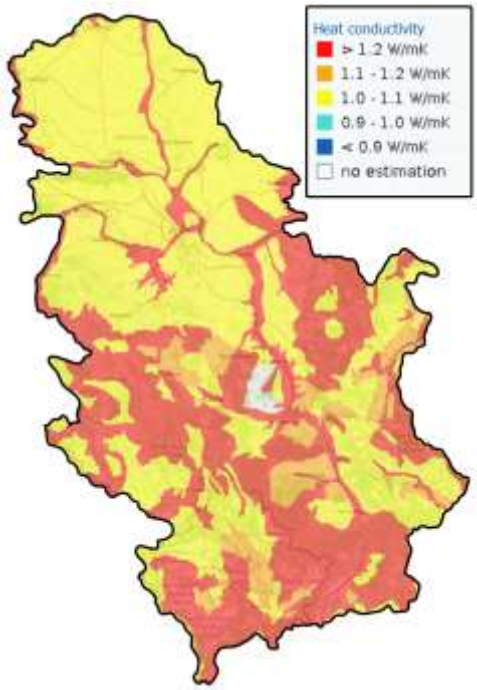


Figure 6.42. Heat conductivity (W/mK) [40]

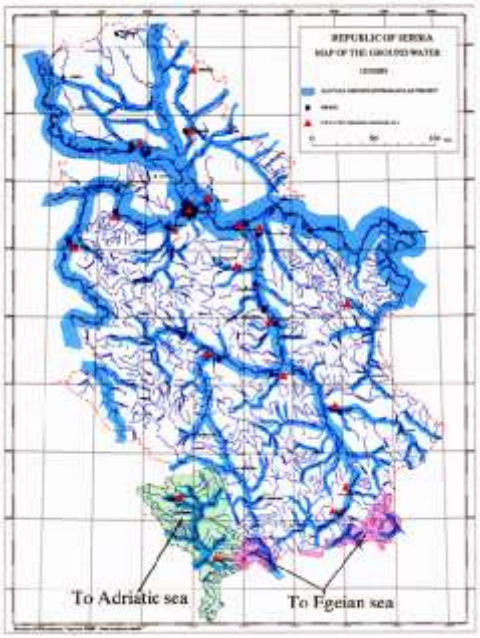


Figure 6.43. Map of alluvial aquifers [40]

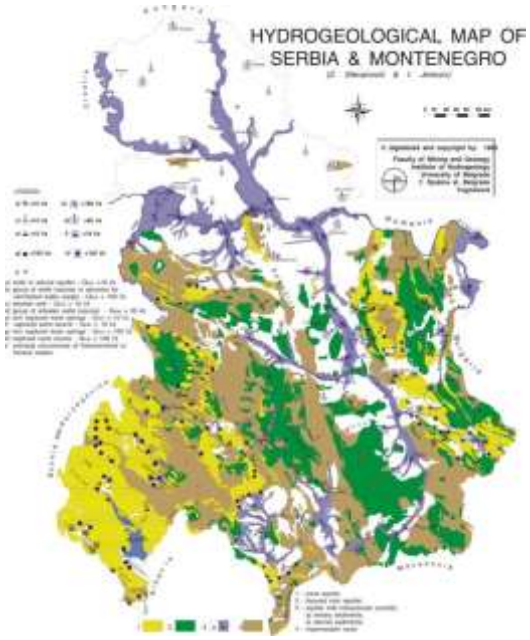


Figure 6.44. Hydrogeological map of Serbia and Montenegro

Figure 6.45. Hydrogeological map [40]

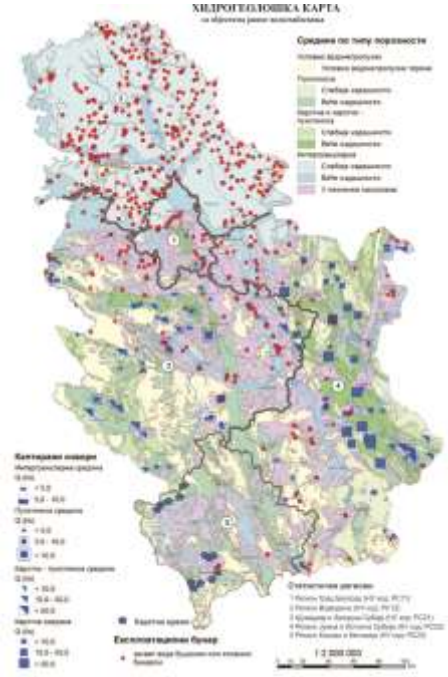


Figure 6.46. Hydrogeological map with public water supply objects

Figure 6.47. Engineering geological map 1:300 000

Figure 6.48. Hydrogeological map with labelled groundwater classes based on temperature 1:500 000

Figure 6.49. Hydrogeological map [40]

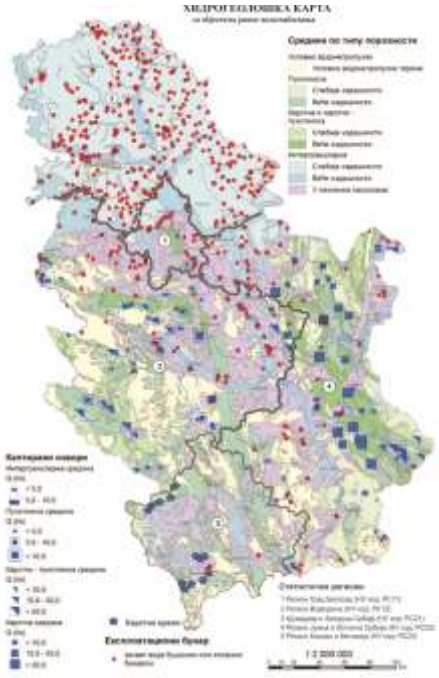


Figure 6.50. Hydrogeological map with public water supply objects

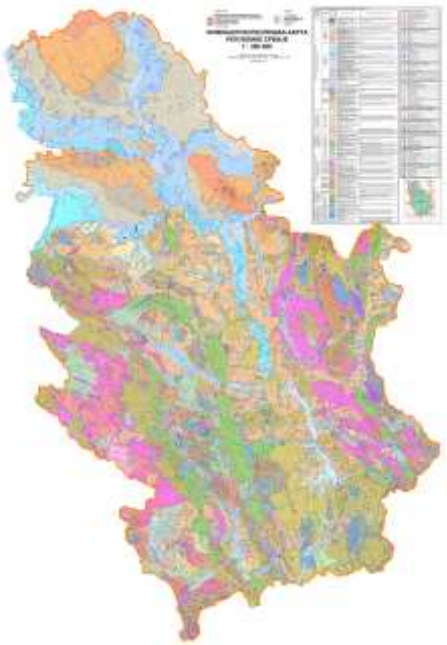


Figure 6.51. Engineering geological map 1:300 000

Figure 6.52. Hydrogeological map with labelled groundwater classes based on temperature 1:500 000

As stated in [42] the Thermal Response Test (TRT) as well as the newly proposed methodology named Thermal Recovery Test has been deployed in Belgrade, in the yard of the Faculty of Mechanical Engineering, University of Belgrade (Figure 6.53. & Table 6.3).

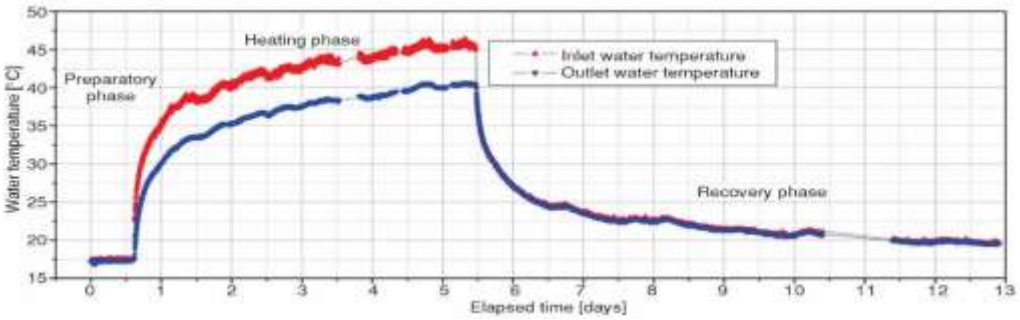


Figure 6.53. Change of the water temperature at the entrance to the buried heat exchanger and the exit from it during the preparatory, heating and recovery phases

Table 6.3. Experimentally obtained values of the thermal conductivity of the soil (wet clay, density 1980 kg/m^3) in the same borehole for three measurements (Thermal Recovery and TRT) according to [42]

	λ [Wm^{-1}K^{-1}]	
Number of measurements	Thermal Recovery Test	TRT
1	1,431	1,496
2	1,438	1,442
3	1,443	1,488

Detailed geological maps of different locations and for the whole territory of Republic of Serbia are available online on https://geoliss.mre.gov.rs/prez/OGK/RasterSrbija/ As examples, maps of Novi Sad, Belgrade and Kragujevac are given below in Figure 6.54., Figure 6.55., Figure 6.56.

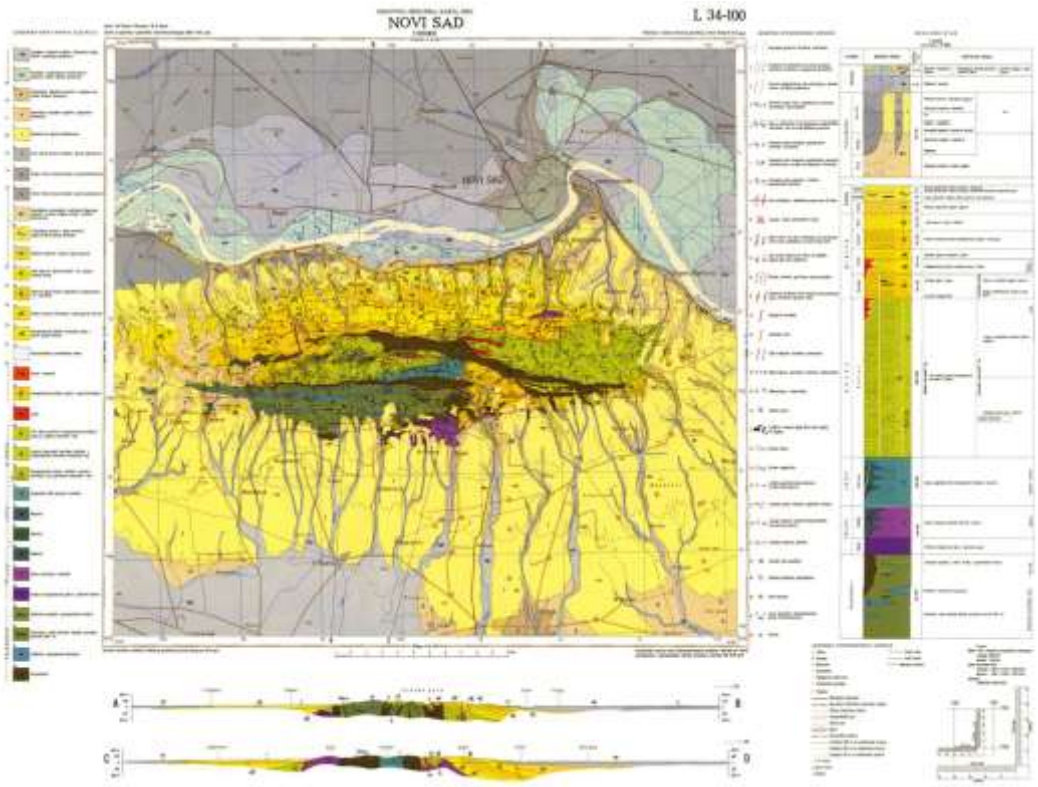


Figure 6.54. Detailed geological map of Novi Sad, Serbia

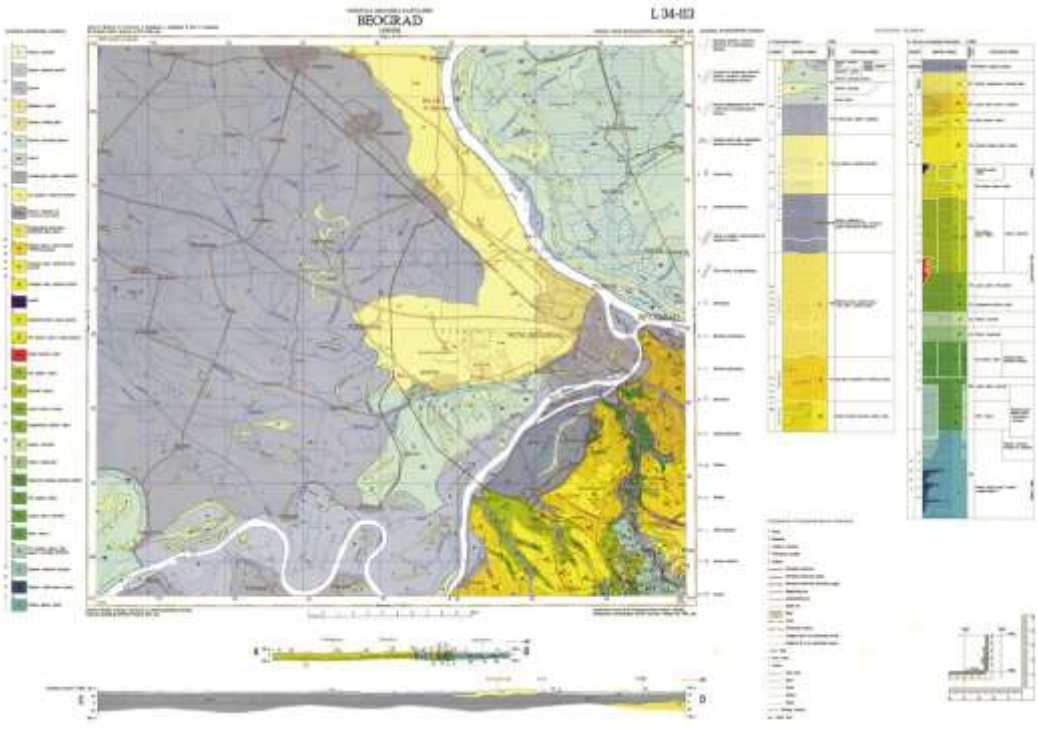


Figure 6.55. Detailed geological map of Belgrade, Serbia

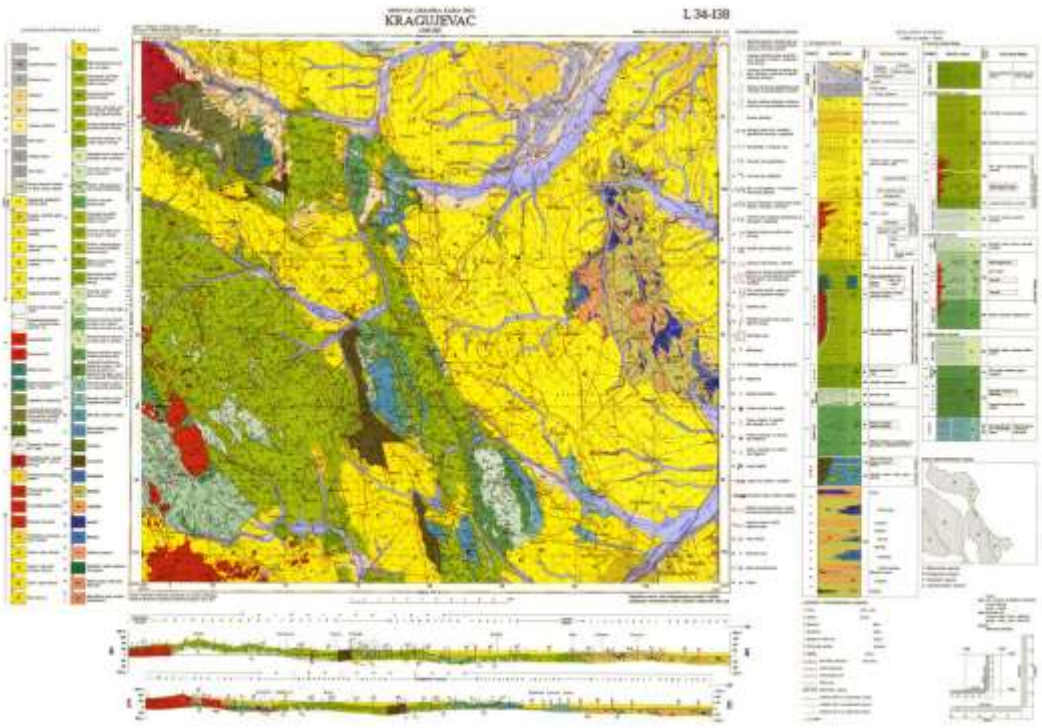


Figure 6.56. Detailed geological map of Kragujevac, Serbia

6.5. Current energy cost comparison for residential and non-residential sector with estimated capital cost of drilling and equipment for shallow geothermal

The prices of electricity in Serbia (per kWh) are among the lowest in Europe (Figure 6.57. and Figure 6.58.). Those circumstances are impacting various fields in both positive and negative ways. One of the impacts of low prices of energy, which is of interest for this study, is lower penetration of new technologies, especially if their utilization relies on the expectation of users to have adequate payback time.

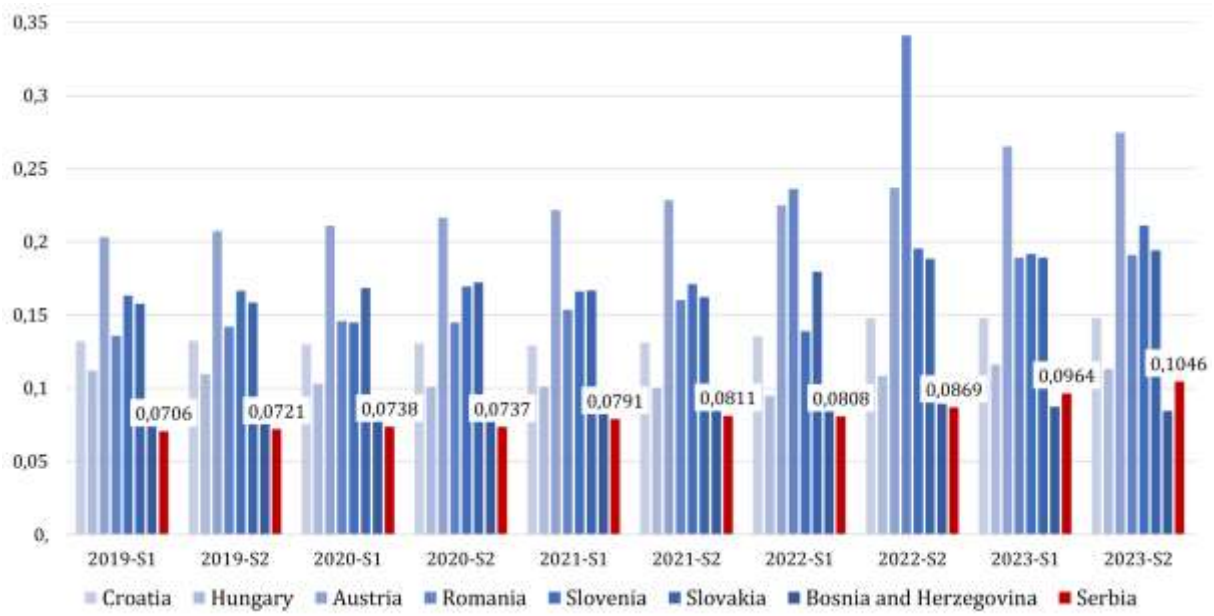


*Figure 6.57. Semi-annual prices of **electricity** (€/kWh) for households (all taxes and levies included) for countries participating in DanubeGeoHeCo Interreg project [43]*

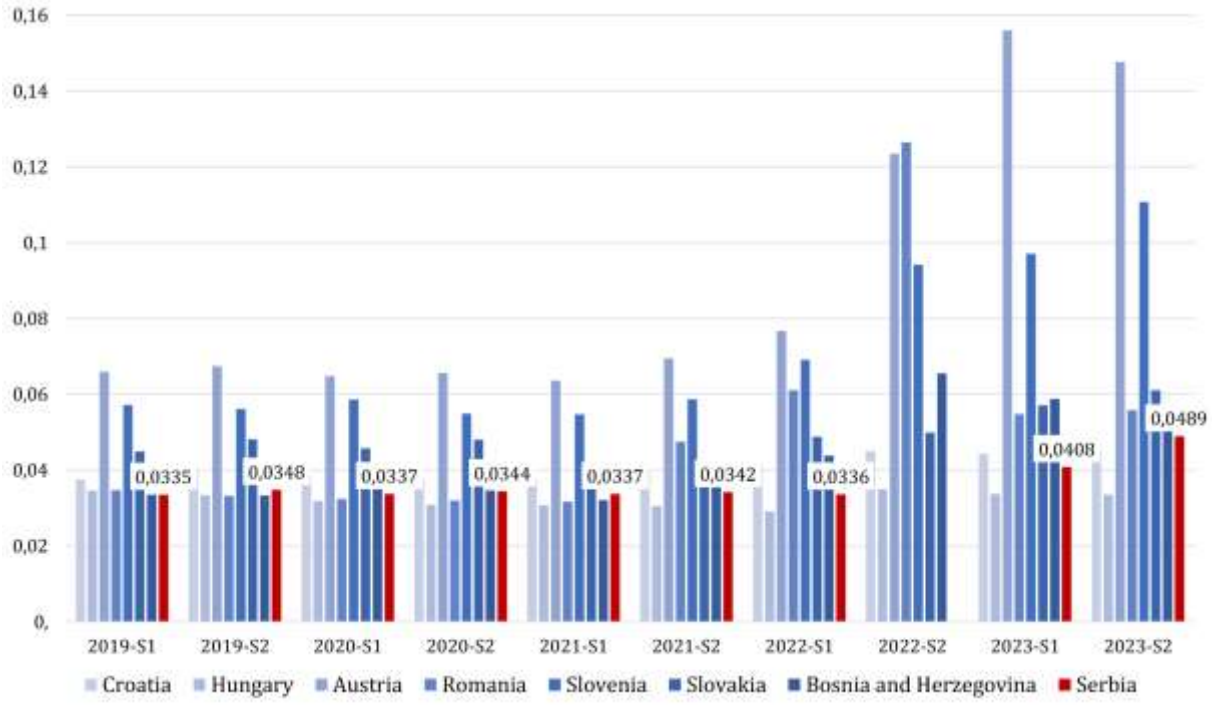


*Figure 6.58. Semi-annual prices of **natural gas** (€/kWh) for households (all taxes and levies included) for countries participating in DanubeGeoHeCo Interreg project [43]*

In the study [3] it is stated that according to the estimates of the Energy Agency of the Republic of Serbia the average estimated consumption during the heating season (180 days) is 150 kWh/m^2, i.e. 25 kWh/m^2 per month. A comparative review of monthly costs for heating by different energy sources

indicates that the consumption of electricity (up to 3.33 EUR/m^2) and fuel oil (up to 3.43 EUR/m^2) are the most expensive sources of energy. Natural gas and coal are most often used for heating due to lower prices (0.99–1.17 EUR/m^2), easy access, and tradition of use. Considering the economic (0.37 EUR/m^2), but also ecological aspects of the use of geothermal energy, it should be given priority over other energy sources in all areas where there are natural and technical conditions for its use. It is important to notice that these values include only the costs of energy supply (i.e. fuel), without costs of investment, periodic inspections, and maintenance. The mentioned notable parameters should be included in detailed analyses for feasibility studies at the local level. Although these costs are not taken into account, the economic viability of the use of geothermal energy is quite observable.

Comparison of heating technologies

Heat pump technology is becoming increasingly popular in Serbia. However, the utilization of heat pump technology is still in its early stages, particularly in terms of ground-source heat pumps. Therefore, there is limited data about prices and costs related to this technology. Some studies were conducted to determine costs and compare them to other technologies.
Jokić et al. [44] have analysed the building of 120 m^2 floor area. The authors have taken into account the climatic characteristics of the country and the medium insulation of the building. Regarding that, the energy demand of 58 W/m^2 and 42 W/m^2, for heating and cooling, respectively is assumed. Annual energy consumption meets the heating demand of the building is 13 MWh, while for cooling it is 10 MWh. Table 6.4. presents a comparison of heating and cooling costs utilising various technologies.

Table 6.4. Annual costs of various technologies for heating and cooling

	coal	natural gas	electricity	pellet*	VGSHP
Price of energy per unit	122 €/t	0.38 €/m^3	0.11 €/kWh	170 €/t	0.08 €/kWh**
Annual cost [€]	732	667	1459	550	380
Cost [€/MWh]	56.3	51.3	112.2	42.3	29.2
Cost [€/m2]	6.1	5.6	12.2	4.6	3.2
Cooling	254 €				

* The price of pellets in 2020
** Electricity price is lower regarding the range of tariffs (green, blue, red)

The total cost of the VGSHP (vertical ground exchangers) system to meet both the heating and cooling demands of the house is 8480 €. Cvetanović and Šušteršič [45] analysed the ground-water heat pump heating system for a residential building, of 120 m^2 area, to estimate costs. Also in the study, different types of heating (gas boiler and solid biomass boiler) were compared (Table 6.5.).

Table 6.5. Annual costs of various technologies for heating

	Biomass	Gas boiler [€]	Heat pump [€]
Cost [€]	588	1094	661
Cost [€/m^2]	5.1	4.8	2.2

Pešić et al. [3] used data from the Energy Agency of the Republic of Serbia (for 60 m^2 area) to estimate heating costs for different energy sources. The calculation used the average expected consumption during the heating season (180 days) of 150 kWh/m^2, or 25 kWh/m^2 per month. A comparison of heating costs by various energy sources shows that electricity and fuel oil are the most expensive for the heating season 2021/2022 (Table 6.6.). It is important to notice that the Table only contains the expenses of energy supply (fuel), not investment, periodic inspections, or maintenance.

Table 6.6. Annual costs of various technologies for heating for the heating season 2021/2022

	Coal	Natural gas	Electricity	Fuel oil	Pellet	Geothermal
Annual cost [€]	399	356	1083	875	454	133
Cost [€/MWh]	44.3	39.5	120.3	97.2	50.4	14.8
Cost [€/m^2]	6.65	5.9	18.05	14.6	7.5	2.2

The authors also have provided a comparison of prices for five heating seasons (Figure 6.59.).

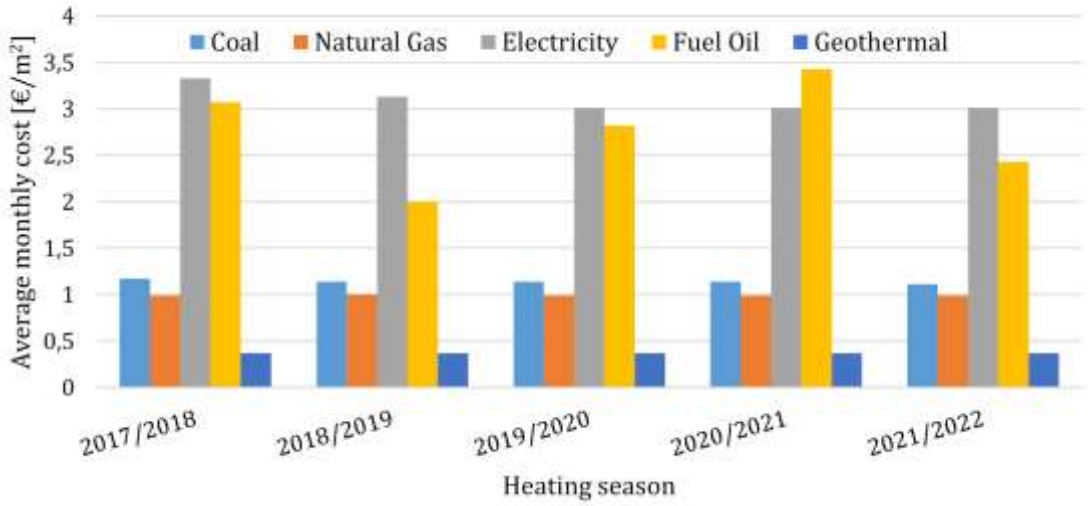


Figure 6.59. Average monthly costs for heating by energy sources [EUR/m^2].

Kljajić et al. [46] assessed the economic feasibility of closed loop heat pump systems for heating and cooling purposes in Serbia's residential sector. The thermal energy unit price was estimated to drop from the current 42 (natural gas) to 17 (shallow heat pump + natural gas to provide the necessary capacity) EUR/MWh of thermal energy.

6.6. Environmental regulations and restrictions related to shallow geothermal development

In the Republic of Serbia, according to Article 4, Clause 26 of the Law on Nature Protection ("Official Gazette of the RS", no. 36/2009, 88/2010, 91/2010 - amended, 14/2016, 95/2018 - other laws and 71/2021), protected areas are defined as areas that have a pronounced geological, biological, ecosystem and/or landscape diversity and are therefore declared protected areas of general interest by the protection act. According to the data of the Institute for Nature Protection of Serbia - http://vvv.zzps.rs, in October 2021 there were 471 protected areas in Serbia, with a total area of 678,237 ha, i.e. 7.66% of the territory of Serbia (Figure 6.60.). According to data from the website https://www.protectedplanet.net/country/SRB, there are 398 protected areas (including inland waters protected area) in Serbia with a total area of 885,090 ha, i.e. 8.14% of the territory of Serbia.
Article 35 of the Law on Nature Protection establishes protection regimes of I, II, and III degrees in the protected area. There is a priority ban on the construction of energy production facilities in the protected areas of the I and II degree protection regimes, so shallow geothermal plants cannot be built either. Level III protection regime limits the construction of energy facilities. According to the Regulation on Protection Regimes ("Official Gazette of the RS", No. 31/2012), the III degree protection regime limits works and activities to the exploitation and primary processing of reserves of mineral raw materials and geothermal resources at distances greater than 2-3 km from the I and II protection regime zones.
According to Article 2 of the Water Law ("Official Gazette of RS", No. 30 of May 7, 2010, 93 of September 28, 2012, 101 of December 16, 2016, 95 of December 8, 2018, 95 of December 8, 2018 - other law), the provisions of this law refer to all surface and underground waters in the territory of the Republic of Serbia, including thermal and mineral waters, except for underground waters from which useful mineral raw materials and geothermal energy can be obtained.
The Water Law stipulates six types of protected areas:

- sanitary protection zones of water supply springs;
- areas intended for abstracting water for human consumption (water bodies of underground and surface water that are used or may be used for human consumption in the future, in an average amount of water greater than 10 m^3/day or for supplying drinking water to more than 50 inhabitants);
- water bodies intended for recreation, including areas designated for swimming,
- areas vulnerable to nutrients, including areas prone to eutrophication and areas sensitive to nitrates from agricultural sources,
- areas intended for the protection of habitats or species, where the maintenance or improvement of water status is an important element of protection, and
- areas intended for the protection of economically significant aquatic species.

Figure 6.60. Protected areas in the Republic of Serbia

In areas that are used as springs for drinking water supply, Article 77 of this Law defines three sanitary protection zones, namely: wider protection zone, narrower protection zone and immediate protection zone.

Rulebook on the method of determining and maintaining sanitary protection zones of water supply sources ("Official Gazette of the RS", No. 92/2008) in Article 27 regulates that even in the wider protection zone, buildings and facilities cannot be built or used, land can be used or other activities can be carried out, if this endangers the health of the water at the source. Among other things, it is defined that surface and sub-surface works, soil blasting, penetration into the layer that covers the underground water and removal of the layer that covers the aquifer cannot be carried out, unless these works are in the function of water supply, which practically means that shallow geothermal plants cannot be used.

Figure 6.61. Protection zones (Natura 2000 from Unit Nature & Biodiversity, DG Environment, European Commission – European Environment Agency EEA. Birds directive and Habitats directive for Central Europe (EU25, EU27, EU12, EU15)) [2]

Figure 6.62. Limited usage [2]

Limited usage of very Shallow Geothermal Potential may be due to:

Protection zones (Legal constraints or complicated authorization process for geothermal installations) Source: Natura 2000 and CDDA for Iceland et al. from European Environment Agency;

Listed soil types (Histosols, Cryosols, Leptosols, Gleysols, Planosols) (Soil types unsuitable for geothermal installations).

In the case of an underground water spring in a porous medium of the intergranular type, the wider protection zone cannot be shorter than 500 m from the water intake facility, and in a porous karst-fissure type environment 1,000 m from the water intake facility in the direction of the water flow.
The wider protection zone of surface water accumulation includes the area beyond the border of the narrower protection zone up to the border that encircles basin area. The narrower surface water protection zone includes the area around the lake, the width of which is 500 m measured in a horizontal projection from the outer border of the immediate protection zone. The zone of direct surface water protection includes the above-ground tributary along the entire stream and the area on both sides of the tributary whose width is at least 10 m in horizontal projection measured from the water level at the water level of the tributary that occurs once in 10 years.

Only a zone of immediate sanitary protection has been defined for streams. It includes the water area and the territory around the water intake, whereby this space in the watercourse is marked by buoys, and on the shore by a fence that prevents uncontrolled access of people and animals, so that this zone extends upstream at least 100 m, 30 m on both sides in relation to the water flow and 20 m downstream.

Article 6 of the Law on Mining and Geological Research ("Official Gazette of RS", no. 101/2015, 95/2018 - other laws and 40/2021) in the area that represents a protected area of nature, a whole of cultural, historical and architectural significance, a tourist-recreational unit, a source of special importance for regional water supply and other protected areas, geological research and the exploitation of reserves of mineral raw materials and geothermal resources, can be approved only under the conditions issued by competent authorities and organizations in accordance with a special law for the issuance of conditions for spatial planning, nature and environmental protection, cultural heritage and other authorities and organizations competent for the relevant area related to the protected area. The same law, Article 21, defines that for the purposes of using hydrogeothermal or petrogeothermal resources, i.e. using the internal heat of the earth's crust, applied geological research is carried out. The area of the research area for performing applied geological research of groundwater and geothermal resources can be up to 10 km^2.

Rulebook on the contents of the study on the conditions of exploitation of underground water or hydrogeothermal resources, i.e. petrogeothermal resources and the conditions and manner of technical control of the study ("Official Gazette of the RS", no. 7/2018) establishes in Articles 6 and 9 that the documentation material of the study for underground water or hydrogeothermal resources, i.e. petrogeothermal resources also contains conditions for the exploitation of underground water, i.e. petrogeothermal energy issued by the Institute for Nature Protection of Serbia.

In addition, according to Article 6, the documentary material of the study for underground water or hydro-geothermal resources must contain the act of the ministry responsible for the sanitary protection of water supply sources, which confirms that the applicant has completed an appropriate study on zones of sanitary protection of underground water deposits. Among other things, the graphic appendices of the study for underground water or hydrothermal resources contain a map of the vulnerability of underground water and a map of the sanitary protection of the underground water source (Article 5).

In the process of obtaining a construction permit, for facilities with a power greater than 1 MW, it is possible to request, and for power greater than 50 MW, the preparation of a Study on the assessment of the impact of the facility on the environment is mandatory. For facilities with a power of over 50 MW, it is also necessary to obtain an integrated permit.

7 Country status report for Slovakia

7.1. Introduction to shallow geothermal energy utilization

General introduction

The studied country of Slovakia is situated in the northern part of the Carpathian-Pannonian region (Figure 7.1.). The great part of this region belongs to one of the very promising parts of Europe suitable for geothermal energy exploitation.

Activities related to geothermal energy source prospecting in Slovakia were devoted to some selected localities, but comprehensive studies of the whole area of Slovakia have also been published. The existing knowledge was concentrated and analysed mainly in the Atlas of geothermal energy of Slovakia (Franko et al., 1995). This important publication presents a summary of the research results from a period of more than two decades of the authors and other scientists working in this subject field as well. Among other problems it also evaluates the thermal, geological and hydrological conditions for geothermal energy, thermal capacity of sources and defines a basic selection of regional to separate source areas. The atlas, mentioned above, becomes the data and cartographic basis for subsequent geothermal energy studies in the region of Slovakia. The prospection and applications were aimed mainly at hydrothermal sources (Majcin, D., Král, M., Bilčík, D., Šujan, M., Vranovská, A. (2017).

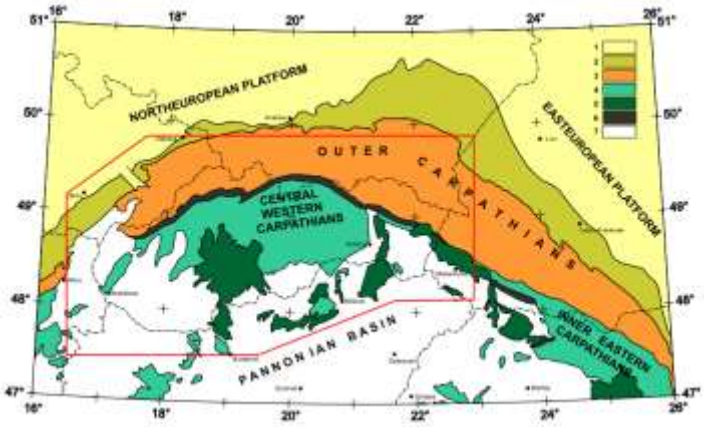


Figure 7.1. Position of the studied area in the northern part of the Carpathian-Pannonian region [1]

Historical overview of shallow geothermal development in Slovakia

The old history of utilization of geothermal energy in Slovakia is mainly the history of utilization of thermal springs. Many archaeological finds discovered at the site and in the surroundings of thermal springs indicate that man was attracted to settle in these friendly areas. Most admired in the literature of past centuries were the well-known spas: Piešťany, Trenčianske Teplice, Rajecke Teplice, Turčianske Teplice, Sklené Teplice, Vyhne, Sliač, but also Svätý Jur, Pezinok, Lipovce, Rudno, etc. First utilization of geothermal waters for energetic purposes is connected with space heating in spas and is dated to the year 1958 [2]

A pioneering systematic description of mineral and medicinal waters spas also from the territory of today's Slovakia are administered by Dr. J. Wernher. In his book On the Wondrous Waters of Hungary

he describes 22 spas and healing springs, most of them located on our territory. In the work, he also mentions physico-chemical characteristics of waters and indicative instructions for their use.
The first geothermal well in Slovakia was drilled in Gánovce, in order to obtain a higher temperature and yield geothermal waters, as the baths here were only supplied with water from natural sources. Drilling work began in 1877 and ended due to the well accident in 1879 at a depth of 183 m. It flowed from a well from a depth of 30 m water with a temperature of 21.5 °C, at a depth of 60 m the water temperature increased to 24 °C.
The success of the well was an increase in the supply of baths (13.5 l/s), which enabled their further development (Rebro 1996). During survey work on coal in Kováčová was in 1899 drilled a well from which it began to flow water (free overflow) with a temperature at the wellhead of 40.5 °C (yield 12.5 l/s). On the basis of the source of geothermal water obtained in this way, a spa was created here and later a thermal swimming pool.
The very first use of geothermal water for energy purposes is again connected with the spa and dates from 1958. That's when it started with experimental use of geothermal heat for heating residential and economic spa buildings. Three basic ones were tested systems, namely direct heating with thermal water (Piešťany, Kováčová, Sklenné Teplice), heating using heat pumps (Piešťany, Turčianske Teplice) and heating/heating of service water through thermal exchangers in Piešťany, Turčianske Teplice and Kováčová. [2]
One of the renewable energy sources that has the potential to replace natural gas to a certain extent in Slovakia is geothermal energy. In Slovakia, we have an above-average geothermal energy potential thanks to our location. Three parts of the Pannonian Basin (Záhorská nížina lowland, Podunajská nížina lowland and Východoslovenská nížina lowland) extend into the territory of Slovakia, extremely rich in geothermal resources that have been used since time immemorial. Moreover, together with our neighbor Hungary we share the Pannonian basin (see map 1), which is very rich in geothermal resources. [3]
The heat flow values in Slovakia according to the Geothermal Energy Atlas range from 40 – 120 MW/m2 (map 2). Maximum values above 90 MW/m2 were measured in the Central Slovak region neovolcanites and in the central part of the Danube basin. [4]

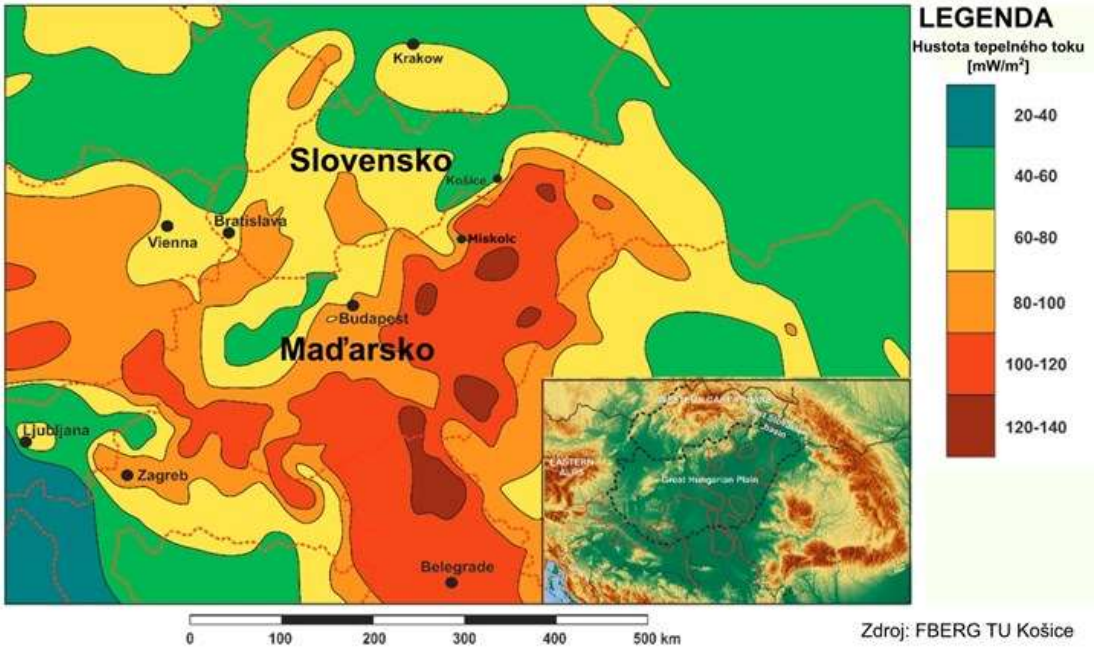


Figure 7.2. Potential of geothermal energy: Heat flux density. [3]

Existence of important geothermal water reservoir in Kosice basin in Eastern Slovakia was found out quite long ago during exploration works on hydrocarbon deposits. Predicted parameters of geothermal water was confirmed by three exploration wells drilled in years 1998-99 in the area of village Svinica. Seismic measurements (2D and 3D seismic) and hydrodynamic tests were carried out during years 2000 - 2001. Based on complex geological-tectonic knowledge obtained during this period it can be stated, that Kosice basin represents one of the most productive and important geothermal fields in European continent. [5]

Based on previous research by experts, the energy potential of geothermal energy in Slovakia is estimated at 5,500 MW. Currently, only a fraction of this geothermal energy is used, somewhere around 250 MW. [3]

In Slovakia, the majority of geothermal energy from geothermal wells is used for recreational purposes, for the purposes of heating and hot water supply, it is used only in the following four cities: Galanta, Šaľa, Sereď and Veľký Meder. [3]

In 2007, geothermal energy was used in Slovakia in 38 locations with a thermally usable output of 142.75 MW. The sources of this energy come mainly from geothermal waters, which are used in agriculture, for heating and for recreation, based on the data from the Concept of geological research and exploration of the territory of the Slovak Republic for the years 2007 - 2011. [6]

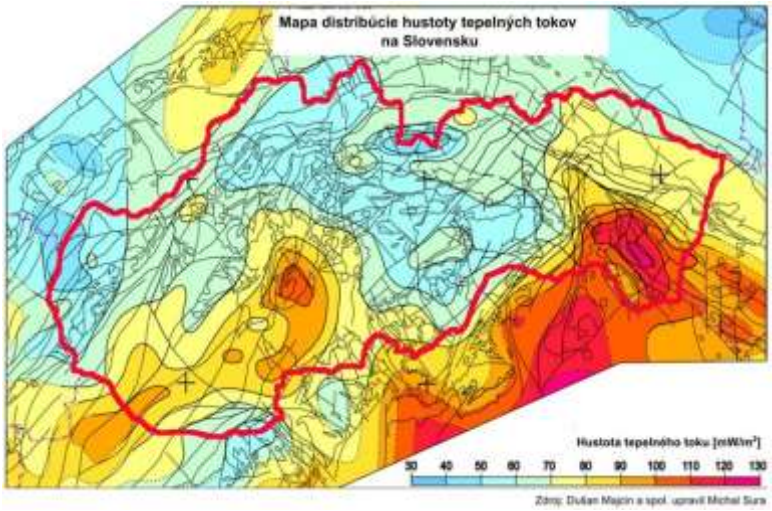


Figure 7.3. Map of heat flow density distribution in Slovakia. [3]

In frame of the concept of geological research and geological survey of the territory of the Slovak Republic, in 2017, was updated status of evaluation of prospective areas of geothermal waters in Slovakia (Figure 7.4.).

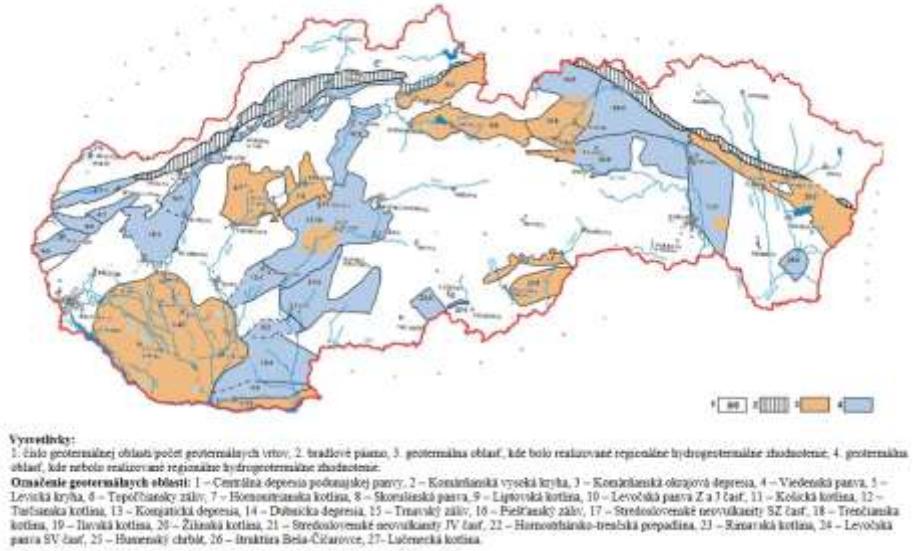


Figure 7.4. Status of evaluation of prospective areas of geothermal waters in Slovakia. [7]

Open loops, waste heat systems

The analysis revealed the most residual heat that could find further use in the east of Slovakia. Waste heat from various operations and equipment is an overlooked source. If it could be used at least partially, Slovakia can significantly reduce the consumption of natural gas and coal for heating.
This is one of the conclusions of the analysis on the potential of residual heat, which was published on (July 26, 2023) by the GreenTalk agency. [8]

Wastewater treatment plants have the greatest potential in cities

In addition to evaluating Slovakian conditions, the analysis works with data sources from two pan-European studies on the amount of unused heat from industry, households and commercial buildings. The first of them is a study of the utilization of urban waste heat in the countries of the Union under the heading of the ReUseHeat project. The second is the analysis of residual heat from industrial sites in Europe developed within the sEEnergies project. The analysis divides the potential sources of residual heat, which could be further used, into two categories: cities and industry. "Urban residual heat comes from seven main groups of producers. These include data centers, metro stations, food businesses, supermarkets, office buildings, residential buildings and wastewater treatment plants. The heat is available as heated air from the cooling units and waste hot domestic water. Their temperature ranges from 10 to over 70 °C," states Ján Janošovský, the main author of the study.
They calculated the total heat potential of municipal waste heat in Slovakia at 9.9 million GJ. The authors of the study analyzed 924 sources of waste heat in Slovakia, of which 645 were located near city heating networks. More than half of the available heat (56%) is represented by waste water treatment plants (WTP). Of the remaining sources, data centers (20%) and supermarkets (17%) were most represented. If only sources near the heating networks were taken into account, the energy potential is at the level of 8.5 million. GJ. [8]
A team of experts at the Faculty of Mechanical Engineering of the University of Applied Sciences in Žilina focused their research on the use of waste heat in industrial operations, especially in the metallurgical industry. Heat recovery is ensured by a so-called recuperation device. The technology already has its industrial use. Confal a.s., a manufacturer of aluminum alloys, has been using this technology for more than three years. Another real use of the technology is, according to the analysis of the commercial potential, carried out by the Slovak Centre of Scientific and Technical Information (CVTI SR), in the field of processing metals, ceramics, bricks, but also in gas burners and heating domestic water. The University of Žilina have cooperated on the commercialization of this technology together with CVTI SR, which implements the NITT SK project aimed at supporting the transfer of research results into practice. [9]
The heating of Trnava, which is supplied by the nuclear power plant in Jaslovské Bohunice, also works on the principle of waste heat. At the end of the 1980s, a heat feeder was built that connected the nuclear power plant with the city. Thanks to the variable component, where fuel costs are projected, the residents of Trnava pay for heat in the long term the least of the entire country. Heat from Bohunice also supplies part of Hlohovec and Leopoldov. However, there is no similar solution in the second atomic plant in Mochovce, the produced heat ends up in cooling towers.
The development of the accumulation capacity of centralized heating is connected with the next, fourth generation of CZT systems. "The existing central energy supply systems will manage the processes of production and supply of heat or cold thanks to the built infrastructure. Only through this built energy infrastructure can these ambitions be achieved," said Paul Voss, managing director of Euroheat & Power from Belgium. [10]

EU past projects experiences

The research project on the possibility of using waste heat from industry for heating in the public and commercial sector in Slovakia focused on the analysis of sources of residual heat in Slovakia and the proposal of its optimal distribution for the needs of heating buildings in the immediate vicinity was successfully completed.

Institute of materials and machine mechanics, *Slovak Academy of sciences (2023)* made research into the possibility of using waste heat from industry for heating in the public and commercial sector in Slovakia in frame of SPHERE project. [11]
The research project *Research on the possibilities of using waste heat from industry for heating in the public and commercial sector in Slovakia focused on the Analysis of waste heat sources in Slovakia and the proposal of its optimal distribution for the needs of heating buildings in the vicinity*
SFÉRA, a.s., participated in the implementation of the project as a consortium partner from March 1, 2022, to September 30, 2023. The applicant was The Institute of Materials and Machine Mechanics of the Slovak Academy of Science, a public research institution, and another partner was Aplik s.r.o. The main result of the project is a feasibility study of ecological heating using residual heat in Slovakia, including laboratory verification of the proposed procedures, which will create rational prerequisites for future investments in research and development in this area, as well as for effectively reducing environmental burdens resulting from building heating. [11]
The output of the project is a map portal of emitters and consumers of residual heat, which is available at: https://odpadove-teplo-mapa.sfera.sk/
Interreg CE project: GeoPLASMA-CE, Shallow Geothermal Energy Resources - Planning, Assessment and Mapping Strategies in Central Europe
GeoPLASMA-CE aimed to foster the share of shallow geothermal use in heating and cooling strategies in central Europe. The project created a web-based interface between geoscientific experts and public as well as private stakeholders to make the existing know-how about resources and risks associated to geothermal use accessible for territorial energy planning and management strategies in Central Europe. Planned outputs of the project focused on promoting an efficient and sustainable use of shallow geothermal in Central Europe. [12]
Research and search for geothermal resources is a part of deep geological exploration. It has been implemented for a long time by the employees of the Institute of Geosciences, Faculty of Mining, Ecology, Management and Geotechnologies of the Technical University in Košice. [13]

Scientific reports and papers, country technical reports related geothermal energy utilization

Ústav materiálov a mechaniky strojov SAV (2023). Výskum možnosti využitia odpadového tepla z priemyslu na kúrenie vo verejnom a komerčnom sektore na Slovensku. Projekt SFÉRA
Marcin, P. et al (2020). Hodnotenie stavu geotermálnych útvarov podzemných vôd na území Slovenskej republiky. Geologická štúdia.
URL:
https://old.vuvh.sk/rsv2/download/02_Dokumenty/10_Podpone_dokumenty_metodiky/Marcin_etal_2020_Hodnotenie_stavu_geotermalnych_utvarov_podzemnych_vod.pdf
Fričovský, B., Černák, R., Marcin, D., Blanárová, V., Benková, K., Pelech, O., Fendek, M. (2019). Geothermal Ene Bartko, L., Badida, M., Horbaj, P., Komkoly, J. (2014). Využitie geotermálnej energie v podmienkach Slovenska. In: Transfer inovácií 29/2014.
URL: https://www.sjf.tuke.sk/transferinovacii/pages/archiv/transfer/29-2014/pdf/304-311.pdfrgy Use, Country Update for Slovakia. In: European Geothermal Congress 2019
Fendek, M., Franko, J., Čavojová, K. (1999). Geothermal energy utilization in Slovak Republic. In: Slovak Geol. Mag., 5, 1-2 (1999).
URL: https://www.geology.sk/wp-content/uploads/documents/foto/MS/SGM/SGM%201-2-1999/Geothermal%20energy%20utilization%20in%20Slovak%20Republic.pdf

7.2. Country statistics of installed shallow geothermal systems and general energy balances

Overview of statistic data regarding to number of installed SG systems

Geothermal energy for the production of heat, supplied by centralized supply systems heat is used in southern Slovakia:

- *Sereď - geothermal energy from the SEG-1 well with a depth of 1,800 m used for heat production in the existing boiler room,*
- *Šaľa - geothermal energy from the new well GTŠ-1 with a depth of 1,800 m is used for the production of heat in the existing gas boiler room CK31. Geothermal water is pumped from the well by electricity submersible pump with the possibility of smooth speed control with a frequency converter.*
- *Veľký Meder - a 2,450-meter-deep opening releasing water with a temperature reaching 93°C provides heating for 1,300 apartments, a school, a kindergarten and a cultural center in the city,*
- *Galanta - a geothermal station that takes geothermal water from two wells and delivers it heat to approximately 1,300 apartments and the adjacent large hospital building.* [14]

Country energy mix report

Although plans, strategies and legislative actions were adopted, the Slovak Republic is still the fossil-fuels oriented economy with roughly 19 % share of renewable energy sources on a primary energy mix. A proportion of geothermal energy on heat production reaches app. 2 % only. [15]

Energy mix in Slovakia
Replacing fossil sources in the Slovak energy mix will take many years. However, the advantage is that during this gradual and inevitable transformation, we can be inspired by countries that are further along in the process and take from them the best examples of what works. [16]
As we can see from following figure 1, the highest proportion on total energy supply in Slovakia was accounted by nuclear (25%), oil (23,9%), natural gas (22,7%), coal (14,7%) and biofuels and waste (12,1%).

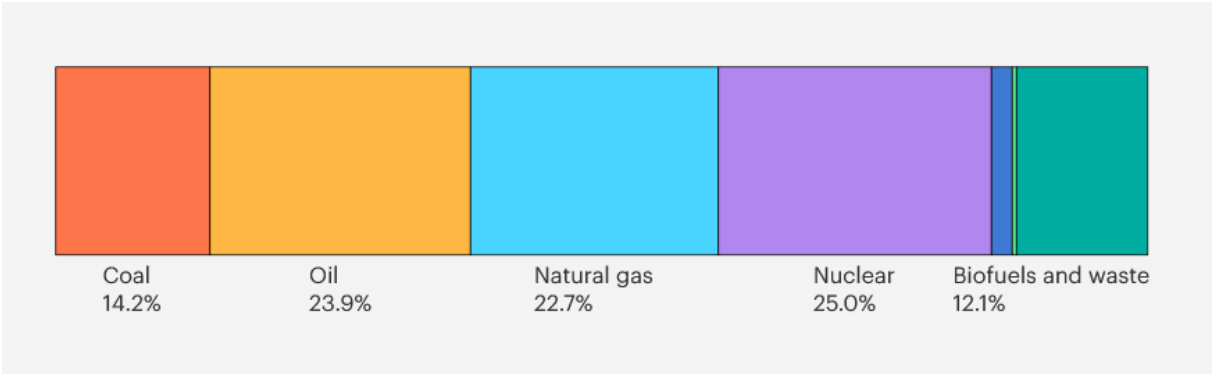


Figure 7.5. Energy mix of Slovakia (total energy supply, 2022). [17]

In case of production (Figure 7.6.), majority of energy in Slovakia is produced from nuclear sources (58,9%), biofuels and waste (29,2%), hydro (4,2%) and coal (3,1%).

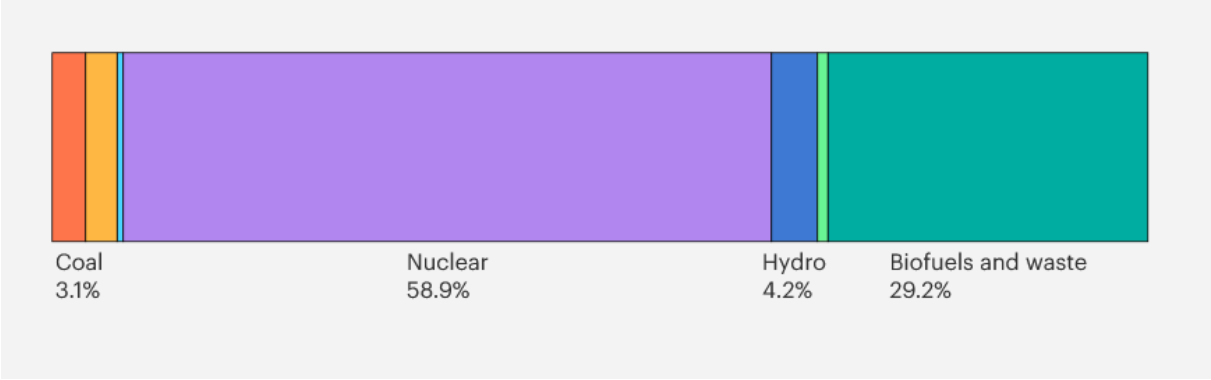


Figure 7.6. Energy mix of Slovakia (production, 2022).). [17]

Related the electricity production in Slovakia (Figure 7.7.), the majority was produced from nuclear sources (59,7%), hydro (14,2%), natural gas (7,9%), coal (7,7%) and biofuels (5,3%).

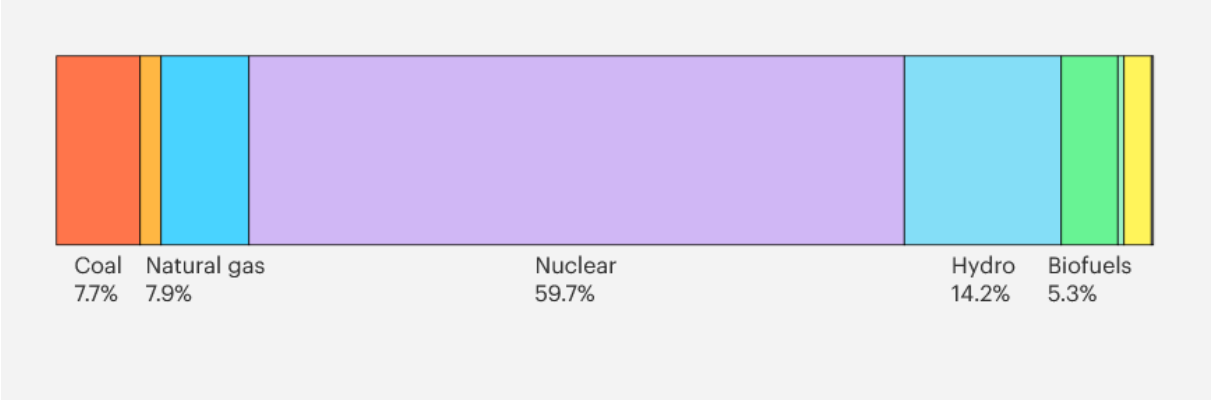


Figure 7.7. Energy mix of Slovakia (electricity, 2022).). [17]

Related to consumption of energy (Figure 7.8.), oil products accounted for (30,5%), natural gas (26,4%), electricity (18,7%), coal (7,2%) and heat (5,0%).

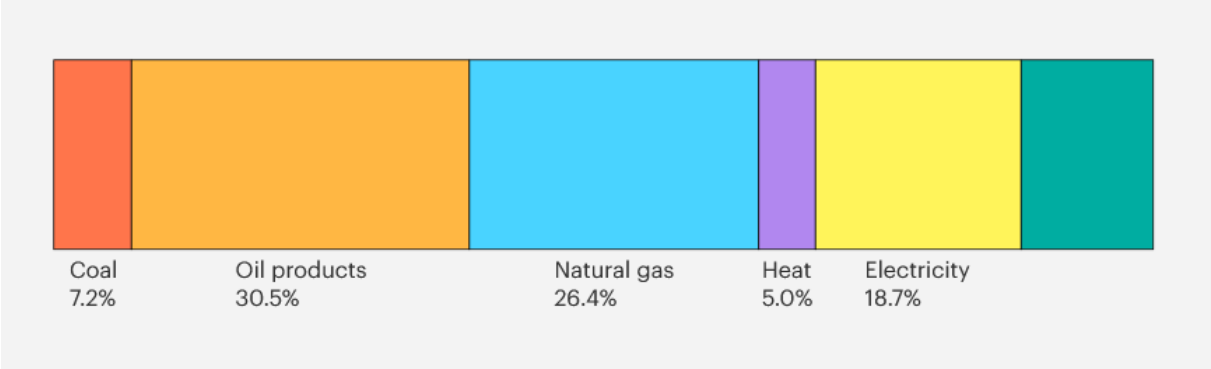


Figure 7.8. Energy mix of Slovakia (consumption, 2022).). [17]

Emissions factor for electricity production

In the long term, there is a steady, even decreasing trend in the quantities of basic pollutants (TZL, SO^2, NOX and CO) discharged. The following Figure 7.9. presents the total production of basic pollutants released into the air from all sources of air pollution of Slovak power plants (2015-2023).

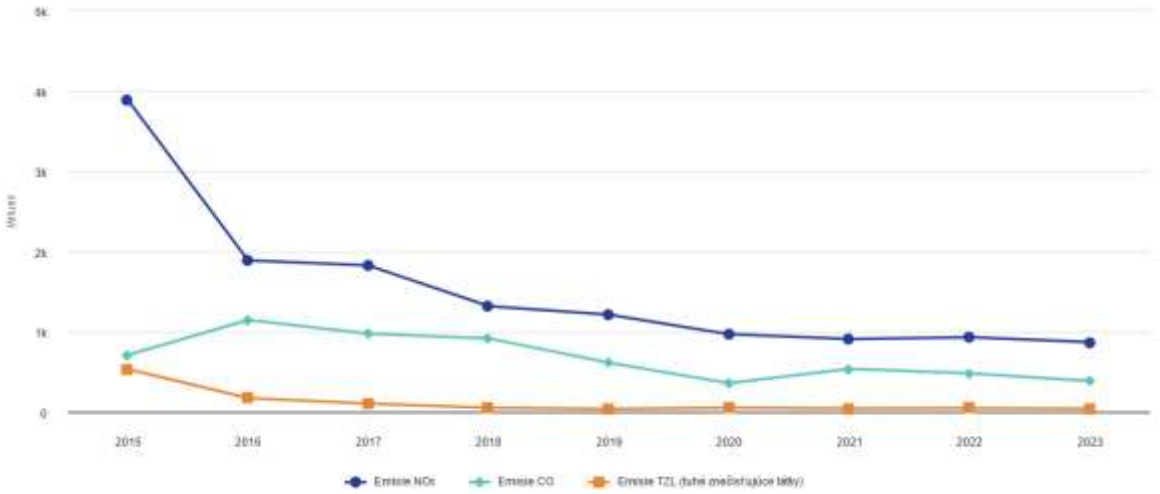


Figure 7.9. Production of air emissions from Slovak power plants. . [18]

7.3. Overview of current regulations, incentives and general policy related to shallow geothermal

Current regulations

Quantifying the potential of waste heat in Slovakia is difficult. Exact statistics do not yet exist. "There are smaller cities that have very little such potential, and the waste heat may concern some small businesses. Then there are big cities like Bratislava, where there are factories with great potential for use." Regulation in Slovakia does not yet consider this alternative. If you want to fulfill all currently valid legislative obligations, it is difficult to set up a business relationship between partners so that it is mutually beneficial. The heating workers are calling for relief from the heat supplier. The one who today disposes of the residual heat is considered a producer who makes the supply for the purpose of profit. Therefore, it must have a valid license issued by the ÚRSO for doing business in thermal energy. What is questionable above all is how the price of such purchased heat is determined. According to the current legislation, it must be two-fold and subject to the approval of the office. The unknown in this case is the fixed component or the method of determining the regulatory input and also compliance with quality standards. "There are still many problems that have not been solved, they are hanging in the air," added Ďuďák. However, according to him, there is a promise from ÚRSO and the Ministry of Economy of the Slovak Republic to clear up these shortcomings. [10]

Shallow geothermal promotion and utilization

The Ministry of Environment of the Slovak Republic has prepared a long-awaited amendment to the Act on Environmental Impact Assessment (EIA Act - Environmental Impact Assessment), which the public and institutions could comment.
The amendment regulates the permitting processes, but also the so-called threshold values, which decide whether a given investment plan will fall under the investigation procedure, the so-called small EIA, or immediately under the more complex mandatory assessment, the so-called large EIA. According to the new system, wells deeper than 500 meters are only subject to an investigative procedure and not to the mandatory environmental impact assessment, which was administratively and time-consuming until now.
The change in threshold values for geothermal wells is intended to shorten the permitting process. However, if an environmental risk is detected during the investigative procedure in the case of deep wells, the investor will be obliged to prepare a full environmental impact assessment. The rules are also changing for shallower wells up to 300 meters, no action will be required for them. Acceleration and simplification of the permitting process was also one of the milestones of the Recovery and Resilience Plan and was supposed to accelerate the development of geothermal energy in Slovakia. [19]
The Ministry of Economy of the Slovak Republic requests that it be determined in detail what conditions apply to wells deeper than 600 meters. "(...for these wells) it should be specified that they are wells other than wells for the exploitation of geothermal energy, (such as wells) for water resources and wells for research and exploration not related to mining activities and for monitoring wells for investigating soil stability ."
Furthermore, the department also lacks information on how reinjection wells will be assessed, in which the used geothermal water is pushed back underground. [19]
At least 60 geothermal wells will be certified. This will ensure public access to information about geothermal locations in Slovakia. Online information published on the website of the State Geological Institute of Dionýz Štúr will include at least the following data: the location of the well, its depth, technical condition, water parameters and the potential for geothermal use. [20]

Thanks to the new approved environmental policy Greener Slovakia – Strategy of the Environmental Policy of the Slovak Republic until 2030 (the Envirostrategy 2030), Slovakia determined a way of how to face the biggest environmental challenges and address the most serious environmental problems. [21]

Waste heat

The advantage of using waste heat is that it not only reduces the direct consumption of raw materials (coal or natural gas), but also increases energy efficiency. If the heat is used directly at the source or in the immediate vicinity, there are also minimal temperature losses during its distribution. In Slovakia, so much heat escapes into the air that it could cover at least part of the annual heating consumption. [22].
On the following map 5 we can see the potential of using residual heat in Slovakia. The analysis identifies the highest potential for its use in the Košice region in Eastern Slovakia.

Figure 7.10. The potential of using residual heat in Slovakia. [22]

7.4. General country geology, hydrogeology and thermogeological parameters

General country geology

The country is marked by two distinct geological features (Figure 7.11.) the Carpathian Mountains and the lowlands. Young tectonic processes have formed most parts of the country, e.g., the uplift of the Alpine type Carpathian Mountains. In addition, volcanism during the Tertiary period was another feature. The lowlands are filled with the erosion products of the uplifted mountains, a process starting in the Late Mesozoic.

Parts of the country belong to the Inner West Carpathian and Outer West Carpathian Mountains. In the Inner West Carpathians, Mesozoic sediments and the cores of Palaeozoic and Precambrian rocks have been folded and uplifted by Cretaceous Alpine type mountain building. In depressions and in the lowlands, sediments of Palaeogene and Neogene age have been deposited. The Outer West Carpathians are composed of flysch sediments, which were folded in the Late Tertiary by the Alpine type processes.

The sedimentary processes responsible for the Inner West Carpathians, also deposited ore-bearing rocks of Permian age. The sedimentary sequence consists of conglomerates, sandstone, siltstone and effusive rocks. Uranium is associated with copper and molybdenum mineralization and is linked to tuffaceous rocks, quartz porphyries and shales. Some uranium deposits were found during exploration conducted prior to the dissolution of the former Czechoslovakia into the Czechia and Slovakia occur in this geological environment, as exemplified by the Novoveska Huta and Muran deposits in the Slovenske Rudohorie, NW of Kosice.

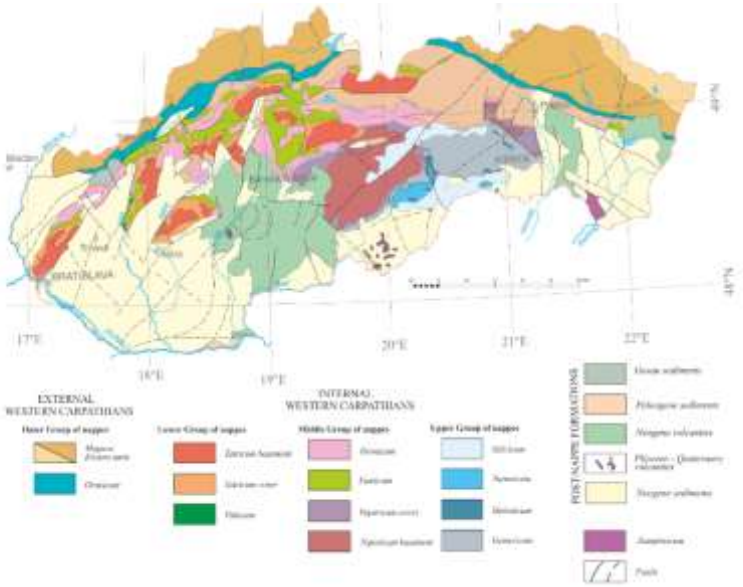


Figure 7.11. Position of principal Alpine tectonic units and post-nappe formations in the territory of Slovakia (based on Hók et al., 2014). [23]

Geological structure

- The "Flysch" Zone: altering (changing) layers of permeable sandstones with impermeable claystones
    - lack of raw materials, sandstone quarrying only
    - Biele Karpaty (mountains), Myjavská pahorkatina (uplands), Javorníky, Kysuce, Orava, Spiš, Šariš, the northern part of eastern Slovakia
- The Klippen Belt: narrow limestone belt
    - limestone quarries only
    - from the Malé Karpaty Mountains and the Považie region – Biele Karpaty – along the Váh river towards Žilina to the Orava region, the Pieniny, Humenné to Ukraine
    - many castles built upon klippens, e.g. Čachtice, Beckov, Trenčín, Oravský castles
- The Crystalline Mountains: cores of the mountain ranges are made of granites, gneiss, wart together with ferrous and non-ferrous metals, e.g. Fe, Cu, Sb, magnesite.
    - various limestones, schists, dolomites and sandstones layered upon the cores
    - Malé Karpaty, Strážovské vrchy, Malá Fatra, Veľká Fatra, Nízke Tatry a Slovenské rudohorie
- The Volcanic Mountains: volcanic rocks like andesite, basalt, non-ferrous and precious metals, e.g. Au, Ag, Cu
    - Slanské vrchy, Vihorlat, Poľana, Tríbeč, Vtáčnik
- The Neogene Hollow Basins: southern rim of the Carpathians.
    - oil, black coal, lignite, rock-salt, clays and gravel
    - Besides the Záhorská Lowland, the Podunajská and the Východoslovenská are the largest owlands in the country. [23]

Hydrogeology

In the current period, respectively in the time interval between the present and the inter-com, which represents the year 2000, we can hydrogeological works of a regional nature, which took place on the territory of the Slovak Republic, to be divided into (a) hydrogeological surveys associated with the calculation quantities of underground water; (b) compiling the base-hydrogeological and hydrogeochemical maps on a scale of 1:50,000; (c) compiling purpose-built hydro-geological maps and natural water quality maps as part of the edition of maps of environmental geofactors also mostly on a scale of 1:50,000; (d) regionally hydrogeothermal assessments of prospective areas of geothermal waters and (e) hydrogeological surveys associated with quantity calculations and setting out protection mineral water bands. [24]

Thermogeological parameters

The geothermic field is distinctly variable on the territory of the West Carpathians. Its regional character and spatial distribution of geothermal acitivity are mainly determined by Franko et al. (1995): different depth structure of neotectonic blocks of the West Carpathians, mainly manifested by different thickness of earth crust and non-uniform contribution of the earth mantle the course of the main disconformity and fault lines deep -seated in the earth crust spatial distribution of Neogene volcanism distribution of radioactive resources in the upper parts of the earth crust hydrogeological conditions.

To the end of 1998 geothermal waters were proved by 63 geothermal boreholes in 15 areas. By geological boreholes these waters were proved in further 8 areas. So far 4 areas have not been proved. The yield of boreholes varies within the range of 5-100 I.s and temperature of waters 40-90 °C. SLOVGEOTERM Bratislava investtgated the geothermal waters in the Kosicka kotlina Depression with temperatures 120-130 °C and yield of boreholes about 60 -120 I.s. When we subtract the yield of natural outflows with temperatures 15-20 °C so the yield of geothermal boreholes is nearly by 370 l.s higher in favour of waters with temperatures more than 40 °C. [24]

The Slovak THFD values, used here for the analyses, were determined in 155 boreholes. The data represent practically all the basic structural-tectonic units of the Western Carpathians and the northern offsets of the Pannonian Basin as well. The constructed terrestrial heat flow density distribution Figure 7.12. is shown together with the main surface structural boundaries and faults. The determined heat flow density values for boreholes within the studied area of Slovakia span the interval of 40–130 MW/m^2. In general, the THFD increases across the structures of the Carpathian arc from the outer Carpathian units toward the Pannonian basin units. The greatest heat flow (values of THFD greater than 120 MW/m^2) exterrestrial heat flow density (THFD) data exists in the eastern part of the East Slovakian Basin – Trebišov Depression.

Values greater than 100 MW/m^2 were observed in the prevailing part of this basin. Heat flow density over 100 MW/m^2 is also typical for the central part of the Central Slovakian Neovolcanics. THFD values greater than 90 MW/m^2 were determined in Gabčíkovo Depression in the central part of the Danube Basin. The smallest heat flow densities with mean value of 55.0 ± 10.2 MW/m^2 characterize the thermal state in the area of the Vienna Basin. The terrestrial heat flow densities below the value of 60 MW/m^2 were also observed in the western part of the Outer Carpathian Flysch Belt and moreover they are typical for the Tatra Mountains as well as for mountain regions in the Central part of Slovakia. The eastern part of the Outer Flysch Zone is characterized by THFD values between 70 and 80 MW/m^2. In other regions of Slovakia, the thermal activity is average with the heat flow density data predominantly within the range of 60 – 70 MW/m^2. The final map of the terrestrial heat flow density distribution in

Slovakia and adjacent areas predicts the selection results of regions suitable for the utilization of geothermal energy in the electric power production. It determines mainly the parameters of thermal renewability of source areas. [1]

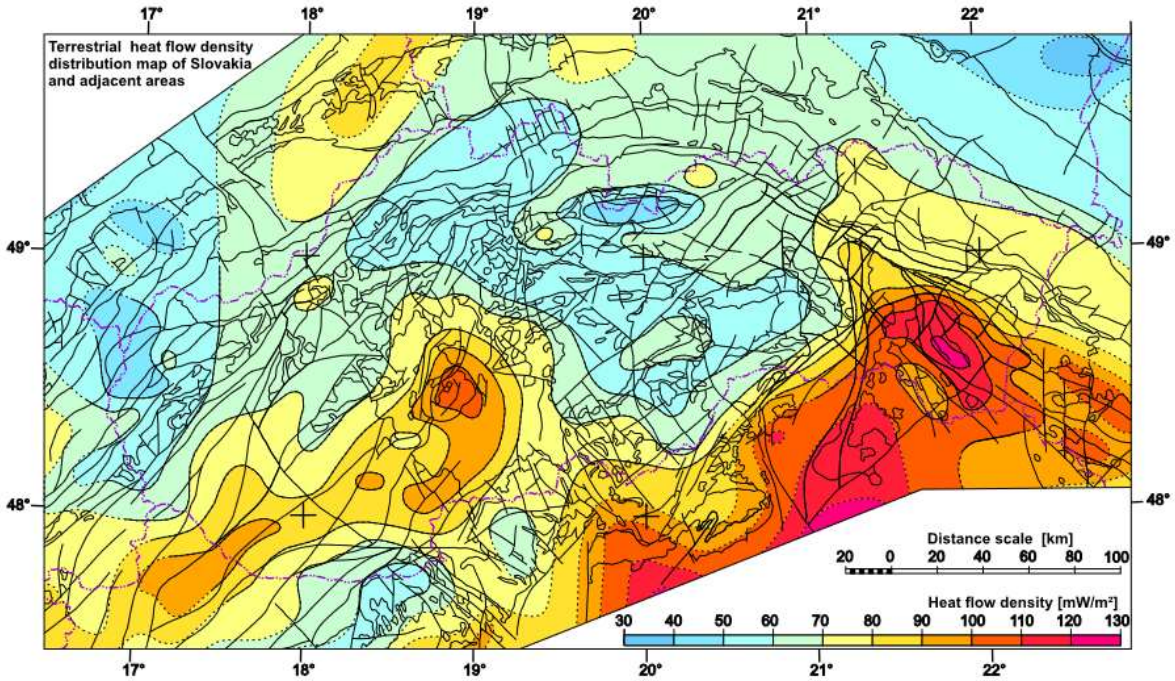


Figure 7.12. Terrestrial heat flow density distribution [MW/m²] in the Slovakia and adjacent area. Basic scheme of surface structure boundaries and faults (Lexa et al., 2000). Source: Majcin, D., Král, M., Bilčík, D., Šujan, M., Vranovská, A. (2017)

7.5. Current energy cost comparison for residential and non-residential sector with estimated capital cost of drilling and equipment for shallow geothermal

Current energy cost comparison for residential and non-residential sector

In April 2024, the average wholesale electricity price in Slovakia stood at 62.73 euros per MW-hour, a year-over-year decline of roughly 40%. Electricity prices in the country had been on a mostly upward trend from mid-2020 to summer 2022, soaring in the following years amid an energy supply shortage that severely impacted Europe. This was the result of a myriad of factors, including increased heating demand due to cold winters, a rise in natural gas and coal prices, a decrease in wind power generation due to low wind speeds, and, more recently, Russia's invasion of Ukraine and extreme temperatures in the summer of 2022. [25]

Electricity prices for household consumers

According to the latest Eurostat data (2023), Slovak households pay approximately one third less for energy than the European average. In terms of electricity prices in the first half of 2019, we are in ninth place from the end, that is, we pay about a third less than the EU average and half less than in the most

expensive country, Germany. Slovak households have the sixth cheapest gas in the EU. For comparison, Czech households have significantly more expensive electricity and gas. Even these latest Eurostat data thus confirm the results of the office's consistent regulatory policy.[1] The latest data (2023) on the European level is seen on the Figure 7.13. and map 7.

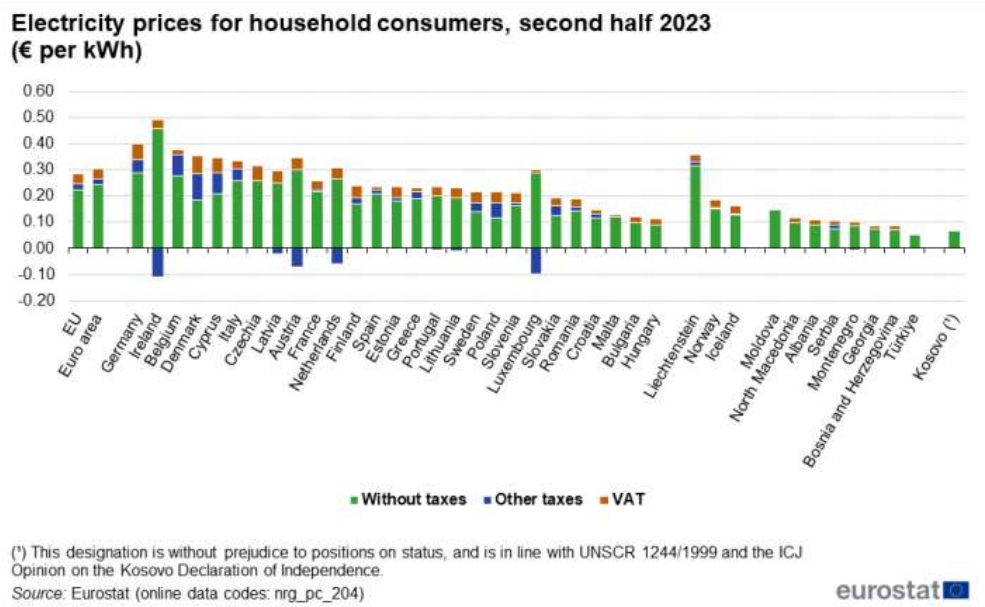


Figure 7.13. Electricity prices for household consumers in EU. Source: Eurostat[2]

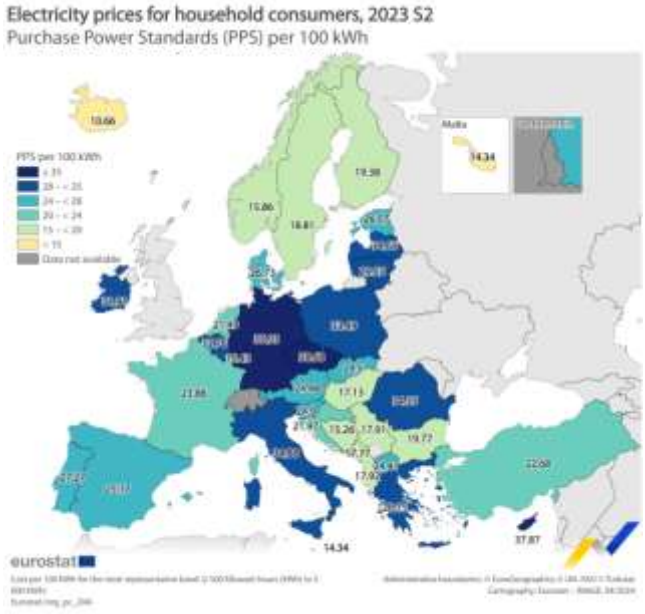


Figure 7.13. Electricity prices for household consumers (2023). [26]

[1] https://www.urso.gov.sk/eurostat-energie-pre-domacnosti-v-sr-medzi-najlacnejsimi/
[2]https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics#Electricity_prices_for_household_consumers

In case of Slovakia, final energy prices (electricity, natural gas, heat from central heat supply systems) in 2023 for households and others customer groups were the result of the application of regulatory tools by ÚRSO and as well of extraordinary state measures - changes to the legislation in the NR of the Slovak Republic and decisions of the Government of the Slovak Republic - which had priority before ÚRSO regulation. ÚRSO used systemic as well as extraordinary tools of the EU and SR legislation to mitigate increases regulated energy prices in 2023, e.g. use of revenues from cross-border auctions for stabilization electricity transmission fees.

The result of the mentioned legislative and executive state measures is relatively fundamental protection households and other groups of vulnerable energy consumers from the extreme impacts of energy crisis. The increase in the price of electricity for the average household in the Slovak Republic in 2023 was less than 3% compared to 2022, which with an average annual electricity consumption of 2,4 MWh, it represents an increase in costs of approx. 1 EUR per a month. In the Table 7.1. we can see estimation of the average price of electricity for households in Slovakia

Table 7.1. Final price of electricity for households in 2023. . [27]

Estimation of the average price of electricity for households (EUR/MWh)	**2022**	**2023**	
		URSO price decisions	With extraordinary government measures
Supply	79,62	83,83	83,83
Distribution and transfer	53,15	94,85	53,15
TSS	6,30	10,13	6,30
TPS	15,90	25,48	15,90
NJF	3,27	3,27	3,27
Final price of electricity, without VAT	158,24	217,56	162,45
VAT	31,65	43.51	32,49
Final price of electricity, with VAT	189,89	261,08	194,94

Electricity prices for non-household consumers

The Slovak government approved a ceiling on electricity and gas prices for companies with regulated energy prices. How much will they pay and what to do if the advance invoice has already arrived? On January 16, 2023, a regulation was approved capping the prices of regulated electricity and gas supply for small businesses. These are business entities that consume electricity up to 30 MWh per year and gas up to 100 MWh per year. In 2023, these entrepreneurs will pay a maximum of 199 EUR/1 MWh (without VAT) for electricity. [28]

Other customers - the so-called small businesses as well as unregulated consumers of electricity have state-capped prices for electricity supply in the amount of 199 EUR/MWh for 80% of their consumption, with a limit of the maximum amount of compensation per customer, and other fees (TSS, TPS, distribution, transmission) for electricity are capped at the level of 2022. [27]

The latest data on electricity prices for non-household consumers (2023) on the European level is seen on the figure 7.

Non-household consumers are defined as medium-sized consumers with an annual consumption between 500 MWh and 2 000 MWh. As depicted in Figure 7.14., electricity prices in the second half of 2023 were highest in Cyprus (€0,2759 per KWh) and Hungary (€0,2695 per KWh). The lowest prices were observed in Finland (€0,0885 per KWh) and Sweden (€0,0901 per KWh). The EU average price in

the second half of 2023 was €0,2008 per KWh. The aggregates are weighted averages taking into consideration the average consumption in each band. [26]

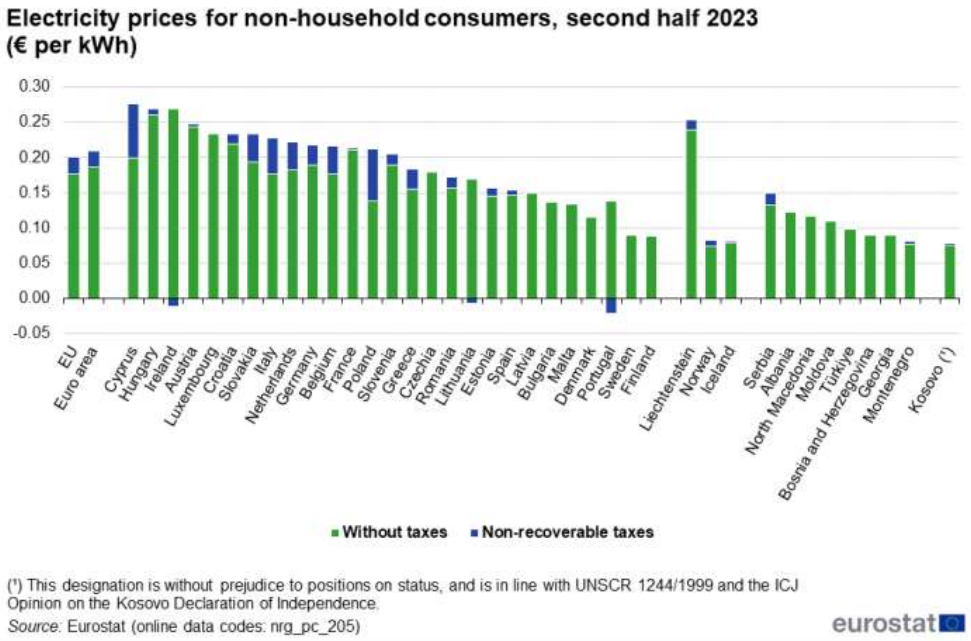


Figure 7.14. Electricity prices for non-household consumers. [26]

In case of Slovakia, electricity prices for non-household customers peaked in 2022 (Figure 7.15.) during the global energy crisis. That year, both electricity prices for consumers with annual consumption between 500 and 2000 MWh and between 20000 and 70000 MWh stood at approximately 23 euro cents per KWh. [29]

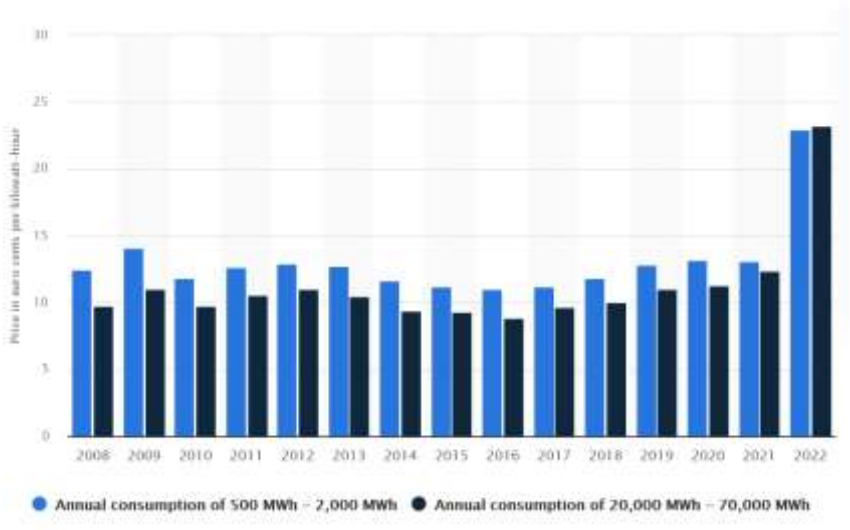


Figure 7.15. Electricity prices for non-household consumers in Slovakia from 2008 to 2022, (in euro cents per KWh). Source: STATISTA (2024)

Estimated capital cost of drilling and equipment for shallow geothermal

The uncertainty associated with subsurface resources makes it difficult ensuring financing of projects; states that the initial phase of a project such as exploration and construction phase, requires significant initial costs and high business risk hindering the investment decision. [30]
The volume of investments only in the geothermal well without additional connection and infrastructure ranges in the order of millions of euros. At the same time, however, the result in the form of its real usability is uncertain. The expected potential in specific parameters such as water temperature, yield, or mineral content is not always confirmed. [31]
However, the high capital requirement of exploratory geothermal wells is a barrier to development. They are the riskiest part of the investment in geothermal energy and range in the order of millions of euros. However, without them, it is not possible to find out the parameters of the geothermal source, and thus not even predict whether the project will be successful. [32]

7.6. Environmental regulations and restrictions related to shallow geothermal development

According to the legislation, each new well is defined as "exploratory" until the aforementioned two documents are obtained - the approval of the final report and the permit for pumping and discharge or reinjection. Subsequently, the well can be reclassified as "pumping".
A permit to extract geothermal energy in a given area and with specific parameters is issued in Slovakia for a maximum of ten years, after which it can be renewed.
One more thing is needed in the permit package - the use of geothermal energy also falls under the mining law. It is therefore necessary to obtain a mining permit, as there is a special intervention in the earth's crust.
According to the scope of the project, construction and water law proceedings are divided between the building office and the state water administration body. The first assesses objects that are not in "contact" with geothermal water, for example shelters of geothermal wells or objects of exchanger stations, the second objects in "contact" with geothermal water, i.e. pipelines or technological equipment.
The use of geothermal energy also entails an ongoing obligation to record the amount of extracted water. A so-called hydrological balance is created, which the customer must send to the Slovak Hydrometeorological Institute every year.
However, the obligations do not end at this point either, because the production of energy itself - for example, the supply of heat - is regulated by law. It is possible to do business in thermal energy only on the basis of a permit. A condition for its issuance is, among other things, a Thermal energy is additionally subject to the Act on Regulation in Network Sectors. According to him, heat is considered a commodity and its price must be determined for the given regulatory period on the basis of a decree approved by the Network Industry Regulation Office (ÚRSO). At the same time, he continuously supervises compliance with the rules in the area of heat prices.
From the moment of thinking about the use of underground energy sources to the heating of homes or use in industry, there is a rather thorny path. However, every investor in Slovakia must pass it. However, it is worth it for a more ecological alternative to traditional fossil fuels that pollute the environment violently. [33]

The Ministry of Economy of Slovak Republic together with the Ministry of Environment of the Slovak Republic reminded that all projects must be implemented in accordance with the requirements for environmental protection and the principles of sustainability.
"Geothermal energy is one of the cleanest energies. However, when using it, all the effects of geothermal wells on the environment must be taken into account. That is why it is not possible to completely remove administrative barriers during permitting," the environment department told EURACTIV Slovakia.
The Ministry of Environment of the Slovak Republic also emphasized that "based on past experience, the absolute majority of successful geothermal wells are also subject to an environmental impact assessment in accordance with the Act on Impact Assessment, which must be carried out prior to authorisation".
In the future, according to the environmental department, it is possible to count on changes in the EIA law for investment projects, including geothermal wells. "It is not possible to completely eliminate the assessment of geothermal wells from the point of view of their expected effects on the environment, as Slovakia is also bound by the European EIA directive," the ministry pointed out. [32]
How does someone who decides to use geothermal energy as a renewable energy source proceed?
In the beginning, it is necessary to develop a so-called geological task project and at the same time obtain a decision on the determination of the exploration area where an exploration well can be implemented. It is a license valid for four years. However, if its holder does not invest at least 10% of the planned budget in the first two years of use and then 70% of the planned budget by the end of the fourth year, the exploration territory is "cancelled". If the conditions are met, on the other hand, it is possible to extend the license and continue the further development of the project.
An Environmental Impact Assessment (EIA) process is required to begin geothermal drilling. In Slovakia, all wells with a depth greater than 500 meters are subject to mandatory evaluation, which increases the time required for the implementation of geothermal projects and contributes to their slower development.
Although the assessment of environmental impacts also concerns the geothermal power plant or heating plant itself, an investigative procedure (so-called "small EIA") is sufficient for devices with a capacity of up to 50 MW. However, the "Big EIA" is necessary precisely because of the implementation of the well, which is the basis of the projects. Investors cannot avoid it, and in connection with it they usually opt for joint proceedings, which, however, also take several months.
Only the investor who goes through this process, and therefore receives a positive final opinion from the Ministry of the Environment, can start the geological task itself, in this case an exploratory well.
As part of the evaluation of the source, a so-called hydrodynamic test is also carried out, which should confirm the assumptions for pumping groundwater. Subsequently, a final report is created, which must be done by a professionally qualified person - a hydrogeologist. The document already states the specific amount of water and geothermal energy used.
With the final report, the investor comes again to the Ministry of the Environment, where he submits it to the opposing committee for stock classification. The commission will start the approval procedure within six months. After that, the investor can apply for a permit for the permanent withdrawal and discharge or reinjection of geothermal waters in accordance with the Water Act, which is also subject to approval of the building and well.
According to the legislation, each new well is defined as "exploratory" until the aforementioned two documents are obtained - the approval of the final report and the permit for pumping and discharge or reinjection. Subsequently, the well can be reclassified as "pumping".
A permit to extract geothermal energy in a given area and with specific parameters is issued in Slovakia for a maximum of ten years, after which it can be renewed. [33]

8 Country status report for Slovenia

8.1. Introduction to shallow geothermal energy utilization

The Geological Survey of Slovenia (GeoZS) has been monitoring the use of shallow geothermal energy for almost 30 years. The first data on geothermal use was published in 1995 [210], and since 2009 it was updated every year. The GeoZS obtains data on ground-source heat pumps (GSHPs) from sellers (also directly from domestic producers), who informs of the number of GSHP units sold and their characteristics (brand, type, typical rated power or capacity, efficiency or COP, approximate hours of operation). Based on a comparison with the records of the Slovenian Water Agency (DRSV), the ECO Fund, the Statistical Office of the Republic of Slovenia and the Ministry of the Environment, Climate and Energy, as well as publications in the media, cross-check is done with data from buildings where heat pumps were installed, but the latter only for GSHP systems with a power of at least 20 kW. Some vendors sell several different brands of heat pumps as well as GSHPs, although there are fewer such sellers [211]. Until 2022, the existing method of obtaining data from sellers was through letters and Excel attachments by e-mail and, if necessary, through telephone interviews (115 different sellers). Due to excessive correspondence and difficult traceability, a new system was developed started with work in 2023. The purpose of the update was to simplify both the vendor reporting side as well as the data processing side of GeoZS and provide feedback to reporters so they can track their progress. In the last two years, only one third of all manufacturers (sellers) decided to enter relevant data in the new system.

In addition to collecting statistical data on operating GSHP systems as part of the country report, GeoZS participates or has participated in several European projects related to the field of shallow geothermal energy:

1. *GEO.POWER (2010-2012):* Geothermal energy to address energy performance strategies in residential and industrial buildings. The general objective of GEO.POWER project was to exchange Best Practices related to low enthalpy geothermal energy supply and, after a technical and cost/benefit assessment, to evaluate the potential of reproducibility to prepare action plans for the large-scale introduction of ground-coupled heat pumps (GCHP, i.e. only closed-loop systems) in each of the Partner regions [212]. The core results achieved by this project have consisted of the elaboration of 8 action plans to encourage the GCHP market. Based on the local legislative and economic situation, as well as on the market potential, each project partner (PP) has developed its own document and suggested different strategies for GCHP implementation. The action plans provide the Managing Authority (MA) of the European Regional Development Fund (ERDF) with an organized set of initiatives to address long-term investments strategy for GCHP applications at wide scale [213]. Therefore, GeoZS prepared an action plan for Slovenia, which includes a set of best legal, regulatory, economic and technical-technological proposals. Their inclusion in regional operational programs should influence the long-term strategy for the widespread use of ground-source HP (GSHP) technology. Related to this one, GeoZS elaborated also a more popular brochure [214]. The GEO.POWER Action Plan provided an extensive analysis and actions for GSHP application at wide scale through structural policy SI 2014-2020. The three core actions which aim at future GSHP development and penetration in Slovenia are [215]:
   A n. 1: Improvement of administrative procedures (OP for human resources development),
   A n. 2: Quantifying GSHP energy delivery (OP for Strengthening regional development potential),

A n. 3: GSHP subsidies for large-scale project and innovative systems (OP of Environmental and transport infrastructure development).

2. *LEGEND (2012-2014)*: The main objective of the project was to promote the use of low-temperature shallow geothermal energy and all its advantages and benefits in energy-efficient designs for heating and cooling buildings in the Adriatic area [216]. This objective was accomplished through:
    - Development of 10 demonstration cases in public & residential buildings utilizing GSHP (5 in Italy, 2 in Croatia, 1 in Albania, 1 in Montenegro, 1 in Bosnia & Herzeg.),
    - Development of cost/benefit monitoring activities and policy & financial supporting schemes to overcome market barriers,
    - Knowledge fertilization through training and workshops for energy managers and technicians to get familiar with GCHP potentialities.

    LEGEND (**L**ow **E**nthalpy **G**eothermal **En**ergy **D**emonstration cases for Energy Efficient Building in Adriatic area) was European project co-financed by the IPA Adriatic CBC Programme. Its overall objective was the promotion of energy efficiency concepts and the low-enthalpy geothermal energy benefits in the Adriatic area through 10 demonstration GSHP cases in public buildings, SWOT analysis, pre-investment surveys, Life Cycle Analysis methods, thematic workshops, technical seminars and political and technical memorandum and guidelines. Natural geological, hydrogeological and ground thermal characteristics in several regions included in this project, belonging to both the Adriatic coast and hinterland were presented at WGC 2015, together with their inter-comparison [217]. Data and description of the values, which are important for proper planning of GSHP installations, were substantially taken from benchmark reports, made by each partner in the framework of the project and for some regions real data originating from 10 demonstration projects. GeoZS also elaborated a booklet titled “Collection of lectures from the cycle of seminars for strengthening competence in the field of low-temperature geothermal energy utilization in Slovenia” [218].

3. *GRETA (2015-2018):* The main aim of the project GRETA (near-surface **G**eothermal **Re**sources in the **T**erritory of the **A**lpine space) was to overcome some of the main barriers to the uptake of GSHPs, focusing on the following issues [219]: 1) the simplification of existing regulations and licensing procedures, based on best existing practices; 2) addressing design and technical issues of different shallow geothermal technologies with a focus on specific Alpine conditions; 3) assessing the geothermal potential and the possible underground interferences with the installation of borehole heat exchangers (BHEs) and wells; 4) developing tools to include shallow geothermal energy in local energy plans of three pilot areas, i.e. Oberallgäu (Germany), Cerkno (Slovenia) and Aosta Valley (Italy); 5) development of a network for interaction and knowledge exchange network with stakeholders. GeoZS successfully established the “Cerkno Geothermal educational trail”, the first of its kind in Slovenia, which consists of 10 location points, together with detailed explanations in a booklet [220].
    The GRETA project studied the opportunities, technical issues and economic viability of applying near-surface geothermal energy to villages, public buildings with specific constraints and isolated Alpine huts [221].

4. *GeoPLASMA-CE (2016-2019):* Shallow Geothermal Energy Planning, Assessment and Mapping Strategies in Central Europe. The GeoPLASMA-CE project aimed to foster the share of shallow geothermal use in heating and cooling strategies in central Europe. The project created a web-

based interface between geoscientific experts and public as well as private stakeholders to make the existing know-how about resources and risks associated with geothermal use accessible for territorial energy planning and management strategies in Central Europe [222].

5. *MUSE (2018-2022):* Managing Urban Shallow geothermal Energy (MUSE) investigates resources and possible conflicts of use associated with the use of shallow geothermal energy (SGE) in European urban areas and delivers key geoscientific subsurface data to stakeholders via a user-friendly web-based GeoERA information platform (GIP) [223]. The assessment of geothermal resources and conflicts of use were used for the development of management strategies considering both efficient planning and monitoring of environmental impacts.

6. *PanAfGeo-2 (2021-2024):* Pan-African Support to the EuroGeoSurveys – Organisation of African Geological Surveys (EGS-OAGS) Partnership (PanAfGeo), is a project that supports the training of geoscientific staff from African Geological Surveys [224].

8.2. Country statistics of installed shallow geothermal systems and general energy balances

Shallow geothermal energy use for space heating and cooling in decentralized small units in Slovenia is becoming more popular and widespread. The market boom in larger scale began during the last 15 years after a slow period in the early 1990s with low interest in SG systems, due to high initial costs, high prices of electricity and low prices of oil and gas. Depending on local conditions, two types of SG systems can be implemented: closed-loop or ground-coupled heat pump (GCHP) systems (with horizontal and vertical heat collectors) and open-loop or groundwater heat pump (GWHP) systems.
The number of GSHP units presently installed, and their capacity and energy supplied are based on heat pump sales reported by domestic manufacturers and numerous sellers of imported units. As of 31st Dec. 2023 (Figure 8.1.Figure 8.1), there are approximately 16166 small GSHP units (typically 12 kW) in operation, extracting 972,21 TJ (270,06 GWh) of geothermal heat in 2023. Of these, 44,1% are open-loop systems, which extracted 486,98 TJ from shallow groundwater, 32,5% are horizontal (incl. thermal baskets) closed-loop (with 278,62 TJ), and 23,4% are vertical closed-loop systems (with 206,61 TJ). Small closed-loop units together extracted 972,21 TJ/yr of heat from the ground. There are also 1203 GSHP units of bigger capacity (>20 kW) installed in public and other buildings, which extracted 461,62 TJ of heat in 2023. Of them, 837 units are of open-loop systems (69,6%), 301 units are vertical (25,0%) and 65 (5,4%) are horizontal closed-loop systems. In 2023, 1433,83 TJ of heat was extracted (Figure 8.2Figure 8.2.), while about 360 TJ/yr of heat was injected into the ground in the cooling mode.

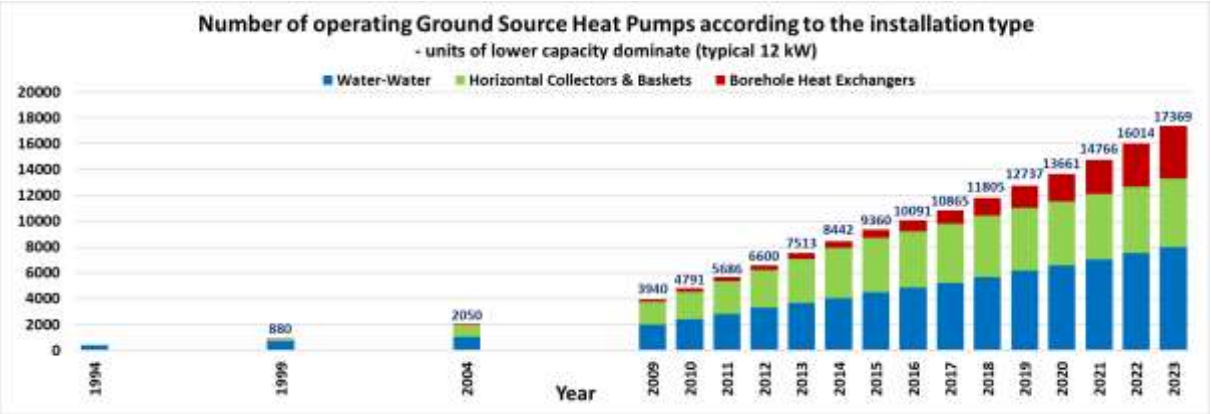


Figure 8.1. Trend of numbers of operating GSHP units (both small & big-rated capacity, surface water HPs incl.) since 1994 by type of installation (updated after [])

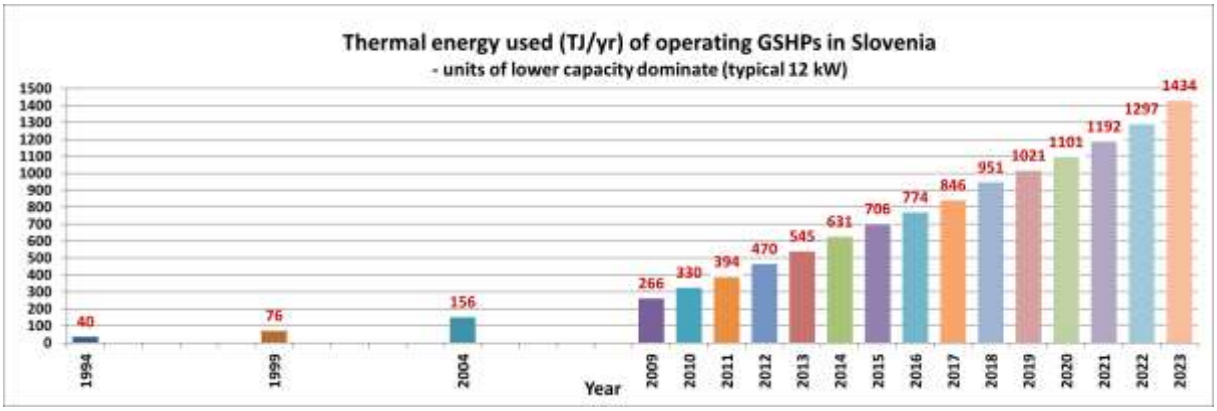


Figure 8.2. Trend of shallow geothermal energy used (TJ) by operating GSHP units (both small & big-rated capacity, surface water HPs incl.) since 1994 (updated after [])

The Slovenian energy balance for 2022 is shown in the table (Table 8.1.Table 8.1) [225]. The energy balance is divided by supply and consumption and by energy source. The Slovenian energy indicators for 2022 are shown in the table (

Table 8.2.) [226]. The Slovenian data on the use of renewable energy and waste for 2022 divided by energy source and type of use, are summarized in table (

Table 8.3.) [227]. The average CO_2 emission factor for electricity generation in 2022 was 0,304 $kgCO_2$/kWhe and GGE 0,306 kg CO_2eq/kWhe [228]. The average emission factor for CO_2 emissions based on data published in January 2023 from records in the period 2002-2022 is 0,45 $kgCO_2$/kWhe and 0,45 $kgCO_2$/kWh for GGE emissions (Figure 8.3.). The emission factor has been significantly lower since 2014 than before this year, which is due to the commissioning of the new TEŠ 6 unit (Šoštanj Thermal Power Plant 6) and the cessation of production in units TEŠ 1-4 and also in TeTol (Ljubljana Thermal Power Plant). The increase in electricity generation from renewable energy sources also contributes to the reduction in the emission factor. The emission factor for district heating was 0,34 $kgCO_2$/kWh in 2022 and 0,35 $kgCO_2$/kWh in the period 2002-2022 (Figure 8.3.) [228].

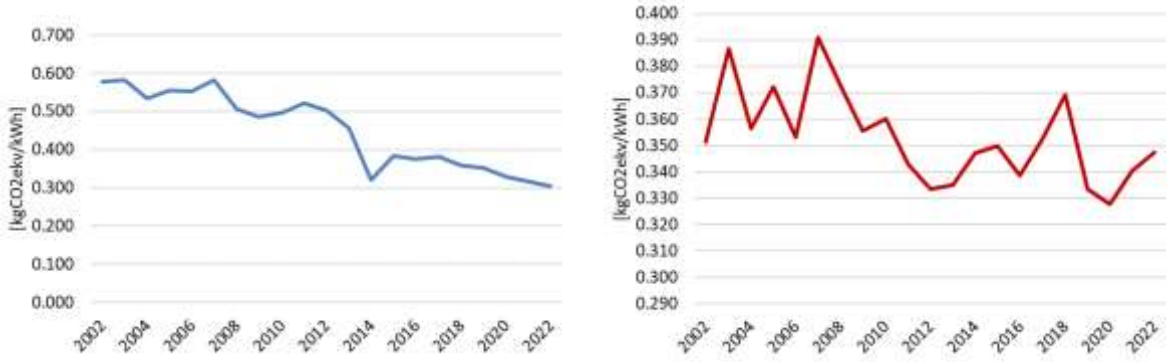


Figure 8.3: Left: Average emission factor for GGE due to electricity production in Slovenia, Right: Average emission factor for GGE due to district heating (source [228])

Table 8.1. Slovenian energy balance (TJ) for 2022 by supply and consumption and energy source (source [225])

	Solid fuels	Crude oil	Petrole. products	Natural gas	Nuclear	Hydro	Geotherm., solar etc.	Renewables and waste	Electricity	Heat	Energy sources - TOTAL
Indigenous production	27381	7	0	147	61151	11335	5849	25266	-	-	131135
Imports	8931	0	192143	28467	-	-	-	4204	36714	-	270458
Exports	-107	-5	-97963	0	-	-	-	-813	-31508	-	-130397
Stock changes	-4882	-1	1575	-	-	-	-	-14	-	-	-3322
Domestic Supply	31323	0	95754	28614	61151	11335	5849	28643	5205	0	267875
Statistical differences	-55	0	0	0	0	0	0	0	0	0	-55
Transformation - Total	-29959	0	-1106	-5128	-61151	-11335	-2387	-4354	49016	8942	-57461
Own use and losses	-	-	-	-	-	-	-	-	-6961	-2135	-9096
Total final consumption	1419	0	94649	23486	0	0	3462	24289	47260	6808	201372
Total final consumption - Energy sector	0	-	27	27	-	-	0	0	305	57	415
Total final consumption - Manufacturing and construction	1155	-	4564	16823	-	-	0	5049	19815	2011	49417
Total final consumption - Transport	0	-	78201	202	-	-	-	3317	989	-	82709
Total final consumption - Households	0	-	5209	4197	-	-	2930	15085	13432	2942	43794
Total final consumption - Agriculture and forestry	0	-	2883	0	-	-	122	0	96	0	3102
Total final consumption - Service activities	0	-	2349	2012	-	-	410	838	10732	1769	18111
Total final consumption - Other consumers	0	-	876	5	-	-	0	0	1891	28	2800
Total final consumption - Non-energy use	263	-	540	221	-	-	-	-	-	-	1024

Table 8.2. Slovenian energy indicators for year 2022 (source [226])

INDICATOR	2022
Indigenous production (1000 toe)	3132
Domestic Supply (DS) (1000 toe)	6398
Total final consumption-TFC (1000 toe)	4810
Energy dependency (%)	52.3
Energy efficiency (%)	75.2
Energy Intensity - DS/GDP (toe/mio EUR 2010)	139
Energy intensity - TFC/GDP (toe/mio EUR 2010)	104
Electricity consumption/GDP (MWh/mio EUR 2010)	285
DS / capita (toe/cap.)	3.02
TFC / capita (toe/cap.)	2.27
Electricity consumption per capita (kWh/cap.)	6201
RES heating and cooling (%)	33.99
RES electricity (%)	37.01
RES transport (%)	7.83
RES overall share (%)	25.00
... of which from cooperation mechanism (%)	2.06

Table 8.3. Slovenian renewable energy and waste use (TJ) for year 2022 (source [227])

ENERGY SOURCE	Transformation	End use	Total
Geothermal and ambient heat* (TJ)	42.230	3042.874	3085.104
Solar thermal (TJ)	-	418.977	418.977
Solar photovoltaic (TJ)	2324.113	-	2324.113
Wind (TJ)	20.632	-	20.632
Industrial wastes - renewables (TJ)	-	135.204	135.204
Industrial wastes - non-renewables (TJ)	407.659	1845.667	2253.326
Municipal Solid Waste - renewables (TJ)	-	-	-
Municipal Solid Waste - non-renewables (TJ)	-	-	-
Wood/Wood wastes/Other Solid Wastes (TJ)	2995.419	18857.181	21852.600
Landfill gas (TJ)	29.894	25.794	55.688
Sewage sludge gas (TJ)	29.496	21.962	51.458
Other Biogas (TJ)	831.751	86.452	918.203
Biodiesel (TJ)	59.948	3035.211	3095.159
Biogasoline (TJ)	-	281.842	281.842

* Ambient heat includes aerothermal, hydrothermal or geothermal energy captured by heat pumps from the environment; energy used to drive heat pumps (electricity etc.) is not included

In the table (Table 8.4.) final energy consumption by end use and energy source in 2022 for the households is presented [229].

Table 8.4. Slovenian final energy consumption by end use and energy source for households in 2022 (source [229])

	Energy source - TOTAL	Extra light fuel oil	Natural gas	Wood fuels	Liquefied petroleum gas	Electricity	Coal	District heat	Solar energy	Ambient heat*
End use – TOTAL	43838	4092	4197	15085	1117	13432	0	2931	419	2511
Space heating	26839	3624	3027	13386	465	2179	0	2388	10	1760
Space cooling	477	-	-	-	-	477	-	-	-	-
Water heating	7212	467	993	1509	146	2393	0	542	409	751
Cooking	1918	-	177	191	506	1045	-	-	-	-
Other	7337	-	-	-	-	7337	-	-	-	-

* Ambient heat includes aerothermal, hydrothermal or geothermal energy captured by heat pumps from the environment; energy used to drive heat pumps (electricity etc.) is not included

8.3. Overview of current regulations, incentives and general policy related to shallow geothermal

Research, exploitation and records of shallow geothermal energy are regulated by two main laws: the Mining Act (ZRud-1) and the Water Act (ZV-1). The Mining Act (ZRud-1) regulates research and exploitation of mineral and energy resources as well as the exploration and exploitation of geothermal energy. Mineral and geoenergy raw materials and geothermal energy as heat from the earth are considered mineral resources and are owned by the Republic of Slovenia as natural resources. The Water Act (ZV-1) regulates the management of surface and underground waters, which are a natural resource owned by the Republic of Slovenia. ZV-1 thus also indirectly regulates activities that interfere with aquifers and could permanently or temporarily affect the water regime or water status. These activities also include the recharge of the aquifer or the return of water to the aquifer (Article 150). A mining permit must be obtained for the exploration of geothermal resources if the borehole is deeper than 300 m. Otherwise, the legal basis for the installation and use of shallow geothermal energy in Slovenia is different for GWHP and GCHP systems.

For GCHP systems, construction can start, if there is no groundwater present in the subsurface. In areas, where groundwater is present, the Water Act [230] must be followed. The research permit must be obtained, if the wells are deeper than 30 m, or are located in the area where groundwater is present (including a drinking water protection zone). The same applies to larger GWHP systems, for which a water consent and a water right must be obtained. The use of groundwater for drinking water supply has priority over the use of water for other purposes, including heating [230]. Since 1. 10. 2018, the procedure for obtaining water rights has been simplified for GWHP wells with pumping rates up to 1.0 l/s and 12.000 m^3/year (equivalent to a heat pump with 16 kW heat power), if this water abstraction has a negligible impact on the groundwater regime and its quantitative status [231]. Based on the Water Act [230], a national database of GWHP systems was established in 2004, and from 2018, locations of recorded special use of water for heat production have been collected [232].

The installation of GSHP systems is also regulated by drinking water protection zones [233]. The zones are divided into abstraction (VVO 0), inner (VVO I), middle (VVO II) and outer (VVO III, VVO IV) protection zones [234]. In the abstraction and inner protection zones, no research permits for boreholes can be granted. For the use of shallow geothermal energy in the middle and outer protection zones, the acquisition of water rights depends on the regulations for a specific water source and corresponding risk analysis. There are also two special types of protection zones – for artesian aquifers and mineral water. In the protection zone for artesian aquifer, only GCHP systems are allowed, while

in the mineral water protection zone there are no special restrictions for the implementation of GSHPs [233].

To stimulate the use of shallow geothermal energy in Slovenia, the Eco Fund helps with financial mechanisms such as grants to support environmental-friendly investments [235]. In the period from 2016–2022, the implementation of 1674 GCHP and 1435 GWHP systems was subsidised [235]. Practical guidance for planning and implementing SGE projects is described in the guidelines [236].

Error! Reference source not found.

8.4. General country geology, hydrogeology and thermogeological parameters

The shallow subsurface of Slovenia mainly consists of sediments and sedimentary rocks, which account for about 93% of the surface area (Figure 8.4.) [237]. Half of the territory (49,5%) is covered with sediments and clastic sedimentary rocks. Sediments (gravel, sand, silt and clay) fill riverbeds and young sedimentary basins. Clastic sedimentary rocks predominate in central, southwestern, and northeastern parts of Slovenia. Carbonate rocks cover 39.3% of the territory. Limestone and dolomite form the massifs in southern Slovenia and in the Alpine region in the northwestern and northern part of the country. Metamorphic rocks account for 3.9% of the area, while igneous rocks cover 3,3% of the area [237].

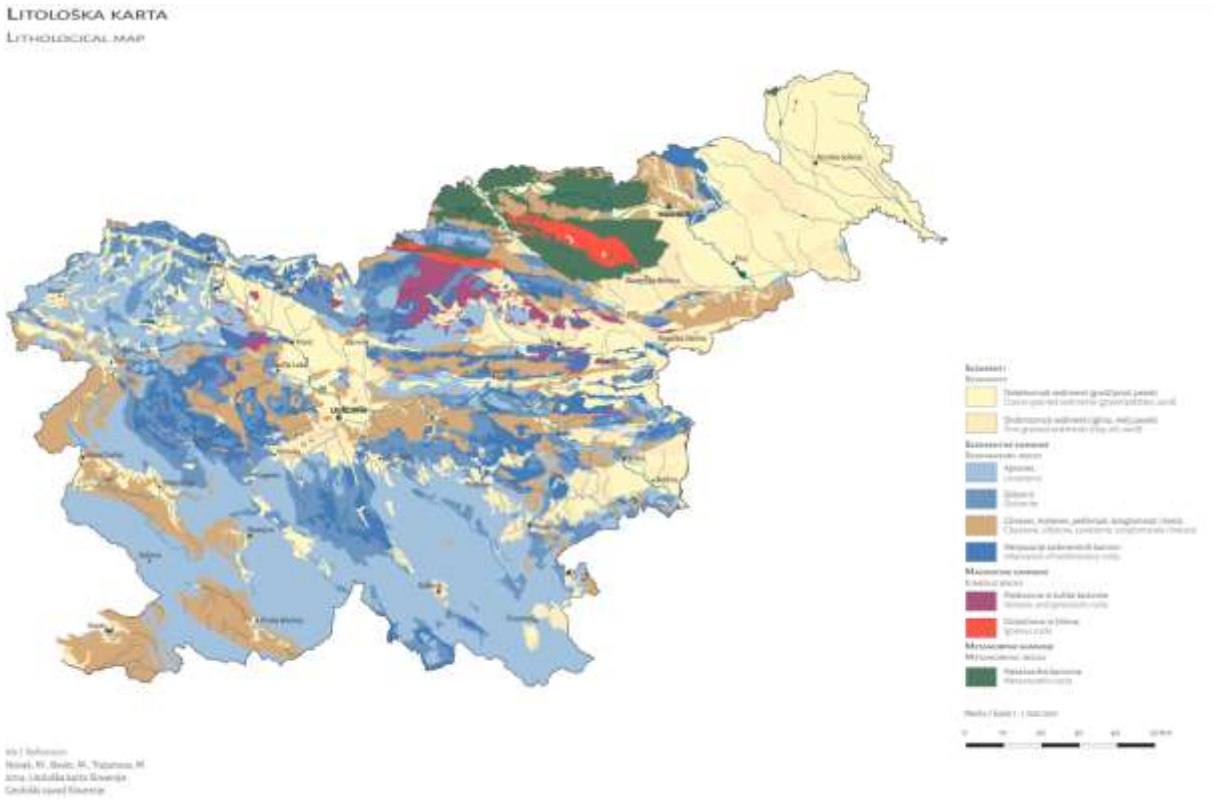


Figure 8.4. Lithological composition of Slovenia on a scale of 1: 1 000 000 [237]

The hydrogeological map of Slovenia (Figure 8.5.) displays porosity type, extensiveness and aquifer yield. It also displays other important hydrogeological information: tracer tests, average groundwater levels, important water resources, and thermal and mineral water resources [238]. The map is designed based on the geological map of Slovenia where lithological units are classified as hydrogeological units consistent with IAH (International Association of Hydrogeologists)

recommendations. Groundwater is the main source of drinking water in Slovenia and 18% of its territory is protected by drinking water protection zones (DWPZ) (Figure 8.6.) [233]. Based on the travelling time of groundwater toward the abstraction well, the zones are divided into abstraction (DWPZ 0), inner (DWPZ I), middle (DWPZ II), and outer (DWPZ III, DWPZ IV) protection zones [233]. The occurrence of groundwater is related to the porosity and other geological characteristics of sediments and rocks. Groundwater temperature is typically between 10 and 15 °C, and the groundwater table is, on average, between 2 and 25 m below the surface in intergranular aquifers [239]. In some parts of Slovenia (e.g., Ljubljana moor), where aquifers are confined, low concentrations of oxygen in groundwater are observed, which can lead to specific hydrochemical conditions where iron and manganese become mobile. In parts with unconfined aquifers, the risk of calcification or corrosion could also be a problem for GWHP systems if groundwater temperature changes exceed 5 K [240].

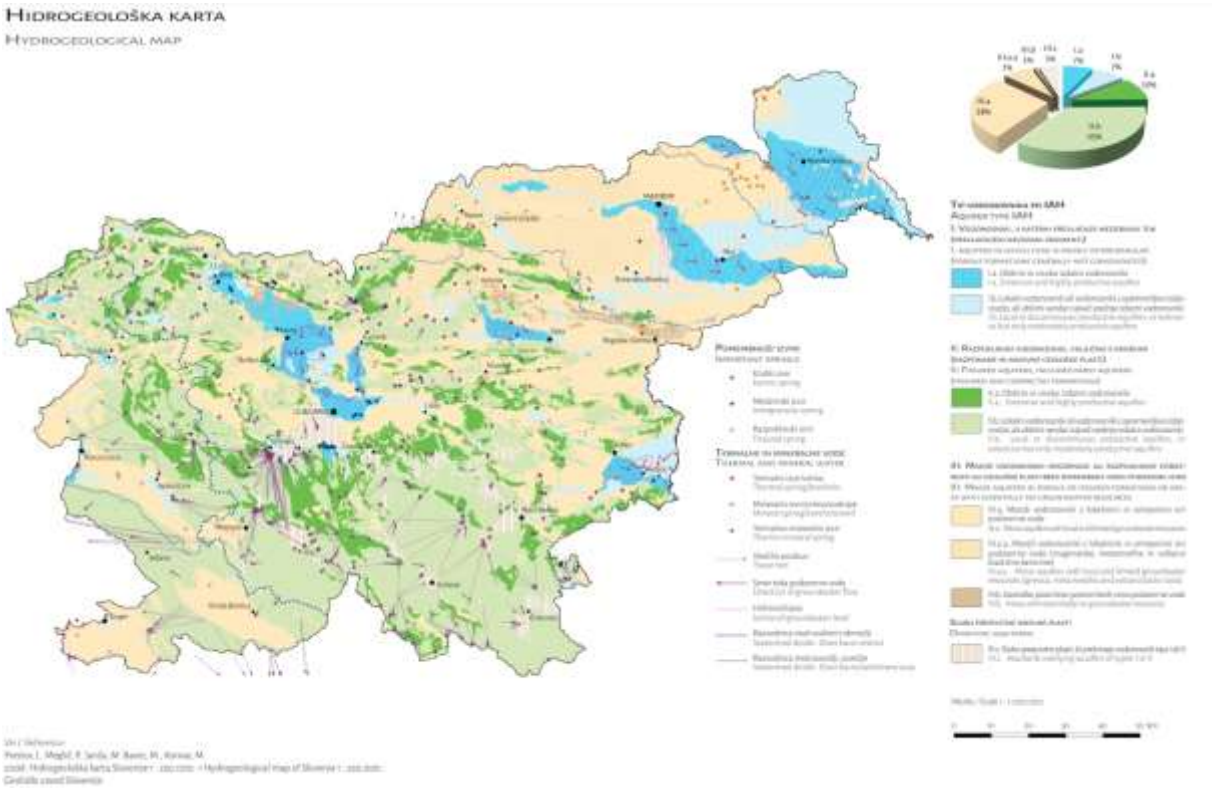


Figure 8.5. Hydrogeological map of Slovenia on a scale of 1:250 000 [238](Prestor et al., 2018).

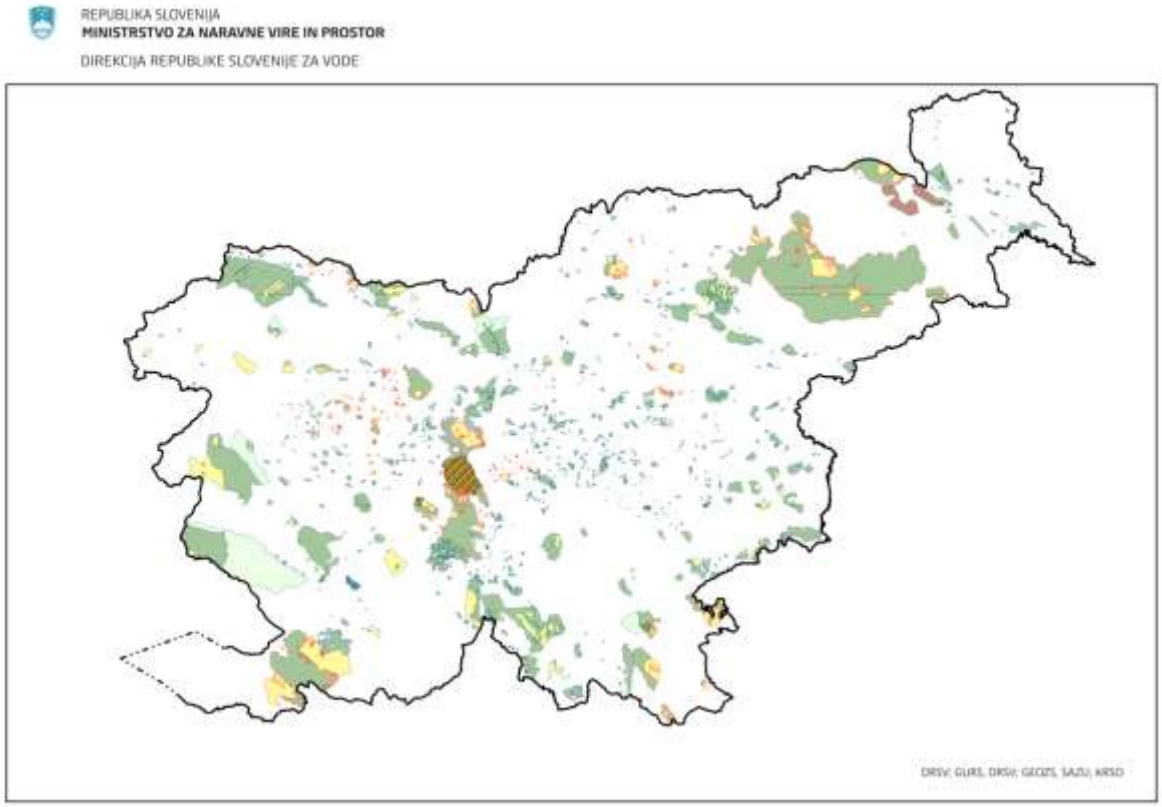


Figure 8.6. Water protection areas (Status: May 2024) [233]

For national purposes, GeoZS created different thermal property maps that are freely accessible through the portal “Trajnostna energija” in Slovenian language [241]:

- *Thermal conductivity map of upper geological layers in Slovenia:* values are assumed based on average measured values for different rock and soil types and attributed to lithological units of the basic geological map of Slovenia at a scale of 1:100000.
- *Volumetric heat capacity map of rocks and soils in Slovenia* (Figure 8.7.): The input data are the basic geological map of Slovenia on a scale of 1:100000 and the average measured values of the volumetric heat capacities of rocks and soils. Only these are attributed to the mapped lithological units based on the presence of certain rock types.
- *Map of temperature distribution on the surface of solid ground in Slovenia*: A raster layer of the 30-year average (1981-2010) of air temperatures measured 2 m above the ground was used as input data. The value for mainland Slovenia is calculated as the cross-section of the difference between the trend lines of transverse air temperature (2 m) and transverse soil temperature (-2 cm) between altitudes of 0 m (1,3°C) and 2864 m (0.7°C). For coastal Slovenia, such a calculation was not possible, due to insufficient data, therefore the value is only estimated [242].
- *Map of the possibility of using geothermal heat pump systems in Slovenia*

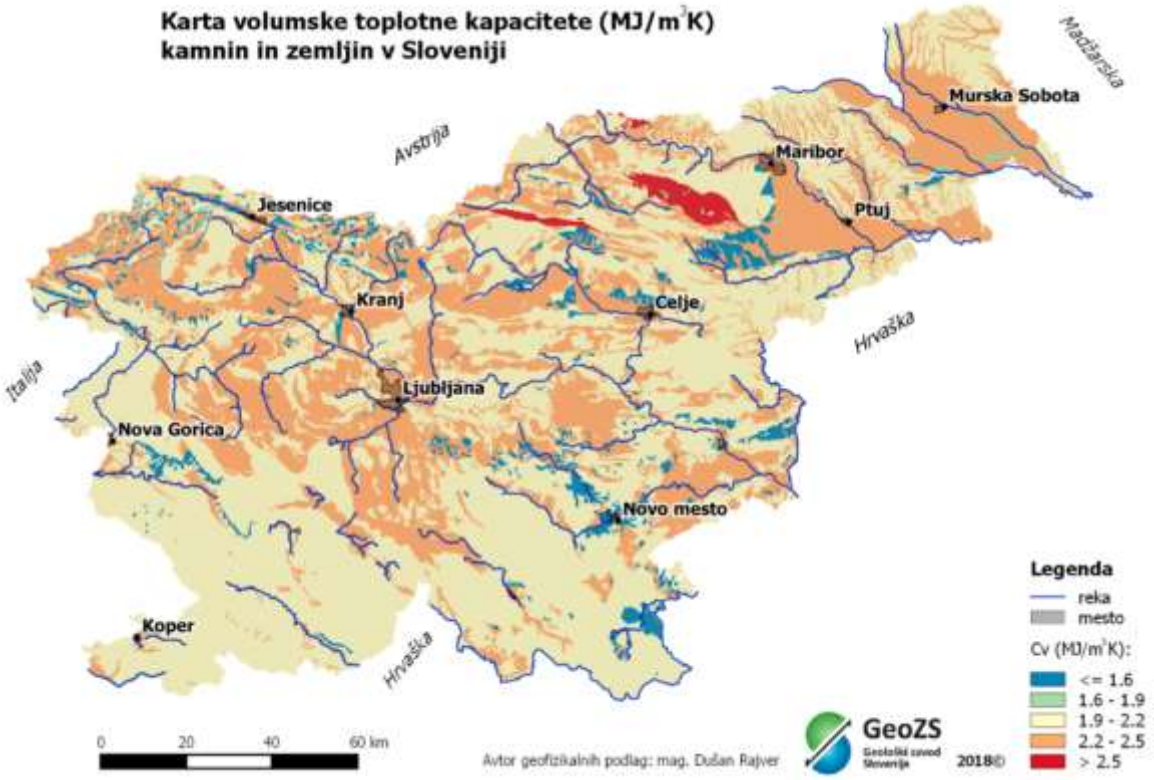


Figure 8.7. Volumetric heat capacity map of rocks and soils in Slovenia 1: 100.000.

General thermal properties of rocks and sediments, that were measured in Slovenia in the period from 1982 to the end of 2022, were published in the paper by Rajver & Adrinek [243]. The results of thermal conductivity measurements on 430 samples from 119 wells, 20 samples from two tunnels and 156 samples from surface locations are presented in Figure 8.8. The samples with the highest thermal conductivities are samples of dolomite, quartz conglomerate and conglomerate, phyllonite, quartz

phyllite and gneiss. The lowest thermal conductivity was measured on samples of sediments such as clay, lignite with clay, peat and dry sand.

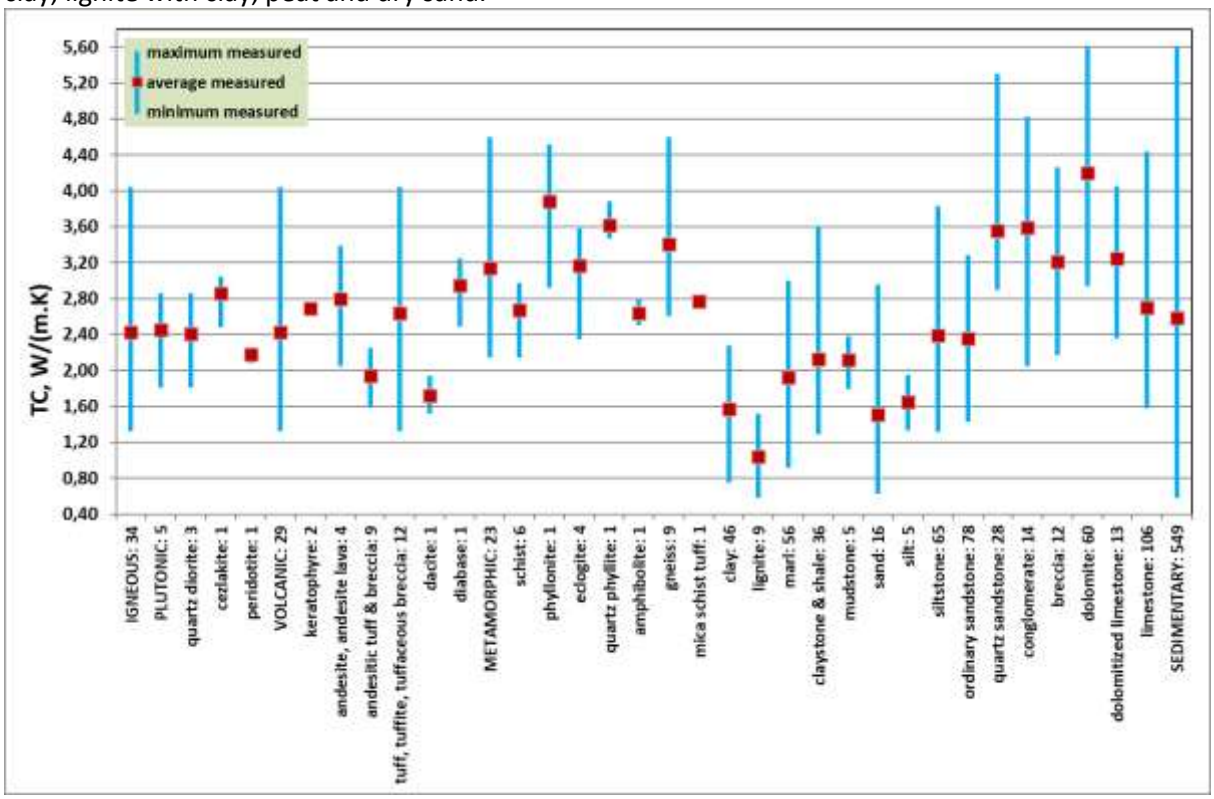


Figure 8.8. Thermal conductivity (TC) of a total of 606 rock and sediment samples with the number of samples by lithology and a total number of samples by main groups of rocks (status: March 2023) (Source: Rajver & Adrinek, 2023).

Thermal diffusivity (TD) was measured on 27 rock samples from eight boreholes and on 104 samples from surface locations [243]. The range for measured thermal diffusivity of rocks and sediments varies between 0,22 mm^2/s for peat with organic clay and 0,42 mm^2/s for clayey sediment of Quaternary (Holocene) age on the low side and 2,31 mm^2/s and 3,62 mm^2/s for quartz sandstone of Ladinian and Upper Carboniferous age, respectively, on the high side.

8.5. Current energy cost comparison for residential and non-residential sector with estimated capital cost of drilling and equipment for shallow geothermal

Current energy prices in Slovenia of main energy sources are gathered in the table (
Table 8.5.) [244]. The data represent the prices from the last quarter of 2023. The electricity and gas price for household customers is an average price with all taxes, while the price for non-household customers is without VAT.

Table 8.5. Slovenian energy prices for the last quarter of year 2023.

ENERGY SOURCE	2023 - Q4
Electricity – Household consumers (EUR/kWh)	0,197

Electricity – Non-household consumers (EUR/kWh)	0,209
Natural gas – Household consumers (EUR/kWh)	0,110
Natural gas – Non-household consumers (EUR/kWh)	0,065
Motor gasoline 95 (EUR/l)	1,528
Diesel (EUR/l)	1,613
Light fuel oil (EUR/1000 l)	1187

The average drilling costs for vertical closed loop systems with a depth of 100-150 m are between 50-60 €/1m, including drilling, material and cementing. For open-loop systems, the costs are between 100-120 €/1m, including the plastic pipes. These prices do not include transportation of the equipment (drilling machine, pipes, etc.).

The costs for heat pumps vary greatly. For a typical household with a 10 kW open-loop heat pump, the price varies between 5000 – 15000 €, while commercial use with a 100 kW open-loop heat pump ranges between 15000 – 30000 €. For the 10 kW closed-loop heat pumps, the price is between 6000 – 18000 €, and for the 100 kW between 18000 – 33000 €.

8.6. Environmental regulations and restrictions related to shallow geothermal development

Shallow geothermal development is limited to a greater extent by water protection zones, as already described in Chapter 8.3. Some other possible special areas with restrictions related to shallow geothermal development are gathered in our Shallow geothermal drilling guidelines [236] and shown in the table (**Error! Reference source not found.**). It is not prohibited to install shallow geothermal systems in these areas, but special regulations may apply.

Table 8.6. Special areas where specific regulations may apply [236].

<table>
<tr><th></th><th>Special area</th><th>Reference</th></tr>
<tr><td>1</td><td>Drinking water protection areas</td><td>DRSV -Slovenian Water Agency;
MOPE - Ministry of the Environment, Climate and Energy;
Municipal Decrees on water protection areas</td></tr>
<tr><td>2</td><td>Contaminated areas, landfills</td><td rowspan="7">ARSO – Slovenian Environmental Agency (Atlas okolja);
DRSV -Slovenian Water Agency (e-Vode);
ZRSVN – Institute of the Republic of Slovenia for Nature Conservation</td></tr>
<tr><td>3</td><td>Riparian and coastal areas</td></tr>
<tr><td>4</td><td>Areas for the protection of other types of water use (mineral, thermal, technological water, ...)</td></tr>
<tr><td>5</td><td>Areas of interaction with other facilities and water rights</td></tr>
<tr><td>6</td><td>Areas of permanent or temporary influence on the water regime or water condition</td></tr>
<tr><td>7</td><td>Natural protected areas for water-dependent ecosystems</td></tr>
<tr><td>8</td><td>Flood and erosion risk areas</td><td rowspan="2">DRSV -Slovenian Water Agency (e-Vode);</td></tr>
<tr><td>9</td><td>Landslide danger zones</td></tr>
</table>

	Special area	Reference
10	Areas designated for underground storage of gas, oil or chemicals, ...	Mining Registry Book – MZI Ministry of Infrastructure

9 Analytical Hierarchy Process theory

9.1. Introduction

Making decisions is present in our daily lives and professional activities and also in various engineering problems, for instance in decision making and designing process of shallow geothermal hybrid heating and cooling systems. Decision making is a process of choosing the best among two or more available alternatives or choices, taking into account multiple criteria or factors in order to achieve a predetermined goal. The decision maker is a single person or a group of people making decisions. Major issues in many decision problems are the presence of multiple, usually conflicting criteria as well as opposed goals and personal biases of decision makers participating in group decision making []. Main decision making methods that consider more than one criterion in the decision making process are multi-criteria decision making (MCDM) methods. They are used in different fields. They can be classified into two groups: MADM (multi-attribute decision making, the discrete form of MCDM) and MODM (multi-objective decision making, more than one objective - the continuous type of MCDM) []. MCDM includes various methods for decision making, such as the ELECTRE method family, the PROMETHEE method family, the TOPSIS method, the VIKOR method, and one of the commonly applied methods of multi¬criteria decision making is the Analytical Hierarchy Process (AHP) method. []

The Analytic Hierarchy Process (AHP) was developed by Thomas L. Saaty in the 1970s. It is a structured group decision making technique for organizing and analyzing complex decisions involving multiple criteria. The methodology of AHP allows decision makers to model a complex problem in a hierarchical structure, compare the elements of the hierarchy in pairs, and derive priority scales based on their judgments. It is capable of quantifying otherwise subjective decision problems by developing measures in physical or social environments when physical or statistical measures are unavailable by converting quantifiable and/or subjective assessments of relative importance into a set of weights [], []. One of the basic principles of AHP is that in the decision making the experience and knowledge of people is at least as valuable as the data they use [5]. The fundamental properties of the AHP are based on stimulus-response theory, rigorous mathematics, and practical necessities. In this way the AHP process mitigates many of the limitations of less ”grounded” methods while maintaining broad applicability []. Due to its simplicity, effectiveness and robustness in dealing with both qualitative and quantitative data, AHP has been widely applied in conflict resolution and decision theory in different fields such as business, government and engineering. Decision situations to which the AHP can be applied include []: choice (the selection of one alternative from a given set of alternatives, usually where there are multiple decision criteria involved); ranking (putting a set of alternatives in order from most to least desirable); prioritization (determining the relative merit of members of a set of alternatives, as opposed to selecting a single one or merely ranking them); resource allocation (apportioning resources among a set of alternatives); benchmarking (comparing the processes in one’s own organization with those of other best-of-breed organizations); quality management (dealing with the multidimensional aspects of quality and quality improvement); conflict resolution (settling disputes between parties with apparently incompatible goals or positions).

As declared by Saaty, the seven pillars or fundamental properties of the AHP are 6]: 1) ratio scales derived from reciprocal paired comparisons; 2) paired comparisons and the psychophysical origin of the fundamental scale used to make the comparisons; 3) conditions for sensitivity of the eigenvector to changes in judgments; 4) homogeneity and clustering to extend the scale from 1-9 to 1-∞; 5) additive synthesis of priorities, leading to a vector of multi-linear forms as applied within the decision structure of a hierarchy or the more general feedback network to reduce multi-dimensional measurements to a unidimensional normalized ratio scale; 6) allowing rank preservation (ideal mode)

or allowing rank reversal (distributive mode); and 7) group decision making using a mathematically justifiable way for synthesizing individual judgments which allows the construction of a cardinal group decision compatible with the individual preference.

The advantages of AHP are as follows. Primarily, the method is capable to transform a multidimensional and multiscale problem into a one-dimensional problem over a single scale. This feature allows decision makers to combine vastly different criteria in a rational, context¬ preserving, and meaningful way [6]. Further, the use of paired comparisons in judgment matrices is intuitive and easily carried out in practice. Although the process of calculating priority vectors limits the number of elements that can be compared, this difficulty can be easily overcome by using absolute rating. In addition, in case of unproportional element comparisons, the hierarchical clustering can be applied which effectively expands the original 1-9 scale to 1-100, What's more, in AHP either rank preservation or rank reversal can be accommodated, depending on the desires of the decision maker and the needs of the decision problem. Finally, cardinal ratio scale preferences permit one to include multiple decision makers in the process and to incorporate their individual judgments in a fair manner at the same time reconciling the experts' specialised knowledge, experience, and authority [].

9.2. Key principles and objectives

The AHP is a method that can be used to establish measures in both the physical and social domains [8]. In using the AHP to model a problem one needs a hierarchic or a network structure to represent that problem and pairwise comparisons to establish relations within the structure. In the discrete case these comparisons lead to dominance matrices [].

The following principles are applied in AHP (see Figure 9.1.): problems are decomposed by identifying those factors that are important; comparative judgments are made on the decomposed elements of the problem; measures of relative importance are obtained through pairwise comparison matrices which are finally recombined into an overall rating of available choices [].

In general, in order to make a decision in an organised way to generate priorities we need to decompose the decision into the following steps [10].

1. Define the problem and determine the kind of knowledge sought.
2. Structure the decision hierarchy from the top with the goal of the decision, then the objectives from a broad perspective, through the intermediate levels (criteria on which subsequent elements depend) to the lowest level (which usually is a set of the alternatives).
3. Construct a set of pairwise comparison matrices. Each element in an upper level is used to compare the elements in the level immediately below with respect to it.
4. Use the priorities obtained from the comparisons to weigh the priorities in the level immediately below. Do this for every element. Then for each element in the level below add its weighed values and obtain its overall or global priority. Continue this process of weighing and adding until the final priorities of the alternatives in the bottom most level are obtained.

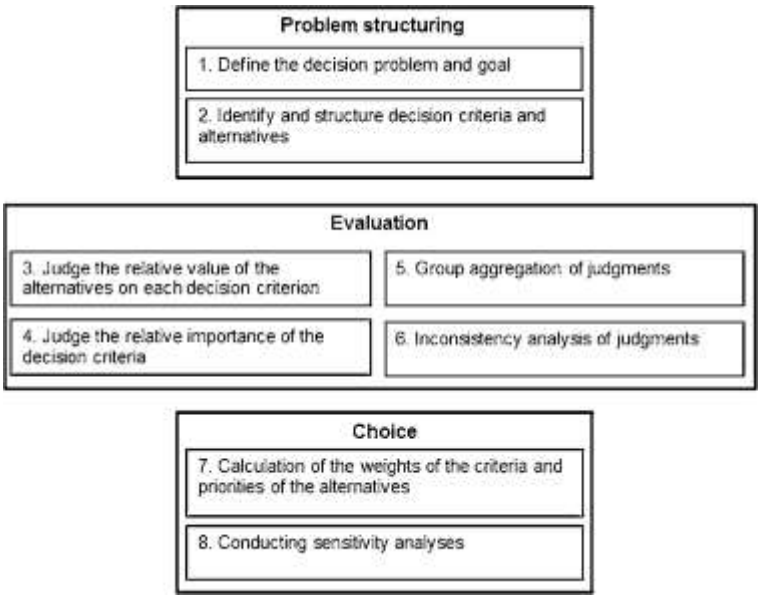


Figure 9.1. The procedural steps of the analytic hierarchy process (from [9])

More precisely, the process of applying the AHP can be summed up as follows [].

Define the problem and structure the hierarchy: identify the goal, criteria, sub-criteria, and alternatives.

Construct pairwise comparison matrices: for each level of the hierarchy, compare the elements of that level pairwise in their strength of influence on an element form the level immediately above. Construct pairwise comparison matrices using Saaty's scale.

Calculate priority vectors: compute the priority vector by finding the eigenvector with the largest eigenvalue, λ_{max}.

Check consistency: compute C.I. and C.R. for each matrix to ensure the reliability of the judgments.

Synthesize overall priorities: combine the priority vectors to determine the overall priorities of the alternatives.

The following four axioms govern the AHP, with the notion of paired comparisons taken as a basis [5], [8]:

Axiom 1 (Reciprocal Comparison): The decision maker must be able to make comparisons and state the strength of his preferences. The constructed comparison matrices are formed of paired reciprocal comparisons: the intensity of the decision maker's preferences must satisfy the reciprocal condition: if A is x times more preferred than B, then B is $1/x$ times more preferred than A.

Axiom 2 (Homogeneity): The preferences are represented by means of a bounded scale.

Axiom 3 (Independence): When expressing preferences, criteria are assumed independent of the properties of the alternatives. The criteria should be independent of each other.

Axiom 4 (Expectations): For the purpose of making a decision, the hierarchic structure is assumed to be complete. This axiom is merely the statement that thoughtful individuals who have reasons for their beliefs should make sure that their ideas are adequately represented in the model. All alternatives, criteria and expectations (explicit and implicit) can be and should be represented in the hierarchy. This axiom does not assume rationality. People are known at times to harbor irrational expectations and such expectations can be accommodated.

9.3. Hierarchical structuring

The first step in AHP procedure is to decompose the decision problem into a hierarchy of more easily comprehended sub-problems, each of which can be analyzed independently. The hierarchy typically consists of three levels:

- Goal: the overall objective of the decision problem.
- Criteria and sub-criteria: factors that contribute to achieving the goal.
- Alternatives: different choices, options or strategies available to achieve the goal.

The hierarchy of the AHP method is a formalization of intuitive understanding of the idea in terms of partially ordered sets [1]. The top level of a hierarchy consists of a single element; each element of a given level dominates or covers (serves as a property of a purpose for) some or all of the elements at the level immediately below. Elements of a single level are pairwise compared with respect to a purpose from the adjacent higher level and this process is repeated up the hierarchy. In this way composite priorities of alternatives with respect to multiple criteria are obtained from their priorities with respect to each criterion. Different methods for deriving priorities within the same hierarchy can lead to different final priority values for the alternatives [].

The elements of a hierarchy are grouped in clusters according to homogeneity and a level may consist of one or several homogeneous clusters. The elements in each level may be regarded as constraints, refinements or decompositions of the elements above. A hierarchy is “complete” if all the elements at one level have all the elements in the succeeding level as descendants; the levels can be seen as single homogeneous clusters. Otherwise a hierarchy is “incomplete” [].
A general suggestion on the dimensions of the hierarchy is that it should be complex enough to capture all the aspects of the particular decision making problem, but also small and agile enough to be sensitive to changes. To all participants in the decision making it must be clear from the start what the focus of the hierarchy is and how the elements in the second level either serve to fulfill that focus or are its consequence, and so on down the hierarchy for each parent element and its descendants [].

9.4. Scale

AHP method is based on pairwise comparisons of elements at each level of the hierarchy with respect to their impact on an element in the level immediately above. In order to realize comparisons, one requires a scale of absolute judgments that will point out how many times stronger effect one element has over another element on a given higher-level element. The judgments on this scale bring the information on which of the two elements has the given higher-level property more, or which one of them satisfies the higher level criterion more, i.e. which one is considered more important under that criterion.

Standard Stevens’ [] categorization of scales of measurement includes nominal, ordinal, interval and ratio scale. Each of the scale categories has properties of a category above it plus some additional properties. A ratio scale is a set of positive numbers whose ratios remain the same if all the numbers are multiplied by an arbitrary positive number. The product or quotient of two ratio scales is also a ratio scale, but it is not true for the sum or the difference []. In order for multiplication and summation of the judgments to make sense, a ratio scale is needed in the AHP.

The standard (”fundamental”) scale in AHP is the ratio scale containing natural numbers ranging from 1 to 9. It is used to assign numerical values to judgments made by pairwise comparing of the two elements in this way: the lesser element is considered as the unit and the greater one is estimated by a value from the 1-9 scale, which is a multiple of that unit [14]. The 1-9 intensity scale of dominance of an element over the other one is a quantification of an associated descriptive scale of dominance.
The fundamental scale is presented in Figure 9.2. It was derived and suggested by Saaty [], [] as follows. Assuming that in making pairwise comparisons of relatively comparable activities the stimuli arise, and based on the theory of stimuli and responses by Weber and Fechner (19th century), Saaty [15] first arrived at the sequence 1,2,... as the scale. Then he concluded that an upper limit of 9 should be set on the scale due to several arguments []:

- The items being compared should be of the same order of magnitude regarding the property used to make the comparison;
- If we assume “objects of the same magnitude ” to differ by no more than a factor of 10, the scale should have values somewhere between one and ten, otherwise we would compare things that are widely disparate in magnitude which would disturb the stability of the scale;
- Our ability to make qualitative distinctions is well represented by five attributes: equal, weak, strong, very strong, and absolute; together with compromise in-between attributes this leads to a nine-point scale;
- People have a capacity to divide their response to stimuli into regions of rejection, indifference, acceptance; for finer classification each is further subdivided into low, medium, and high, yielding nine shades of meaningful distinctions;
- The classical psychological observation (G. A. Miller, 1956.) is that the human brain can simultaneously process not more than 7 + 2 items in a simultaneous comparison.

The fundamental AHP scale is an absolute scale of numbers representing estimates of two ratio scale numbers involved in paired comparisons. The numbers used in the scale do not represent the order between elements but absolute magnitudes which means that the scale does not allow comparisons with intensity greater than 9. Therefore, elements must be put into clusters so that the elements within each cluster are comparable on given scale. Then the clusters must be compared with this scale [].

Intensity of Importance	*Definition*	*Explanation*
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favour one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity *i* has one of the above non-zero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	A reasonable assumption
1.1–1.9	If the activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities.

Figure 9.2. The Saaty fundamental scale (from [])

There are alternative numerical AHP scales, for example, a nine-point scale with a range from 1.1 to 1.9 to compare alternatives that differ only slightly []. More on why the 1 to 9 scale is preferable to other possible scales can be found in [], [], [].

Clustering

Questioning naturally whether the finite 1-9 scale could be extended to an infinity, one comes to the conclusion that in order to keep an idea of how large the measured or evaluated value can become, the scale must be finite. Since we still want to be able to compare the objects of strongly disparate weights, it is suggested to divide the objects into *clusters* []. Thereby the objects put into each cluster are within the range of the scale when compared between themselves, and the largest object in one cluster is used as the smallest one in the next larger cluster. The scale values of that limit object in the two neighbouring clusters enable one to continue the measurement from one cluster to the next one []. In this way the scale is eventually extended from 1-9 to 1-∞ by passing gradually from a cluster to the subsequent cluster [].

When providing pairwise judgments between subcriteria, the pairs of subcriteria from the same cluster are compared while subcriteria from different clusters are not compared directly.

In order to create a well-managed decision structure, it is recommended that the number of criteria and the number of sub-criteria within each cluster are between three and five [].

9.5. Pairwise comparisons

After establishing the hierarchic structure of the problem, for each level of hierarchy elements from that level are compared pairwise with respect to an element from the level immediately above. A *comparison* or *judgment* is the numerical representation of a relationship between two elements that share a common parent []. It is given on a standard 1-9 scale (see Figure 2). Judgments comparing the set of elements with itself are represented in a square matrix which is called *comparison matrix* or

judgment matrix. Each judgment represents the dominance of an element from the column on the left over an element from the row on top, saying both which of the two elements is more important with respect to a higher level criterion, and how many times more important it is. If the element on the left is k ($k \in \{1, \dots, 9\}$) times more important than the one on the top, we enter k at the position in the matrix determined by that row and column. If it is k times less important, the reciprocal value $1/k$ is entered at that position [14]. In this way elements a_{ij} are obtained for $i < j$. At all diagonal positions one puts value 1 which is consistent with any element being equally important as itself. Finally, at the positions ji reciprocal values $1/a_{ij}$ are automatically entered.

The meaning of the numbers between 1 and 9 is as follows (see Figure 2). For elements *A* and *B*, if *A* and *B* are equally important, 1 is put in the position *(A*, *B*) where the row of *A* intersects the column of *B*; if *A* is weakly more important than *B*, put 3; if *A* is strongly more important than *B*, put 5; if *A* is demonstrably or very strongly more important than *B*, put 7; if *A* is absolutely more important than *B*, put 9 [11].

For a set of *n* elements, a pairwise comparison matrix *A* is of order $n \times n$. The entry a_{ij} represents the relative importance of element *i* over element *j* and the reciprocal property holds for $i, j = 1, \dots, n$: $a_{ji} = 1/a_{ij}$. The matrix *A* therefore looks like this:

$$A = \begin{pmatrix} 1 & a_{12} & a_{13} & \cdots & a_{1n} \\ \frac{1}{a_{12}} & 1 & a_{23} & \cdots & a_{2n} \\ \frac{1}{a_{13}} & \frac{1}{a_{23}} & 1 & \cdots & a_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \frac{1}{a_{3n}} & \cdots & 1 \end{pmatrix}.$$

If n elements are being pairwise compared, there are $\binom{n}{2} = \frac{n(n-1)}{2}$ ways to choose two of them so $\frac{n(n-1)}{2}$ comparisons are made and the matrix *A* consists of $\frac{n(n-1)}{2}$ independent entries.
At each level of hierarchy, the rater pairwise compares elements from that level with respect to each element from a level one above. When the hierarchy consists of three levels - the goal, the m criteria and the n alternatives - this will result in the total of $m + 1$ comparison matrices of order $n \times n$. From each comparison matrix the priorities are then calculated.
It should be noted that the way one formulates the question a rater is asking himself while producing pairwise comparisons can influence his judgments and hence also change the comparison matrix [8].

Mathematical background - positive reciprocal matrices

As we have seen, matrices containing pairwise comparisons of criteria and alternatives in the AHP method are square, positive and reciprocal. Therefore, now we present the definitions and basic properties of this class of matrices [], [].

A matrix with n rows and n columns is called a *square matrix* of size n. If *A* is a square matrix of a size n, an element of *A* in *i*-th row and *j*-th column is denoted by a_{ij} and we write $A = (a_{ij})$.

Definition 1 *Let* $A = (a_{ij})$ *be a real matrix of size n.*

1. *A is called* positive *if* $a_{ij} > 0$ *for all* $i, j = 1, \dots, n$.

2. *A is called* reciprocal *if* $a_{ij} = 1/a_{ji}$ *for all* $i, j = 1, \dots, n$.

From Definition 1 it follows that the diagonal elements of a positive reciprocal matrix are equal to 1. A general positive reciprocal matrix has the form

$$A = \begin{pmatrix} 1 & a_{12} & a_{13} & \cdots & a_{1n} \\ \frac{1}{a_{12}} & 1 & a_{23} & \cdots & a_{2n} \\ \frac{1}{a_{13}} & \frac{1}{a_{23}} & 1 & \cdots & a_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \frac{1}{a_{3n}} & \cdots & 1 \end{pmatrix}.$$

Definition 2 *Let A =* (a_{ij}) *be a positive reciprocal matrix of size n. A is said to be* consistent *(in Saaty'sense) if* $a_{ij} = a_{ik}a_{kj}$ *for all* $i, j, k = 1, \dots, n$.

The consistency of a judgement matrix means that for any elements *i*, *j*, *k* it holds: if the *k*-th element is *x* times more important than the *i*-th one and the *j*-th element is *y* times more important than the *k*-th one then the *j*-th element *i* is *xy* times more important than the *i*-th one.

The following properties of consistent matrices hold:

- A consistent matrix is necessarily reciprocal since from $a_{ik} = a_{ij}a_{jk}$ we get $a_{ij} = a_{ik}/a_{jk}$ so $a_{ji} = a_{jk}/a_{ik} = {a_{ij}}^{-1}$.
- Matrix *A* = (a_{ij}) is consistent if and only if there exist a positive vector $\boldsymbol{w} = (w_1, w_2, \dots, w_n) \in R^n$ such that $a_{ij} = w_i/w_j$ for all $i, j = 1, \dots, n$.

A matrix is said to be *near consistent* if it is a small perturbation of a consistent matrix [].

If each of the ratio pairwise comparisons given by the decision maker were perfectly coherent, the resulting judgment matrix would be consistent. What is meant by coherency in the context of AHP is not just the transitivity of preferences, but also that the intensity with which the preference is expressed transits through the sequence of objects being compared [].

In general, by being consistent we mean that when we have a basic amount of raw data, all other data can be logically deduced from it [11].

However, consistency in any kind of measurement or estimating cannot be taken for granted. When obtaining subjective estimates of relative value, some variance necessarily occurs. For that reason multiple estimates of the ratios appear and judgment matrices are in practice not consistent [4]. Still, one can study the consistency of judgment and its validity for a particular problem []. The inconsistency of a matrix will be expressed through its consistency index.

9.6. Calculation of priorities

An essential point in any decision-making problem is derivation of priorities (weights, relative scores) for criteria and alternatives from the judgment matrices. These priorities are referred to as *local*, in contrast to the *global* priorities of alternatives with respect to the overall goal. Vector of priorities of a set of alternatives should provide a ranking of the alternatives indicating an order of preferences between them, but the ordering should also reflect intensity of preferences indicated by the ratio scale elements of a comparison matrix (and therefore it must be unique up to a positive

multiplicative constant) []. There is not a unique way to calculate the local priorities and the chosen means affects the choices one makes at the end of the decision-making process. Anyhow, it is desirable that the priorities capture the order of judgments expressed in the pairwise comparison matrix, and that the obtained order of priorities is unique. In AHP the priorities form a cardinal scale which makes preferences explicit and more evident than if using a less-informative ordinal scale []. Some of the simplest ways to calculate relative scores are averaging the weights associated to a particular element being compared in a judgment matrix, which is a relatively unstable method, or obtaining their geometric mean, which has theoretical advantages and is being relatively easy computationally []. Other prioritization methods include the arithmetic mean method, the row geometric mean method, the additive normalization method, the eigenvector method, the logarithmic least squares method, the weighted least squares method, singular value decomposition method, logarithmic goal programming method, cosine maximization method, fuzzy preference programming method [], [], []. Among them, the *eigenvector method* (EVM), suggested and justified by Saaty [15], is commonly used and yields a robust estimator of the priorities at the same time providing a way to assess the relative consistency of a matrix []. Moreover, it was shown [12] that the principal eigenvector is the only plausible candidate for representing priorities derived from a positive reciprocal near consistent pairwise comparison matrix.

Priorities are ranked into a *priority vector*. The concept of a priority vector is valid primarily for a consistent or a near consistent matrix and much less for an arbitrary positive reciprocal matrix [].

In the eigenvector method the principal right eigenvector of comparison matrix *A* is the sought priority vector []. It has been shown [] that for a consistent *A*, the components of the principal right eigenvector give the true priorities of the elements being compared. Moreover, even in case of inconsistency the priorities given by the eigenvector are still a very acceptable approximation of the true (unknown in most cases) priorities, assuming that the inconsistency is small, that is, that the decision maker is not making random comparisons [], [].

Advocating for the EVM as the prioritization method, Saaty [] argued that the priority vector must reproduce itself on a ratio scale (it should remain invariant under multiplication by a positive constant *c*) and it should also be invariant under hierarchic composition for its own judgment matrix (so that by repeated generating of priority vector one does not get new, different priority vectors). The conclusion is that a priority vector **x** must satisfy the relation $A\boldsymbol{x} = c\boldsymbol{x}$, $c > 0$ so **x** must be the principal right eigenvector of *A* while *c* is the corresponding principal eigenvalue [].

In general, an advantage of the eigenvector method over other prioritization methods is that it deals with the (in)consistency of a matrix by a single numerical index, and points to the reliability of the data and to revisions in the matrix []. Compared with another commonly used method, the least-square method, the EVM captures more information due to redundancy of information obtained by the use of reciprocals in pairwise comparisons [].

Mathematical background - eigenvalues and eigenvectors

Now we introduce the eigenvector method that can be used to generate the relative importance of attributes and the performance scores [], [], []. We start with necessary mathematical definitions and results.

Definition 3 *Let* $A = (a_{ij})$ *be a square matrix of size* n. *A scalar* λ *is called an* eigenvalue *of a matrix A if there exists a vector* $\boldsymbol{w} \neq 0$ *such that it holds*

$$A\boldsymbol{w} = \lambda\boldsymbol{w}. \tag{1}$$

The vector $\boldsymbol{w} \neq 0$ satisfying (1) is called a *right eigenvector* (or just *eigenvector*) of a matrix *A* corresponding to the eigenvalue λ. We note that if $\boldsymbol{w}$ is an eigenvector corresponding to the eigenvalue λ, then so are also all the multiples $\alpha\boldsymbol{w}, \alpha \in R$.

We call a vector $\boldsymbol{w} = (w_1, w_2, \dots, w_n) \in R^n$ *normalized* if $\sum_{i=1}^{n} w_i = 1$. Any vector can be normalized by dividing each of its components by the sum of all its components.

The eigenvalues and eigenvectors of a matrix *A* are found by solving the equation (1). It reduces to solving an equation

$$(A - \lambda I)\boldsymbol{w} = 0,$$

which is a matrix form of a homogeneous system of linear equations with unknowns $(w_1, w_2, \dots, w_n)$. Here I is an identitiy matrix of a size n. A homogeneous system always has a trivial solution $w_1 = w_2 = \cdots = w_n$, and it can have also non-trivial solutions, i.e. solutions for which is at least one $w_i = 0, i = , \dots, n$.

Proposition 1 *A homogeneous $n \times n$ system of linear equations written in a matrix form as $A\boldsymbol{x} = 0$ has*

- *only a trivial solution, if and only if rank* (*A*) = *n i.e.* det(*A*) = 0;
- *non-trivial solutions, if and only if rank* (*A*) < *n i.e.* det(*A*) = 0,

In the AHP method analysis one is dealing with the eigenproblem for a positive reciprocal matrix. An essential result concerning eigenvalues and eigenvectors of a positive matrix is given by the following theorem of Perron ([11], Theorem 7.4).

Theorem 1 *Let A* = (a_{ij}) > 0, *Then*

i) A has a real positive simple (i.e., not multiple) eigenvalue, denoted by λ_{max}, such that the modulus of λ_{max} is larger than the moduli of all other eigenvalues of A.

ii) The eigenvector of A corresponding to the eigenvalue λ_{max} has positive components and is unique up to a multiplication by a constant.

For a positive matrix *A*, its largest eigenvalue λ_{max} is called the *principal eigenvalue*, and the associated eigenvectors are called the *principal eigenvectors*. The fact that λ_{max} is a simple eigenvalue implies that the eigenspace corresponding to λ_{max} is one-dimensional so eigenvectors associated to λ_{max} differ from each other by a multiplicative constant.

Now we present some properties of positive reciprocal matrices.

Proposition 2 *[] For a positive reciprocal matrix it holds $\lambda_{max} \geq n$*

Theorem 2 *[] A positive reciprocal matrix is consistent if and only if $\lambda_{max} = n$.*

Proposition 3 *[] For a consistent positive reciprocal matrix A of a size n it holds:*

1. *rank*(*A*) = 1*;*
2. *$\lambda_{max} = n$ and n is the only non-zero eigenvalue of A;*

3. *If the eigenvector* $\boldsymbol{w} = (w_1, w_2, \dots, w_n)$ *corresponds to the eigenvalue* $\lambda = n$*, then for all* $i, j = 1, \dots, n$ *it holds*

$$a_{ij} = \frac{w_i}{w_j}.$$

In AHP method the priority vector is obtained from the judgment matrix. This vector provides the weights or priorities of the elements being compared. The question is now how to obtain the priority vector. As mentioned earlier, it will be done by using the eigenvector method.

Let us first assume that the rater is able to deliver perfectly consistent pairwise comparisons between criteria or alternatives, as if they were result of precise physical measurements. In that case the judgment matrix *A* consists of "ideal" set pairwise comparisons of *n* objects according to their relative weights. If objects' weights are denoted by $w_1, w_2, \dots, w_n$ then matrix *A* satisfies

$$a_{ij} = \frac{w_i}{w_j}$$

i.e. it has a form

$$A = \begin{pmatrix} 1 & w_1/w_2 & w_1/w_3 & \cdots & w_1/w_n \\ w_2/w_1 & 1 & w_2/w_3 & \cdots & w_2/w_n \\ w_3/w_1 & w_3/w_2 & 1 & \cdots & w_3/w_n \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ w_n/w_1 & w_n/w_2 & w_n/w_3 & \cdots & 1 \end{pmatrix}. \quad (2)$$

The priority vector of a matrix *A* given by (2) is exactly the vector of objects' weights

$$\boldsymbol{w} = (w_1, w_2, \dots, w_n),$$

or any multiple of **w**. Such a matrix *A* is obviously positive, reciprocal and consistent. From Proposition 3 or Theorem 2 we also know that $\lambda_{max} = n$. Moreover, it is easy to see that for $\boldsymbol{w} = (w_1, w_2, \dots, w_n)$ it holds

$$A\boldsymbol{w} = n\boldsymbol{w}. \quad (3)$$

From (3) we conclude that the priority ranking vector **w** of a matrix *A* given by (2) is a principal eigenvector of *A*, associated to the eigenvalue $\lambda = n$. The same conclusion holds for any multiple of **w**. Since all columns of *A* differ by a multiplicative constant from vector **w**, it follows that any column of *A* is the principal eigenvector and the priority vector of *A*. In order to make the priority vector unique, the convention in AHP is to normalize it by dividing its entries by their sum which yields the sum of the elements of a priority vector equal to 1.

So when *A* is consistent, the priority vector is the normalized principal eigenvector of the judgment matrix [6]. This vector is given by any normalized column of *A* and it is unique.

If we have a general consistent pairwise comparison matrix $A = (a_{ij})$ we have seen that it must be $a_{ij} = \frac{w_i}{w_j}$ for all $i, j = 1, \dots, n$ and for some positive vector $\boldsymbol{w} = (w_1, w_2, \dots, w_n)$. Therefore elements of a consistent matrix *A* are necessarily "perfect" ratios of pairwise comparisons between objects (criteria or alternatives) and the preceding analysis can be performed for the matrix *A*. In particular, $\boldsymbol{w}$ (and any multiple of $\boldsymbol{w}$ so also any column of *A*) is the priority vector of *A* and also an eigenvector of *A* corresponding to the eigenvalue $\lambda = n$. The components of $\boldsymbol{w}$ represent weights of the objects up to a multiplicative constant.

In practice consistency in any kind of measurement and especially in judges' estimates cannot be taken for granted and a judgment matrix is often inconsistent []. It is difficult for a human being to be

perfectly consistent, especially when trading off “intangible” variables, due to variations in the human rater’s relative preferences among the alternatives. Also, if the number of objects comparing pairwise is large, one needs to make more and more judgments and it is likely that there will be inconsistency in how one has prioritized elements over one another. However, it turns out that for an inconsistent matrix we can also derive the priorities through the eigenvector.

As judgments get inconsistent, small errors between the judgment and the true weight appear which leads to small changes in the elements a_{ij} of a matrix *A*, and *A* becomes inconsistent. In this situation rank of *A* becomes greater than 1, the largest eigenvalue gets strictly greater than n and there are multiple eigenvalues different from 0 and multiple corresponding eigenvectors.

The natural question is then how sensitive the priorities given by the eigenvector are to small changes in the judgment values. It is obviously desirable that the priorities do not vary strongly if the changes in judgment are little.

It is known that small perturbations of the entries in any positive reciprocal matrix imply small perturbations in the eigenvalues from their original value (which does not hold for general positive matrices) []. According to [], as long as changes of a_{ij} are small and *A* does not become too inconsistent, the largest (or principal) eigenvalue of *A* remains close to n. Therefore, the principal eigenvector is still a good approximation to the consistent-case eigenvector **w** [6]. The same analysis of [11] provides the important conclusion that in order to assure the stability of an estimate of an underlying ratio scale from pairwise comparisons, the elements being compared should be relatively comparable, and their number should be small. In social sciences they empirically arrived at the limit of 7 + 2 [11].

More precisely, it was shown [] that the priority vector of a near consistent matrix (the matrix obtained by a small and continuous perturbation of a consistent matrix *A*) coincides with its principal eigenvector, which is in turn obtained as a perturbation of the corresponding principal eigenvector of matrix *A*. Thus if we assume that a judgment matrix is obtained as a small perturbation of a starting consistent matrix defined by a vector of weights **w**, the priority vector of this judgment matrix is the same as its principal eigenvector, which is a small perturbation of the vector **w** [].

Thus the problem (3) for a consistent matrix *A*, from which one determines the priority vector of *A*, with an inconsistent judgment matrix A' becomes

$$A'\boldsymbol{w}' = \lambda_{max}\boldsymbol{w}'. \tag{4}$$

Here A' is a positive reciprocal inconsistent pairwise comparison matrix, obtained by small perturbations from a consistent matrix *A*; λ_{max} is the largest eigenvalue of A' (small perturbation guarantees that λ_{max} is close to *n*) and $\boldsymbol{w}'$ is an eigenvector of A' associated to eigenvalue λ_{max} .

From what was said before, we know that the vector $\boldsymbol{w}'$ is the priority vector of matrix A', and that $\boldsymbol{w}'$ is a small perturbation or an approximation of **w**. The goal is to derive exact value or at least an estimate of $\boldsymbol{w}'$ []. Note also that in (4) both λ_{max} and $\boldsymbol{w}'$ are unknown.

Solving the full eigensystem exactly is in general difficult because it requires solving an algebraic equation of high degree (equal to the size of the matrix). However, since in the eigenvector method only the principal eigenvector of the matrix is needed, in practice some of the approximation methods is used [].

As suggested by [], some of the procedures of approximating the principal eigenvector $\mathbf{w}'$ that solves (4) are the following:

i) The normalized row sums: sum the elements in each row and normalize by dividing each sum by the total of all the sums.

ii) Take the sum of the elements in each column and form the reciprocals of these sums. Normalize the resulting numbers by dividing each reciprocal by the sum of the reciprocals.

iii) Averaging over the normalized columns: normalize each column so that the sum of entries in any column is 1 and then take the average over the rows of the normalized matrix.

iv) Geometric mean: multiply the n elements in each row and take the n-th root. Normalize the resulting numbers.

v) The power method: raising the matrix to a sufficiently large power. In *k*-th iteration an approximate priority vector **w** is found by summing over the rows of $(A')^k$ and normalizing. The procedure converges and it stops when the stopping criterion is satisfied, that is, when the difference between components of the priority vector obtained at the *k*-th power and at the (*k* + 1)-th power is less than some predetermined small value [].

The power method is the most commonly used way to obtain the approximate priority vector. When a matrix is not consistent, methods i) - iv) give different results. For a consistent comparison matrix any of the methods i) - iii) gives the actual priority eigenvector, while method iv) gives a good approximation of it []. The approximation iii) was labeled *additive normalization (AN)* by [20] and there it was reported that "[The] popularity and wide use in practice AN owes to its extreme simplicity. Although considered inferior it significantly outperforms more sophisticated methods". For matrices of order $n < 3$ method iv) gives the true eigenvector, regardless of the (in)consistency of the matrix [8].

It was suggested by [8] that for important applications one should only use the eigenvector derivation procedure because approximations can lead to rank reversal in spite of the closeness of the result to the eigenvector.

Note that if $\boldsymbol{w}' = (w_1', w_2', \dots, w_n')$ is obtained by solving (4), the matrix whose entries are w_i'/w_j' is a consistent matrix, which can be seen as a consistent estimate of the matrix A' [].

After obtaining the exact or approximate value of $\boldsymbol{w}'$ in any way, from the equation (4) one can readily obtain the exact or approximate λ_{max} by computing $A'\boldsymbol{w}'$, dividing each of the components of the resulting vector by the corresponding component of $\boldsymbol{w}'$, and averaging the components of the resulting vector. If $\boldsymbol{w}'$ is the true principal eigenvector, all components of the resulting vector will be equal to λ_{max} .

When the actual or estimated value of $\boldsymbol{w}'$ is known in normalized form, the actual or estimated λ_{max} can simply be derived by summing the columns of *A* and multiplying the resulting vector with the vector $\boldsymbol{w}'$ [].

We can then use this estimate of λ_{max} to compute the consistency index *C.I*.

9.7. Consistency

Positive reciprocal matrices bring information about pairwise comparisons of criteria, pairwise comparisons of sub-criteria within each cluster, comparisons between alternatives regarding each sub-criterion. If consistent, such matrices have a unique eigenvalue that is equal to the order of the matrix, n []. Any deviation from consistency generates a change of eigenvalues. From Proposition 2 and Theorem 2 it follows that an inconsistent matrix of order n has a maximum eigenvalue strictly greater than n. The degree of inconsistency is therefore measured by the quantity $\lambda_{max} - n$, where λ_{max} is the principal eigenvalue []. Normalizing by the size of the matrix leads to the following definition.

The *consistency index* of a comparison matrix is defined by []

$$C.I. = \frac{\lambda_{max} - n}{n-1} \tag{5}$$

where λ_{max} is the largest eigenvalue of the comparison matrix, and n is the size of the comparison matrix.

The consistency index is a measure of the raters' logical consistency in their pairwise comparisons. It tells if each pairwise comparison is logically correct with respect to the remaining comparisons and if not, what is the extent of this inconsistency. The consistency index provides information on consistency of both the ordinal and cardinal comparison of the two elements [6].

For a consistent comparison matrix *C.I.* is equal to 0, In general it is desirable to have a consistency index as small as possible. According to [11], the judgments are considered satisfactorily consistent if *C.I.* is less than 0,1. Larger *C.I.* can serve as an indication to the decision makers to reconsider their preferences. Note that in order to calculate or estimate *C.I.* one needs to compute or estimate λ_{max}.

Since the sum of the eigenvalues of any matrix equals the trace of the matrix, for a comparison matrix the sum of eigenvalues is equal to n. Therefore, the consistency index can also be seen as the negative average of eigenvalues $\lambda_i, i = 2, \dots, n$ [].

Consistency index can be used to validate whether the inconsistency of the judgments in a given comparison matrix is greater than the inconsistency expected from a random distribution of reciprocal matrices of the same size with elements from the standard scale. This is achieved by comparing the consistency index of a comparison matrix with the average value of consistency index for matrices containing the judgments taken randomly from the 1-9 scale [].

In [11] the *random index* (*R.I.*) is defined as the consistency index of a randomly generated reciprocal matrix whose entries are from the scale 1 to 9. Here the strict upper triangle of a matrix is randomly distributed while the diagonal and the strict lower triangle are determined by the demand of reciprocity. The values of the random index depend on the matrix size. Figure 9.3. shows values of *R.I.* obtained by averaging the consistency indices of a set of 50000 randomly generated reciprocal matrices with values from {1/9, 1/8, ..., 1, 2, ..., 8, 9}, for matrices of size n = 1, 2, ..., 15.

Order	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
R.I.	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	1.52	1.54	1.56	1.58	1.59
First-Order Differences		0	0.52	0.37	0.22	0.14	0.10	0.05	0.05	0.04	0.03	0.02	0.02	0.02	0.01

Figure 9.3. Random index (from [16])

The *consistency ratio C.R.* is defined by

$$C.R = \frac{C.I.}{R.I.} \tag{6}$$

Consistency ratio is the rescaled version of consistency index. It acts as an indicator of how close the pairwise judgments in a comparison matrix are to a random set of pairwise comparisons [9].

Value of *C.R.*=0 indicates full consistency of the matrix and *C.R.*=1 means the elements of the matrix were obtained by random evaluation.

Saaty [15] proposed that a consistency ratio lower than 0,1 is considered acceptable, meaning that in such case the decision maker can be considered to have made sufficiently consistent assessments [11], [4]. In general, a consistency index threshold of 10% is advised for comparisons involving 9 or less elements (Saaty, 1995). Higher inconsistency levels may be tolerable for comparisons of more than 9

elements [6] so in these cases even a *C.R* of 0,2 could be tolerated, but not a larger one [21]. On the other hand, the judgments resulting in *C.R*. above 0,2 have a questionable credibility. Such judgments should be either discarded or the decision makers should be advised to check for accidental mistakes and to revise their pairwise comparisons so as to improve upon logical consistency, until the consistency index smaller than 0,10 is achieved [11], [9]. The AHP method thereby encourages gaining additional information, further learning, adjustment in understanding, observation and reflection [6].

In [11] it was further suggested that for the matrices of order three and four the thresholds for *C.R*. can be taken as 0,5 and 0,8, respectively [18].

The magnitude of *C.R*. in general should also not be too small (a threshold of 1% is suggested) because "inconsistency itself is important, for without it new knowledge which changes preference order cannot be admitted" [8].

Different definitions of a consistency index have also been proposed, for instance the geometric consistency index [18].

A more detailed explanation of why 10% inconsistency is chosen as a limit level is as follows [14], [8]. Inconsistency is inherent in the judgment process and the objective of developing a wide-ranging consistent framework depends on admitting some inconsistency. However, the error in measurement or evaluation brought by inconsistency can be considered a tolerable error in measurement only if it differs by an order of magnitude from the actual measurement itself. Otherwise, the inconsistency would bias the result by a sizable error comparable to or exceeding the actual measurement itself. On a scale from 0 to 1 this means the inconsistency should not exceed 0,10 by very much.

This reasoning is related to the suggestion that the number of elements compared should be small. If a large number of elements is compared, their relative priorities will be small and then the error can notably deform these priorities. On the other hand, when the number of elements is small and their priorities are comparable between themselves, a small error will not affect the order of magnitude of the answers and hence the relative priorities would not change a lot. This will be the case if there are less than 10 elements so that each has a relative priority of > 10% and hence remains relatively unaffected by a small error of for example 1% [8].

9.8. Synthesis of priorities

After priority vectors have been obtained for all levels of hierarchy, a kind of synthesis must be performed in order to obtain the final weights of the alternatives with respect to the overall goal. Several different ways of synthesizing have been developed for different decision making settings and purposes.

First point is that any multi-criteria decision making method must be able to deal both with *closed systems*, in which there is a fixed amount of resources and possible lacks of resources have to be taken into account, and *open systems*, in which resources can be added or removed and there will be no lack of resources [7].

Besides that, in traditional decision theory it has been known that when a new criterion or alternative is introduced, a reversal of the alternatives' or the criteria's ranking can occur [8]. Early research in this area axiomatically set that introducing alternatives, particularly "irrelevant" ones, should not cause rank reversal [14]. However, there are realistic situations in decision making where rank reversals can and should occur and also realistic situations in which rank reversals should not take place. Any decision making method that either always allows or never allows rank reversals is inadequate [7], [22].

In AHP, by choosing the appropriate synthesis technique either closed or open systems can be accommodated and at the same time the rank can either be allowed to reverse or be preserved. The

choice depends on the wishes of the decision maker and the needs of the decision problem [14].

The AHP method in general includes three different modes for establishing priorities: the absolute measurement mode, and the distributive and ideal modes of relative measurement. The terms ”relative” and ”absolute” here refer to the two kinds of comparisons - relative and absolute - that people have been well known to make [14]. In absolute comparisons, people compare alternatives with a standard while in relative comparisons, they pairwise compare alternatives according to a common criterium [14].

One way to always preserve rank in AHP is by absolute measurement, that is, to rate the alternatives one at a time with respect to each criterion and a complete set of intensity ranges with the largest value intensity value equal to one. This process cannot give rise to rank reversal [14]. Another way to preserve rank is to perform relative measurement in ideal mode by using an ideal alternative with full value of one for each criterion [6].

More precisely, there is a way to allow rank to change (by using the distributive mode of the relative measurement approach of the AHP), and there are two ways to preserve rank (in the case of irrelevant alternatives by using the ideal mode of the AHP relative measurement approach, and preserve rank absolutely by using the absolute measurement mode of the AHP [14], [6].

Distributive and ideal synthesis - rank reversal and rank preservation

Two ways of synthesizing the local priorities of the alternatives in AHP by using the global priorities of their parent criteria in relative measurement are the *distributive mode* and the *ideal mode*.

In the distributive synthesis (referred to also as the closed system) the unit value priority assigned to the decision goal is distributed proportionately among the alternatives. This is achieved by normalization, dividing the alternatives’ weights under each criterion by the sum of the weights of the alternatives so that they sum to one. Accordingly, the priorities of the lowest level subcriteria are distributed to the alternatives in the same way as the global priority of the goal (standardized to one) is distributed to the criteria, and then to the lowest level subcriteria [7]. When a new alternative is added in the distributive mode, it will take over a share of the unit from the previously existing alternatives. This creates a dependence between the alternatives, wherefore in the distributive mode a rank reversal is allowed [14], [22].

On the other hand, in the ideal mode (or the open system) instead of distributing each criterion’s or subcriterion’s weight to the alternatives proportionally, the most preferred alternative under each criterion or subcriterion receives the full weight of the criterion or subcriterion, and each of the other alternatives receives a weight proportional to its preference relative to the most preferred alternative. For each criterion one alternative effectively becomes an ideal alternative while the local priorities of the other alternatives are divided only by the largest local priority over all alternatives. In this manner the derived priorities of the alternatives do not add up to the local priority of a parent criterion or subcriterion. By using the ideal mode the single best alternative is distinguished regardless of what other alternatives there are. The ideal synthesis mode is appropriate for the choice making situations in which the addition or removal of an irrelevant alternative should not cause a change in ranks of the existing alternatives. This follows since in the ideal mode synthesis we just compare a new alternative with the ideal one (with the weight of one), the result is below or above the ideal, and the new alternative could itself become the ideal. As a result, an alternative that falls far below the ideal on every criterion will not affect the rank of the best chosen alternative. In this way the ideal mode prevents an alternative that is rated low or irrelevant with regards to all the criteria from influencing the rank of higher rated alternatives [7], [14], [22].

The synthesis originally implementated in AHP was the distributive mode; an improved version of

the AHP includes also the ideal mode and is capable of deriving ratio-scale priorities for both closed and open system settings [7].

As pointed out in [22], the core difference between the two synthesis modes is that with the distributive mode the preference for an alternative under each criterion depends on its performance when compared with all other alternatives while the ideal mode determines the preference for an alternative under each criterion by comparing its performance only to a fixed benchmark. In that sense the guidelines given in [22] on choosing which mode to use are as follows: the distributive synthesis mode should be used when the decision maker is concerned with the extent to which each alternative dominates all other alternatives under the criterion, for instance in allocating resources, in voting and in distributing resources among the alternatives. The ideal mode should be used when the decision maker is concerned with how well each alternative performs relative to a fixed benchmark.

The only difference between employing the AHP with a closed (distributive) or open (ideal) system is in performing a synthesis - model structuring and judgments are the same for closed and open systems [7]. Finally, choosing between an open and a closed system (between the distributive and the ideal synthesis) for a particular problem must be made by the decision maker and it should not be prescribed by a methodology or its axioms [7].

Distributive mode synthesis

Priority vectors contain weights (priorities) of all elements from some level of a hierarchy with respect to a single element from the level appearing immediately above it in a hierarchy. When the hierarchy consists of three or more levels and the priority vectors for all levels of the hierarchy are determined, these priority vectors are combined to obtain one final vector of overall priorities for the bottom level (the alternatives) [11]. The final priority vector presents the impact of the lowest elements on the top element of the hierarchy [1]. There are two ways to perform this combining: the *multiplicative synthesis* and the *additive synthesis* [6].

The additive synthesis yields the overall priority as the weighted average of all priorities by multiplying priorities of nodes from one level with the corresponding priorities of their parent nodes and adding the products over all such nodes. Meanwhile the multiplicative synthesis accounts to raising the nodes' priorities to the power of corresponding priorities of nodes from the level immediately above and multiplying the results over all higher level nodes [6]. In both variants the procedure is repeated from the bottom up to the top of the hierarchy [10], [4]. Additive and multiplicative syntheses can be seen to give similar results by simple analytical manipulations. However, it was shown (Saaty and Hu (1998)) that regardless of the similarity of priorities derived by the two methods from any consistent judgment matrix, not only the final rankings of the alternatives in a decision obtained by the two methods are different but even the final synthesised priorities differ, which can cause an improper allocation of resources. Therefore, using multiplicative synthesis is not recommended [6].

Assume the hierarchy consists of the goal, the m criteria $C_1, C_2, \dots, C_m$ and the n alternatives $A_1, A_2, \dots, A_n$. Let us denote the priority vectors of alternatives with respect to the criterium C_i by $\boldsymbol{w}_{A|C_i}$ ($i = 1, \dots, m$), the priority vector of criteria with respect to the given goal by $\boldsymbol{w}_C$ and the final overall priority (weight) vector of the alternatives with respect to the given goal by $\boldsymbol{w}_A$. By using the additive synthesis, we have

$$\boldsymbol{w_A} = \sum_{i=1}^{m} (\boldsymbol{w}_C)_i \boldsymbol{w}_{A|C_i}$$

where $(\boldsymbol{w}_C)_i$ denotes the *i* -th component of the vector $\boldsymbol{w}_C$, i. e. the priority of the criterium C_i with respect to the goal. The final priority of the alternative A_j is therefore expressed as

$$(\boldsymbol{w_A})_{\boldsymbol{j}} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{m}} (\boldsymbol{w}_C)_{\boldsymbol{i}} \boldsymbol{w}_{A_j|C_i}$$

for $j = 1, \dots, n$. Here we write $\boldsymbol{w}_{A_j|C_i}$ for the priority (weight) of the alternative A_j with respect to the criterium C_i, that is, a j-th component of $\boldsymbol{w}_{A|C_i}$. The sum of weights over all alternatives adds to 1. By employing the multiplicative synthesis we obtain

$$(\boldsymbol{w_A})_j = \prod_{i=1}^{m} \boldsymbol{w}_{A_j|C_i}{}^{(\boldsymbol{w_C})_i} \quad (7)$$

Priority vectors at a given level with respect to a single element from the next higher level can be combined as the columns of a *priority matrix* for that level and a fixed element from the next higher level. The priorities for the given level are then obtained by multiplying the priority matrix for that level on the right by the priority matrix (or vector if this next level is one level from the top) of the next higher level [15]. In the case of alternatives and criteria the described calculation corresponds to formula (7).

After deriving the final priority vector, one either selects the option (alternative) with the highest weight (if a single decision is required) or the resources are distributed to the options proportionally to their weights in the final priority vector [15].

9.9. Group decision making - aggregation of priorities

Group judgments in any decision making problem can be brought either by a consensus vote on the pairwise comparisons, or by some sort of combining the judgements of individual judges to obtain a single judgement for the group [9]. Several commonly used approaches to aggregate information from individuals participating in a decision process include AIJ (aggregating individual judgments) and AIP (aggregating individual priorities). The strategy of AIJ is to aggregate the individual judgments for each set of pairwise comparisons into an 'aggregate hierarchy' which is then synthesized. On the other hand, in AIP one synthesizes each of the individual's hierarchies and then aggregates the resulting individual priorities [23]. In both variants, satisfying the *reciprocal property* is set as important in aggregating the individual judgments, meaning that the judgements must be combined in such a way that the synthesized value of the reciprocals of the individual judgements should be the reciprocal of the synthesized value of the original judgements. It was proved that it is necessary to apply geometric mean (and not for instance the commonly used arithmetic mean) when aggregating in order for the reciprocal property to hold [10]. In particular, computing the geometric mean of the original judgments is the only way to aggregate individual judgments so that the derived group judgements satisfy the following conditions: separability (the influences of the individual judgements can be separated multiplicatively); unanimity (if all individuals give the same judgement, that judgement should also be the synthesized judgement); homogeneity (if all individuals judge a ratio *u* times as large as another ratio, then the synthesized judgement should also be *u* times as large); reciprocity (the synthesised value of the reciprocals of the individual judgements should be the reciprocal of the synthesized value of the original judgements) [6]. Recall that the *geometric mean* of $x_1, x_2, \dots, x_n$ ($x_i > 0$ for all $i = 1, \dots, n$) is defined as

$$\sqrt[n]{x_1 x_2 \cdots x_n}.$$

When bringing the group decisions one may additionally allow judging individuals to have different importance when the judgements are synthesized. This is in line with the idea that some people are more educated, wiser, sensible or powerful than the others. For that setting it was shown that only the weighted geometric mean yields the group judgment with desirable above mentioned properties and the group rankings are given in the following result [6].

Theorem 3 *If x_j^i is a ranking of the j-th alternative by the i-th judge (for n alternatives and m independent judges) and if a_i is the importance of judge i developed from a hierarchy for evaluating the judges (so $\sum_{i=1}^{n} a_i = 1$), then the combined ranks of the alternatives for the m judges are given by*

$$\left(\prod_{i=1}^{m} x_1^{a_i}\right)^{1/m},\ \left(\prod_{i=1}^{m} x_2^{a_i}\right)^{1/m},\ \ldots,\ \left(\prod_{i=1}^{m} x_n^{a_i}\right)^{1/m}.$$

Recall that in general form, for $\mathrm{x}_1, \mathrm{x}_2, \ldots, \mathrm{x}_\mathrm{n}$ ($\mathrm{x}_\mathrm{i} \geq 0$ for all $\mathrm{i} = 1, \ldots, \mathrm{n}$) and their weights $\mathrm{w}_1, \ldots, \mathrm{w}_\mathrm{n}$ ($\mathrm{w}_\mathrm{i} \geq 0$ for all $\mathrm{i} = 1, \ldots, \mathrm{n}$) their *weighted geometric mean* is given by

$$\left(\mathrm{x}_1^{\mathrm{w}_1} \cdot \mathrm{x}_2^{\mathrm{w}_2} \cdots \mathrm{x}_\mathrm{n}^{\mathrm{w}_\mathrm{n}}\right)^{1/\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{w}_\mathrm{i}}. \tag{8}$$

If the weights are normalized so that the sum of the weights is equal to 1, the weighted geometric mean of $\mathrm{x}_1, \mathrm{x}_2, \ldots, \mathrm{x}_\mathrm{n}$ from (8) reduces to

$$\mathrm{x}_1^{\mathrm{w}_1} \cdot \mathrm{x}_2^{\mathrm{w}_2} \cdots \mathrm{x}_\mathrm{n}^{\mathrm{w}_\mathrm{n}}. \tag{9}$$

Note that the expression (9) is a geometric mean of $x_1, x_2, \ldots, x_n$ in case all weights w_i are equal (to $1/n$).

Additional argument for using geometric mean in aggregation (instead of arithmetic or some other mean) is that the geometric mean fits with the notions of judgments and priorities in AHP [23]. Pairwise comparisons are ratios showing how many times one factor is more important than another, and similarly the ratio of priorities of two alternatives says how many times one alternative is more preferable to the other. Therefore for example the ratio of geometric mean of two pairwise comparisons to the ”lower” rate will be the same as the ratio of the ”higher” rate to the geometric mean. Suggestions on how to choose between AIJ and AIP are provided in [10].

When the group consists of individual experts, they each make their own pairwise comparisons and form the hierarchy but do not combine their judgements until they each obtain their final outcomes from their own hierarchy. In this setting AIP is employed, meaning that only in the last (choice) stage of the decision analysis, the individual outcomes are aggregated. A geometric mean of the final priorities is applied in aggregation [10]. In this scenario the group members only need to agree upon the final choice of one of the alternatives, regardless of the differences in rationale behind this choice [9].

If group members are not acting as individual experts, but act in compliance and pool their judgments to develop more accurate comparisons, then AIJ should be used. In AIJ approach aggregation takes place during the evaluation stage, when members’ judgments for each pairwise comparison are averaged by using geometric mean into one aggregate hierarchy [23]. Then in the choice stage priorities are calculated from the obtained group averages [9].

According to [10], apart from the question of how to aggregate individual judgements from a group into a single representative judgement for the entire group, another important issue in group decision making is how to construct a group choice from individual choices. Interestingly, if only the ordinal preferences (when alternatives are ranked just from the best to the worst) of the individuals are available, it was shown [6] that it is not possible to derive a group choice which satisfies the following relevant conditions: decisiveness (the aggregation procedure must generally produce a

group order); unanimity (if all individuals prefer alternative A to alternative B, then in the group order A must be preferable to B); independence of irrelevant alternatives (given two sets of alternatives which both include A and B, if all individuals prefer A to B in both sets, then the group, given any of the two sets of alternatives, prefers A to B), no dictator (no single individual preferences determine the group order). Meanwhile, since the individual preferences in AHP are given on a ratio scale and therefore are cardinal (not ordinal), it can be shown that by using AHP it is possible to obtain a rational group choice satisfying the aforementioned four conditions [6].

9.10. Hybrid geo system optimization and project design in Danube GeoHeCo project

Criteria for determining the most influencing factor in the design of the SG hybrid system were evaluated by using the AHP method. As a first step, a decision hierarchical structure was established from the top to the bottom in three levels (see Chapter 9.3.): the overall goal or the focus (hybrid geo system optimization and project design), the criteria, and the sub-criteria as the lowest level (Figure 9.4.). The criteria are considered as categories, subdivided into sub-criteria.
Next, a list of relevant criteria (factors) which affect the design and technology optimization of shallow geothermal hybrid heating and cooling systems and eventually their installation in different building environments, was proposed. The list consists of 20 criteria that were arranged as sub-criteria for the following four categories of criteria:

- technical and technological criteria: monthly peak heating and cooling loads; monthly heating and cooling energy demand; drilling depth of BHE and well geometry and completion; installation year of existing system; BHE thermal resistance or well loss
- geological, thermogeological and hydrogeological criteria: thermal or hydraulic conductivity for ground or aquifer; geothermal gradient; undisturbed ground or aquifer temperature or waste heat temperature; unconfined aquifer presence thickness or spring water yield; type of lithology and heterogeneity
- socioeconomic criteria: cost of electricity households or enterprise; cost of natural gas or fuel oil households or enterprise; GSHP or GWHP cost of periodic rework for entire system; cost of BHE or water well drilling and completion; cost of HP installation compared to existing system
- environmental, policy and climate criteria: water protection area impact on project cost; landuse conflicts or available area for geothermal system; bivalent temperature for hybrid system setup; monthly average air temperature and air amplitude; direct government local incentives for renovation.

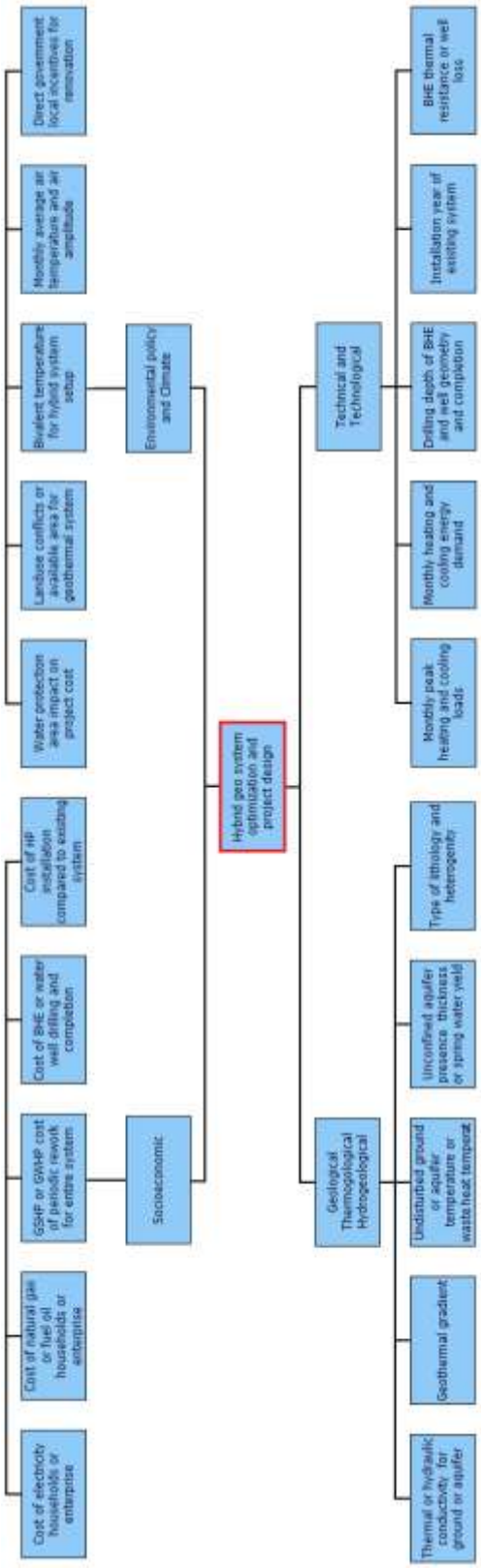


Figure 9.4. Hierarchical structure of the problem

The proposed set of criteria includes both quantitative criteria (e.g. monthly peak heating and cooling loads, geothermal gradient, cost of HP installation compared to existing system, monthly average air temperature and air amplitude...) and qualitative criteria (e.g. type of lithology and heterogenity, water protection area impact on project cost, landuse conflicts or available area for geothermal system...) The criteria were chosen in accordance with the principles of the AHP method (see Chapter 9.2.). In particular, they satisfy the independence axiom which states that the criteria should be independent of each other.

As a next step the pairwise judgment matrices (see Chapter 9.5.) using the Saaty 1-9 scale (see Chapter 9.4.) were produced independently by 15 expert decision makers. More precisely, each decision maker delivered a matrix of pairwise comparisons of different categories of criteria with respect to the overall goal of hybrid geo system optimization and project design, and four matrices containing pairwise comparisons of sub-criteria from the same category of criteria with respect to the parent criterium, for each of the four categories (technical and technological criteria; geological, thermogeological and hydrogeological criteria; socioeconomic criteria; environmental, policy and climate criteria). Sub-criteria from different categories were not directly compared.

In order to validate the results, the consistency ratios (C.R.) were calculated (see Chapter 9.7.) for all comparison matrices from all decision makers. The results as well as the corresponding basic descriptive statistics are presented in Table 9.1. Overall individual values of C.R. quite vary, as the individual decision makers' average C.R.s do, however, the average consistency ratios for each type of comparison matrix are between 0,129 and 0,197, with corresponding medians lower than the averages, which falls under the tolerable range of C.R. up to 0,2 (see the references in Chapter 9.7.). Globally the average C.R. is 0,168. Therefore overall, we can consider the decision makers to have made sufficiently consistent assessments.

Table 9.1. Consistency ratios for comparison matrices of individual decision makers

	DM1	DM2	DM3	DM4	DM5	DM6	DM7	DM8	DM9	DM10	DM11	DM12	DM13	DM14	DM15	mean	median	min	max	variance	s. d.
Table 1	0,163	0,119	0,095	0,082	0,448	0,000	0,316	0,256	0,256	0,095	0,018	0,018	0,119	0,011	0,090	0,139	0,095	0,000	0,448	0,016	0,128
Table 2	0,169	0,260	0,311	0,029	0,104	0,196	0,229	0,097	0,074	0,024	0,139	0,049	0,099	0,078	0,072	0,129	0,099	0,024	0,311	0,008	0,087
Table 3	0,270	0,836	0,115	0,058	0,261	0,000	0,142	0,322	0,366	0,018	0,037	0,034	0,113	0,121	0,269	0,197	0,121	0,000	0,836	0,045	0,212
Table 4	0,150	0,203	0,013	0,043	0,144	0,111	0,517	0,413	0,109	0,009	0,078	0,022	0,109	0,646	0,235	0,187	0,111	0,009	0,646	0,037	0,192
Table 5	0,259	0,181	0,058	0,081	0,255	0,005	0,686	0,413	0,218	0,155	0,202	0,034	0,136	0,050	0,108	0,189	0,155	0,005	0,686	0,030	0,174
mean	0,202	0,320	0,118	0,059	0,242	0,062	0,378	0,300	0,205	0,060	0,095	0,031	0,115	0,181	0,155						
median	0,169	0,203	0,095	0,058	0,255	0,005	0,316	0,322	0,218	0,024	0,078	0,034	0,113	0,078	0,108						
min	0,150	0,119	0,013	0,029	0,104	0,000	0,142	0,097	0,074	0,009	0,018	0,018	0,099	0,011	0,072						
max	0,270	0,836	0,311	0,082	0,448	0,196	0,686	0,413	0,366	0,155	0,202	0,049	0,136	0,646	0,269						
variance	0,003	0,086	0,013	0,001	0,018	0,008	0,049	0,017	0,014	0,004	0,006	0,000	0,000	0,069	0,008						
s.d.	0,057	0,293	0,114	0,023	0,134	0,088	0,221	0,131	0,117	0,063	0,076	0,012	0,014	0,263	0,090						

Thereafter the aggregation of individual decision makers' assessments was performed by the AIJ (aggregating individual judgments) technique. In the AIJ approach the individual judgments for each set of pairwise comparisons are combined into an ’aggregate hierarchy’ which is then synthesized. Since in our analysis the group members are not acting as individual experts, but act in compliance and pool their judgments to develop more accurate comparisons, the AIJ approach was chosen as recommended (see Chapter 9.9.).

In particular, the geometric mean values of the decision makers' assessments were calculated for each type of the comparison matrix. These results are presented in Table 9.2., Table 9.3., Table 9.4., Table 9.5. and Table 9.6. It has been known (see Chapter 9.9.) that, when aggregating the individual judgments, computing the geometric mean of the single judgments is the only way of aggregation guaranteeing that the derived group judgements satisfy the desirable properties like homogeneity, reciprocity or unanimity. Furthermore, the consistency ratios (C.R.) were calculated for the aggregated comparison matrices. The values of the C.R. span from 0,15 to 0,27 which is considered tolerable, especially since they refer to the aggregated comparison matrices and not to the individual ones.

Table 9.2. Pairwise comparison of categories of criteria with respect to the overall goal of Hybrid geo system optimization and project design

	Technical and Technological	Geological Thermogological Hydrogeological	Socioeconomic	Environmental policy and Climate
Technical and Technological	1,000	0,647	1,019	1,318
Geological Thermogological Hydrogeological	1,545	1,000	0,789	1,232
Socioeconomic	0,981	1,267	1,000	1,141
Environmental policy and Climate	0,759	0,812	0,876	1,000

Table 9.3. Pairwise comparison of sub-criteria with respect to the criterium Technical and Technological Criteria

Pairwise comparison with respect to Technical and Technological criteria	Monthly peak heating and cooling loads	Monthly heating and cooling energy demand	Drilling depth of BHE, well geometry and completion	Installation year of existing system	BHE thermal resistance or water well loss
Monthly peak heating and cooling loads	1,000	2,009	1,618	1,794	2,263
Monthly heating and cooling energy demand	0,498	1,000	1,289	1,258	1,212
Drilling depth of BHE, well geometry and completion	0,618	0,776	1,000	1,072	1,314
Installation year of existing system	0,558	0,795	0,933	1,000	1,047
BHE thermal resistance or water well loss	0,442	0,825	0,761	0,955	1,000

Table 9.4. Pairwise comparison of sub-criteria with respect to the criterium Geological-Thermogeological-Hydrogeological Criteria

	Thermal or hydraulic conductivity for ground or aquifer	Geothermal gradient	Undisturbed ground or aquifer temperature or waste heat temperature	Unconfined aquifer presence thickness or spring water yield	Type of lithology and heterogenity
Thermal or hydraulic conductivity for ground or aquifer	1,000	1,306	1,160	0,647	1,762
Geothermal gradient	0,766	1,000	1,059	0,886	1,475
Undisturbed ground or aquifer temperature or waste heat temperature	0,862	0,945	1,000	0,933	1,543
Unconfined aquifer presence thickness or spring water yield	1,544	1,129	1,072	1,000	1,280
Type of lithology and heterogenity	0,568	0,678	0,648	0,781	1,000

Table 9.5. Pairwise comparison of sub-criteria with respect to the criterium Socioeconomic Criteria

	Cost of electricity households or enterprise	Cost of natural gas or fuel oil households or enterprise	GSHP or GWHP cost of periodic rework for entire system	Cost of BHE or water well drilling and completion	Cost of HP installation compared to existing system
Cost of electricity households or enterprise	1,000	0,618	2,575	0,672	0,757
Cost of natural gas or fuel oil households or enterprise	1,617	1,000	2,662	0,819	1,199
GSHP or GWHP cost of periodic rework for entire system	0,388	0,376	1,000	0,581	0,788
Cost of BHE or water well drilling and completion	1,489	1,221	1,721	1,000	1,382
Cost of HP installation compared to existing system	1,321	0,834	1,269	0,724	1,000

Table 9.6. Pairwise comparison of sub-criteria with respect to the criterium Environmental policy and Climate Criteria

	Water protection area impact on project cost	Landuse conflicts or available area for geothermal system	Bivalent temperature for hybrid system setup	Monthly average air temperature and air amplitude	Direct government local incentives for renovation
Water protection area impact on project cost	1,000	1,194	1,020	1,465	1,666
Landuse conflicts or available area for geothermal system	0,838	1,000	1,219	1,149	0,926
Bivalent temperature for hybrid system setup	0,981	0,820	1,000	0,982	1,571
Monthly average air temperature and air amplitude	0,683	0,870	1,018	1,000	1,014
Direct government local incentives for renovation	0,600	1,079	0,637	0,987	1,000

In a final step of the analysis the priorities or the weights and consequently the ranks of criteria and subcriteria are derived from the corresponding matrices of mean values in Table 9.2., Table 9.3., Table 9.4., Table 9.5. and Table 9.6. by using the additive form of the distributive mode synthesis (see Chapter 9.8.). The priority vector of categories of criteria with respect to the overall goal is given in Table 9.7. ; the priority vectors of sub-criteria with respect to their parent criteria are given in Table 9.8., Table 9.9., Table 9.10. and Table 9.11; finally, the priorities of all sub-criteria with respect to the overall goal are shown in Table 9.12.

Table 9.7. Priorities of categories of criteria with respect to the overall goal of Hybrid geo system optimization and project design

Rank	Name	Weight
1	Geological Thermogological Hydrogeological	0,2770
2	Socioeconomic	0,2710
3	Technical and Technological	0,2410
4	Environmental policy and Climate	0,2110

Table 9.8. Priorities of subcriteria with respect to the criterium Technical and Technological Criteria

Rank	Name	Weight
1	Monthly peak heating and cooling loads	0,3220
2	Monthly heating and cooling energy demand	0,1920
3	Drilling depth of BHE and well geometry and completion	0,1780
4	Installation year of existing system	0,1620
5	BHE thermal resistance or well loss	0,1470

Table 9.9. Priorities of subcriteria with respect to the criterium Geological Thermogeological Hydrogeological Criteria

Rank	Name	Weight
1	Unconfined aquifer presence thickness or spring water yield	0,2370
2	Thermal or hydraulic conductivity for ground or aquifer	0,2210
3	Undisturbed ground or aquifer temperature or waste heat temperature	0,2020
4	Geothermal gradient	0,1980
5	Type of lithology and heterogenity	0,1420

Table 9.10. Priorities of subcriteria with respect to the criterium Socioeconomic Criteria

Rank	Name	Weight
1	Cost of BHE or water well drilling and completion	0,2550
2	Cost of natural gas or fuel oil households or enterprise	0,2540
3	Cost of HP installation compared to existing system	0,1910
4	Cost of electricity households or enterprise	0,1860
5	GSHP or GWHP cost of periodic rework for entire system	0,1140

Table 9.11. Priorities of subcriteria with respect to the criterium Environmental policy and Climate Criteria

Rank	Name	Weight
1	Water protection area impact on project cost	0,2450
2	Bivalent temperature for hybrid system setup	0,2080
3	Landuse conflicts or available area for geothermal system	0,2020
4	Monthly average air temperature and air amplitude	0,1790
5	Direct government local incentives for renovation	0,1660

Table 9.12. Weights of Criteria with respect to Hybrid geo system optimization and project design

Rank	Name	Weight
1	Monthly peak heating and cooling loads	0,0776
2	Cost of BHE or water well drilling and completion	0,0691
3	Cost of natural gas or fuel oil households or enterprise	0,0688
4	Unconfined aquifer presence thickness or spring water yield	0,0656
5	Thermal or hydraulic conductivity for ground or aquifer	0,0612
6	Undisturbed ground or aquifer temperature or waste heat temperature	0,0560
7	Geothermal gradient	0,0548
8	Cost of HP installation compared to existing system	0,0518
9	Water protection area impact on project cost	0,0517
10	Cost of electricity households or enterprise	0,0504
11	Monthly heating and cooling energy demand	0,0463
12	Bivalent temperature for hybrid system setup	0,0439
13	Drilling depth of BHE and well geometry and completion	0,0429
14	Landuse conflicts or available area for geothermal system	0,0426
15	Type of lithology and heterogenity	0,0393
16	Installation year of existing system	0,0390
17	Monthly average air temperature and air amplitude	0,0378
18	BHE thermal resistance or well loss	0,0354
19	Direct government local incentives for renovation	0,0350
20	GSHP or GWHP cost of periodic rework for entire system	0,0309

From final Table 9.12. and weighing of all criteria, it can be seen that results are somewhat equable, which is to be expected on large sample of criteria like this one. Nevertheless, distinction can be seen obviously when comparing the first top 5 and the last top 5 of criteria, as differences between are double of emphasis. This effectively means that when designing IT Tool and general model of SG hybrid system, it is out of most importance to obtain upper half of criteria data as accurate as possible. Lower weighting factors are, of course, still important but it is not key to have most accurate onsite data as it is enough to obtain correlated data or typical data range for each criterion. This will still affect an IT Tool sizing process, but the ultimate result will not be very different as opposed to have completely all data available and precise from a microlocation. This is in particular meaningful, as obtaining all possible data for certain microlocation is an exhaustive and economically intense process for project

development. Criteria catalogue like this one, can rather give directions on what criteria should have focus on by developer to have solid, reliable and efficient system at the end.

9.11. Conclusion

The Analytic hierarchy process (Saaty 1980) provides a comprehensive and systematic approach for multi-criteria decision-making. It structures a complex problem into a hierarchy, performs pairwise comparisons and then the consistency check which ensures the reliability of the judgments, and finally synthesizes to derive priority vectors. By doing do, the method allows decision makers to effectively evaluate and prioritize alternatives. This robust methodology facilitates informed and rational decision-making, accommodating both quantitative and qualitative data. All this makes AHP a powerful tool for various applications.

The three components of AHP are: decomposition (the structuring of a problem into a hierarchy consisting of a goal and subordinate features); evaluation (pairwise comparisons between elements at each level); synthesis (propagation of level-specific, local priorities to global priorities) [6]. Subordinate levels of a hierarchy may include objectives, scenarios, events, actions, outcomes and alternatives. Pairwise comparisons are made between all elements at a particular level with respect to elements in the level above it. Comparisons can be made according to preference, importance, or likelihood - whichever variant is most appropriate for the particular elements considered. Saaty (1980) developed the rigorous mathematical approach to combine pairwise comparisons made at different levels in order to produce a final priority value for each of the alternatives at the bottom of the hierarchy [6].

Finally, the AHP provides quantitative priorities to be used in decision support, but it does not include statistical assessment of uncertainties of the results. The consistency ratio, which measures the (in)consistency of the given comparisons and results from AHP calculations provides no direct information about the uncertainty of the priorities obtained [6].

REFERENCES

[1] *Geothermie-Österreich. (2024).* Was ist Geothermie? Retrieved from https://www.geothermie-oesterreich.at/was-ist-geothermie/oberfl%C3%A4chennahe-geothermie/

[2] Rehau. (2022). Innovativ heizen, kühlen und sparen mit Erdwärme Rehau Industries SE & Co. KG 2022

[3] ÖWAV; Österreichischer Wasser- und Abfallwirtschaftsverband. (2009). Regelblatt207: Thermische Nutzung des Grundwassers und des Untergrunds – Heizen und Kühlen Wien 2009.

[4] Wien Energie (2024). Verkaufte Wärmepumpen in Österreich. Abgerufen von https://positionen.wienenergie.at/grafiken/verkaufte-waermepumpen-in-oesterreich/

[5] Statistic Austria (2023). Mikrozensus, 2021/2022. Primary heating system main residences.

[6] Verein Geothermie Österreich & EVN Wärme GmbH (2024). Potenziale der Geothermie für die Energieversorgung in Österreich Gregor Götzl. 23. April 2024

[7] Geothermie-Österreich (2024). Der Vorstand. Retrieved form https://www.geothermie-oesterreich.at/der-verein/vorstand/

[8] Bundesministerium Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie (2023). Der Beitrag von Wärmepumpen zur Wärmewende. Available at https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://www.bmk.gv.at/dam/jcr:dbb6b843-401a-4ebb-a382-3c4a4e1a5d49/BMK_Der%2520Beitrag%2520von%2520W%25C3%25A4rmepumpen%2520zur%2520W%25C3%25A4rmewende%2520-%2520Unterlage%2520zum%2520Branchentreff.pdf&ved=2ahUKEwik2If1-q2GAxXOh_0HHUGsA8wQFnoECBcQAQ&usg=AOvVaw2tUC45VP674x-1ouRReTCN

[9] Veranstaltung „Insight Talk: Potenziale der Geothermie für die Energiewende“ am 23.4.24 von 13:00-14:30,

[10] Umweltbundesamt (2024). Berechnung von Treibhausgas (THG)-Emissionen verschiedener Energieträger. Retrieved from https://secure.umweltbundesamt.at/co2mon/co2mon.html

[11] Wien Energie (2024). Sprechen wir über Geothermie. Retrieved on 13 May 2024 from Tiefe Geothermie » Potential & Zukunftsaussichten | Positionen (wienenergie.at)

[12] VDI-Richtlinie 4640: Thermische Nutzung des Untergrundes, Hrsg.: Verein Deutscher Ingenieure, VDI-Gesellschaft Energietechnik (GET), Beuth Verlag

[13] Büchele, R., Müller, A., Hummel, M., Kranzl, L., & Hartner, M. (2015). Typologie von Wärme-und Kältebedarfs-und Angebotsregionen in Österreich. 9. Internationale Energiewirtschaftstagung (IEWT 2015), Technische Universität Wien, Österreich. Online unter: https://publik. tuwien. ac. at/files/PubDat_243275. pdf (letzter Zugriff: 05.06. 2020).

[14] E-Control (2024). Preisentwicklung. Retrieved from https://www.e-control.at/statistik/g-statistik/archiv/marktstatistik/preisentwicklungen

[15] Biomasseverband (2024). Energieträgervergleich. Retrieved from https://www.biomasseverband.at/energietraegervergleich/
[16] Meyers, S., Schmitt, B., & Vajen, K. (2018). The future of low carbon industrial process heat: A comparison between solar thermal and heat pumps. Solar Energy, 173, 893-904.
[17] Geothermie in Österreich (2023). Potenziale nachhaltiger Wärme aus Geothermie für Gemeinden, Industriebetriebe und Energieversorgungsunternehmen, December 2023
[18] Petrovic, Semin & Delalic, Nijaz. (2023). An overview of the potential of geothermal energy and ways of using it in Bosnia and Herzegovina. Energy from the deep
[19] Đurić, N., & Đurić, D. (2015). Importance of Geothermal Energy in the Area of Semberija in the Republic of Srpska. Contemporary Materials, 6(2), 234-242
[20] Đurić, D., Požar, T., Đurić, N. (2016). Geothermal potentiality of Republic of Srpska and the possibility of using of the available energy
[21] Agency for statistics of Bosnia and Herzegovina. (2024). Short-term indicators of energy statistics. February 2024
[22] Fourth National Communication of Bosnia And Herzegovina under the United Nations Framework Convention on Climate Change (Available at https://unfccc.int/sites/default/files/resource/FNC%20BiH_ENG%20fin.pdf)
[23] Hrvatović H. (2006). Geological Guidebook through Bosnia and Herzegovina. Geological Survey of Federation Bosnia and Herzegovina, Sarajevo
[24] Miošić, N., Samardžić, N., Hrvatović, H. (2010). The current status of geothermal energy use and development in Bosnia and Herzegovina. In Proceedings World Geothermal Congress (pp. 1-10), April 2010
[25] Kurevija, T. (2014). The report on performed TRT measurements on borehole heat exchangers. LIR Evolution, Srbac
[26] Đurić, N., Jovanović, L., Glavaš, S. Hydrological structures and spatial location of aquifers in BiH.
[27] Regulatory Commission for Energy of Republika Srpska. (2022). Decision on tariffs for public supply of electricity in Republika Srpska. December 2022
[28] Elektroprivreda Republike Srpske, Direction for market supply of electricity, ers.ba/snabdijevanje
[29] Eurostat: https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_204__custom_11455087/default/bar?lang=en
[30] Eurostat: https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_205/default/bar?lang=en
[31] Simić, J., Ikić, S.: geothermal power plant and a possible development in Bosnia and Herzegovina, INFOTEH-JAHORINA, March 2011
[32] Geological atlas of Republic of Srpska, Ministry for industry, energy and mining of Republic of Srpska, Zvornik 2012
[33] Study of renewable energy sources with emphasis on biomass, geothermal energy and solar energy in Bosnia and Herzegovina, UNDP, Sarajevo 2019
[34] Strategy of climate change adaptation and low-carbon development of Bosnia and Herzegovina 2020-2030, GEF, UNDP, December 2020
[35] Local report on aspects related to renewable energy sources based on environmental and landscape characters of the area and social as well as economic effects, TERRE project, LIR Evolution, 2014

[36] Law on geothermal research of Republika Srpska, Official Gazette of Republika Srpska, 64/2022
[37] Jelić, K. (1979). Termičke osobine sedimentacionog kompleksa jugozapadnog dijela Panonskog bazena (Thermic properties of sedimentation complex of southwest region of Pannonian Basin). Ph.D. thesis, University of Zagreb, Faculty of mining, geology and petroleum engineering
[38] Jelić, K. and Lukačević, M. (1989). Solar Heat Energy in the Soil of the Pannonian Basin in the Socialist Republic of Croatia. Proceedings of Solar energy meeting, IUC Dubrovnik, 1-12
[39] Jelić, K. and Kevrić, I. (1997): Plitka geotermalna energija u Hrvatskoj (Shallow Geothermal Energy in Croatia). 6. forum Hrvatskog energetskog društva, Zagreb, 1997, 181-190
[40] Kurevija, T. (2008). Analysis of potentials of shallow geothermal resources in heat pump systems in the city of Zagreb. Goriva i maziva, 47, 5, 373-390
[41] Ruševljan, M., Soldo, V., Ćurko, T. (2009). Optimal Sizing of Borehole Heat Exchangers. Strojarstvo, 51, 5, 473-480.
[42] Soldo, V., Ruševljan, M., Lepoša, L., Grozdek, M. and Ćurko, T. (2011). Prvo terensko mjerenje toplinskih svojstava tla u Hrvatskoj u svrhu projektiranja toplinskog sustava s dizalicom topline. In: Klima forum 2011. 3. forum o hlađenju, klimatizaciji i ventilaciji (pp. 72-72).
[43] Soldo, V., Ruševljan, M., Ćurko, T. and Grozdek, M. (2010): Rezultati mjerenja na ispitnoj dizalici topline s bušotinskim izmjenjivačem topline. In: Zbornik radova 9. međunarodnog znanstveno-stručnog savjetovanja Energetska i procesna postrojenja i 4. međunarodnog foruma o obnovljivim izvorima energije.
[44] Kurevija, T. (2010): Energetsko vrednovanje plitkih geotermalnih potencijala Republike Hrvatske (Energetic evaluation of the shallow geothermal potential in the Republic of Croatia). Ph.D. thesis, University of Zagreb, Faculty of mining, geology and petroleum engineering.
[45] Kurevija, T. and Vulin, D. (2010): Determining undisturbed ground temperature as part of shallow geothermal resources assessment. The Mining-Geology-Petroleum Engineering Bulletin (Rudarsko-geološko-naftni zbornik), 22, 1, 27-36.
[46] Kurevija, T., Vulin, D., Krapec, V. (2012). Effect of borehole array geometry and thermal interferences on geothermal heat pump system. Energy Conversion and Management, 60, 134-142.
[47] Kurevija, T., Vulin, D., Macenić, M. (2014). Impact of geothermal gradient on ground source heat pump system modeling The Mining-Geology-Petroleum Engineering Bulletin (Rudarsko-geološko-naftni zbornik), 28, 1, 39-45.
[48] Soldo, V., Borović, S., Lepoša, L. and Boban, L. (2016). Comparison of different methods for ground thermal properties determination in a clastic sedimentary environment. Geothermics, 61, 1-11.
[49] Boban, L., Lepoša, L., Soldo, V., Grozdek, M. (2015). Influence of groundwater flow on implementation of distributed thermal response test. In: 24th IIR International Congress of Refrigeration (ICR2015), 16-22.08.2015., Yokohoma.
[50] Soldo, V., Boban, L., Borović, S. (2016). Vertical distribution of shallow ground thermal properties in different geological settings in Croatia. Renewable energy, 99, 1202-1212.
[51] Tinti, F., Pangallo, A., Berneschi, M., Tosoni, D., Rajver, D., Pestotnik, S., Jovanović, D., Rudinica, T., Jelisić, S., Zlokapa, B., Raimondi, A., Tollari, F., Zamagni, A., Chiavetta, C., Meggiolaro, M. (2016). How to boost shallow geothermal energy exploitation in the Adriatic area: the LEGEND project experience. Energy Policy, 92, 190-204.
[52] MUSE project. Available at: http://geoera.eu/projects/muse/

[53] Kurevija, T., Macenić, M., Borović, S. (2017). Impact of grout thermal conductivity on the long-term efficiency of the ground-source heat pump system. Sustainable Cities and Society, 31, 1-11.
[54] Kurevija, T., Strpić, K. (2018). Hydraulic and thermogeological design differences between two-loop vertical and inclined coaxial borehole heat exchangers. Renewable energy, 117, 314-323.
[55] Kurevija, T., Macenić, M. and Strpić, K. (2018). Steady-state heat rejection rates for a coaxial borehole heat exchanger during passive and active cooling determined with the novel step thermal response test method. The Mining-Geology-Petroleum Engineering Bulletin (Rudarsko-geološko-naftni zbornik), 33, 2, 61-71.
[56] Borović, S., Terzić, J. and Urumović, K. (2018): Installation of ground-and water-source heat pumps in karst terrains (case studies from Croatia). In KARST 2018 Expect the Unexpected.
[57] Boban, L., Soldo, V., Stošić, J., Filipović, E. and Tremac, F. (2018). Ground Thermal Response and Recovery after Heat Injection: Experimental Investigation. Transactions of FAMENA, 42, SI-1, 39-50,
[58] Kurevija, T., Strpić, K. and Koščak-Kolin, S. (2018b): Applying petroleum the pressure buildup well test procedure on thermal response test—A novel method for analyzing temperature recovery period. Energies, 11, 2, 366.
[59] Mapping of Shallow Geothermal Systems in the Republic of Croatia (PLIGES) Project, ref. no.111. financed by Iceland, Liechtenstein and Norway as a part of the Financial Mechanism of the European Economic Area (EEA) 2014 - 2021 with national co-financing by the Republic of Croatia within the framework of the implementation of the 'Energy and Climate Change' Programme. Available at https://www.pliges.eu/index.html
[60] Republic of Croatia, Ministry of economy and sustainable development. Energy in Croatia 2022. Zagreb.
[61] Narodne novine (NN) (2017): Pravilnik o jednostavnim i drugim građevinama i radovima (Ordinance on Simple and Other Buildings and Works). NN 112/17.
[62] Saftić, B., Velić, J., Sztano, O., Juhasz, G., & Ivković, Ž. (2003). Tertiary subsurface facies, source rocks and hydrocarbon reservoirs in the SW part of the Pannonian Basin (northern Croatia and south-western Hungary). Geologia Croatica, 56(1), 101-122.
[63] Cvetković, M., Matoš, B., Rukavina, D., Kolenković Močilac, I., Saftić, B., Baketarić, T., ... & Paškov, T. (2019). Geoenergy potential of the Croatian part of Pannonian Basin: insights from the reconstruction of the pre-Neogene basement unconformity. Journal of Maps, 15(2), 651-661.
[64] Macenić, M., Kurevija, T., & Medved, I. (2020). Novel geothermal gradient map of the Croatian part of the Pannonian Basin System based on data interpretation from 154 deep exploration wells. Renewable and Sustainable Energy Reviews, 132, 110069.
[65] Croatian Geological Survey. Geological map of Croatia 1:300000. Available at: https://www.hgi-cgs.hr/en/geoloska-karta-republike-hrvatske-1300-000/
[66] Bognar, A. (1996). Fizičko-geografske pretpostavke regionalnog razvoja Hrvatske. Zbornik radova I. Hrvatskog geografskog kongresa, Hrvatsko geografsko društvo, Zagreb, pp 51–65
[67] Buday, T. (2014). Reduction of environmental impacts of heat pump usage with special regard on systems with borehole heat exchangers. Acta Geographica Debrecina Landscape & Environment Series, 8(2), 66-77. https://ojs.lib.unideb.hu/landsenv/article/view/2310
[68] Gresz T., Faragó D., Bencs P. (2021). Heat pumps in the future. MATEC Web Conference 345 00004 (2021) https://doi.org/10,1051/matecconf/202134500004
[69] Sarbu, I., Sebarchievici, C. (2014). General review of ground-source heat pump systems for heating and cooling of buildings Energy Build. 70, 441-454

[70] Ádám, B. (2008). Hőszivattyús földhő hasznosítás aktuális helyzete Magyarországon az EU helyzet tükrében, Kistelek, Geotermia a XXI. században szakmai fórum, 2008
[71] Ádám B. (2012). Földhőszondák hőtechnikai viszonyai hőszivattyús rendszereknél Doktori (Ph.D) értekezés, Szent István Egyetem Gödöllő
[72] Ádám B., Szanyi J., Bencsik A., Bozsó G., Pinjung Zs. (2019). A decentralizált geotermikus hőellátás és a hőszivattyúzás aktuális kérdései. – Magyar Tudomány 180/12, 1808–1821. https://doi.org/10,1556/2065.180,2019.12.7
[73] Ádám, B.-Tóth, L. (2012). Heat Technical Measuring of Ground for Vertical Borehole Heat Exchangers Installations, in Journal of Agricultural Machinery Science, 2012, Turkey
[74] Dövényi P., Drahos D., Lenkey L. (2001). Magyarország geotermikus energiapotenciáljának feltérképezése a felhasználás növelése érdekében. H mérsékleti viszonyok (Mapping of the Geothermal Potential of Hungary to Increase Utilization. Temperature conditions). Scientific Report for the Global Environment. Eötvös Loránd University, Department of Geophysics, 1–10 (in Hungarian)
[75] Dövényi P., Horváth F., Drahos D. (2002). Hungary. In: Hurter S, Haenel R (eds) Atlas of Geothermal Resources in Europe. Publication No. 17811 of the European Commission, Office for Official Publications of the European Communities. L2985, Luxembourg. 36–38
[76] Economx (2022): EM: törvénymódosítás élénkítheti a geotermia hazai térnyerését. https://www.economx.hu/magyar-gazdasag/geotermia-torveny-jog-modositas.764377.html (8 May 2024).
[77] EHPA (2021). European Heat Pump Market and Statistics Report 2021. The European Heat Pump Association (EHPA), Brussels
[78] EHPA (2023). European Heat Pump Market and Statistics Report 2023. The European Heat Pump Association (EHPA), Brussels
[79] Erőss, A., Zsemle, F., & Pulay, E. (2015). Heat potential evaluation of effluent and used thermal waters in Budapest, Hungary. Central European Geology Central European Geology, 58(1-2), 62-71. https://doi.org/10,1556/24.58.2015.1-2.4
[80] Fodor Z., Komlós F. (2011). Termálvizes fürdő bővítése hőszivattyúk alkalmazásával. ENERGIAGAZDÁLKODÁS 52/6.
[81] IRENA (2023). Renewable energy statistics 2023, International Renewable Energy Agency, Abu Dhabi.
[82] KEHOP Plusz (2022). Környezeti és energiahatékonysági Operatív Program Plusz. [Environmental and Energy Efficiency Operational Programme Plus] https://www.palyazat.gov.hu/api/download_document?name=Elfogadott%20KEHOP%20Plusz.pdf&urn=workspace%3ASpacesStore%2Fi%2F8fc4eb0a-9d7f-4b8d-888b-2e21a8501124 (13 May 2024).
[83] Kormany.hu (2024). Földgáz helyett földhő: törvénymódosítás élénkítheti a geotermia hazai térnyerését. https://kormany.hu/hirek/foldgaz-helyett-foldho-torvenymodositas-elenkitheti-a-geotermia-hazai-ternyereset (8 May 2024).
[84] Lenkey L., Mihályka J., & Paróczi P. (2021). Review of geothermal conditions of Hungary. Földtani Közlöny, Vol. 151(1), pp. 65–65.
[85] Lenkey, L. (1999). Geothermics of the Pannonian basin and its bearing on the tectonics of basin evolution. – PhD Thesis, Vrije Universiteit, Amsterdam. 215.
[86] Liebe, P. (2001). Tájékoztató. Termálvízkészleteink, hasznosításuk és védelmük. – Környezetvédelmi Minisztérium megbízásából készítette a VITUKI Rt. Hidrológiai Intézete, Budapest. 21.

[87] Lund, J. W. (2010). Geothermal (Ground-Source) Heat Pumps, IGA Education, Wolrd Geothermal Congress, Indonesia
[88] Mádlné Szőnyi, J., Markó, Á., Tóthi, T. (2024). Nem lehet mindenhol mindent, de mindenhol lehet valamit – Geotermikus energia hasznosítás lehetőségei a hazai ellátás diverzifikálása érdekében [Not everything anywhere, but something everywhere – geothermal to diversify the domestic energy supply]. Scientia et Securitas. https://doi.org/10,1556/112.2023.00198
[89] Mádlné Szőnyi, J., Rybach, L., Lenkey, L., Hámor, T., Zsemle, F. (2008). A geotermikus energiahasznosítás nemzetközi és hazai helyzete, jövőbeni lehetőségei Magyarországon – Ajánlások a hasznosítást előmozdító kormányzati lépésekre és háttértanulmány, Magyar Tudományos Akadémia, Budapest
[90] Malhotra, M., Lia, Z., Liu, X., Lapsa,M., Bouza,T., Vineyard, E. (2023). Heat pumps in the United States: market potentials, challenges and opportunities, technology advances. 14th IEA Heat Pump Conference Proceedings (2023)
[91] Ministry of Innovation and Technology (n.d.): National Energy and Climate Plan. https://energy.ec.europa.eu/system/files/2022-08/hu_final_necp_main_en.pdf (8 May 2024).
[92] Nádor A., Kujbus A., Tóth A. (2019). Geothermal Energy Use, Country Update for Hungary European Geothermal Congress 2019, Den Haag, The Netherlands, 11-14 June 2019
[93] NAK (2023). Geotermikus energiahasznosítás szabályai az agráriumban. Nemzeti Agrárgazdasági Kamara. https://www.nak.hu/tajekoztatasi-szolgaltatas/vizgazdalkodas/106060-geotermikus-energiahasznositas-szabalyai-az-agrariumban (8 May 2024).
[94] Németh K., Péter E., Pintér G. (2018). Megújuló energiaforrások szerepe és jelentősége a hazai turisztikai szektorban – az energia mint "helyi termék". Turizmus Bulletin XVIII/1
[95] Nemzeti Földhő Stratégia (2024). Nemzeti Földhő Stratégia, Energiaügyi Minisztérium, Budapest
[96] REN (2022). Renewables 2022 Global Status Report (Paris: REN21 Secretariat). ISBN 978-3-948393-04-5
[97] RePowerEU (n.d.). Hungary's Recovery and Resilience Plan. https://archive.palyazat.gov.hu/download.php?objectId=1096565 (13 May 2024).
[98] REPowerEU terv (n.d.). RePowerEU terv. Széchenyi Terv Plusz – Magyarország Kormánya. https://www.palyazat.gov.hu/download.php?objectId=1098364 (4 February 2024)
[99] Royden, L. H. and Dövényi, P. (1988). Variations in extensional styles at depth across the Pannonian basin system. – In: Royden, L. H. and Horváth, F. (eds.): The Pannonian Basin, a Study in Basin Evolution. American Association of Petroleum Geologists Memoirs, 45: 235–255.
[100] Royden, L. H., Horváth, F., Nagymarosy, A., Stegena, L. (1983). Evolution of the Pannonian basin system: 2. Subsidence and thermal history. – Tectonics, 2: 91–137.
[101] Szanyi J., Nádor A., Madarász T. (2021). A geotermikus energia kutatása és hasznosítása Magyarországon az elmúlt 150 év tükrében. Földtani Közlöny, 151/1,79–102. https://doi.org/10,23928/foldt.kozl.2021.151.1.79
[102] Toleikyte, A., Carlsson, J. (2021). Assessment of heating and coolingrelated chapters of the national energyand climate plans (NECPs) JRC technical report. ISBN 978-92-76-30234-6
[103] Toleikyte, A., Jimenez Navarro, J.P., Carlsson, J. (2023). Consumers in district heating and cooling, Background report on how to evaluate the sustainability of district heating and cooling. JRC technical report. ISBN 978-92-68-03458-3
[104] TOP Plusz (2021). Önkormányzati épületek energetikai korszerűsítése – TOP Plusz 2.1.1-21 https://archive.palyazat.gov.hu/top-plusz-211-21# (10 May 2024)

[105] TOP Plusz (2022). Terület- és Településfejlesztési Operatív Program Plusz 2021-2027 [Territorial and Settlement Development Operational Programme Plus] https://www.palyazat.gov.hu/api/download_document?name=Elfogadott%20TOP%20Plusz.pdf&urn=workspace%3ASpacesStore%2Fi%2F28725ed3-65dc-4501-bfa1-a9de0b4ad9db (13 May 2024).
[106] Zilahi-Sebess L., Merényi L., Paszera Gy., Tóth Gy., Boda E., Budai T. (2012). A hazai ásványi nyersanyag-potenciál. 5. Geotermikus energia (Háttértanulmány) – Kézirat, Nemzeti Energiastratégia, Készletgazdálkodási és hasznosítási cselekvési terv. MFGI, Budapest, 84 p.
[107] Geothermal Resources of Romania: https://www.agir.ro/univers-ingineresc/numar-2-2007/energia-geotermala_1664.html
[108] GEOELEC Workshop Athens 20,12.2011 Geothermal Resources of Romania Marcel G. Roșca University of Oradea, Romania
[109] https://www.europarl.europa.eu/doceo/document/ ITRE-PR-752863_RO.pdf
[110] https://www.europarl.europa.eu/doceo/document/TA-9-2024-0049_RO.html
[111] https://energy.ec.europa.eu/document /download/073c69b1-2865-4fb0-bc91-6591be94b337_en?filename=Report%20on%20evaluation%20potential.pdf
[112] https://www.mmediu.ro/app/webroot/uploads/files/Raport%20de%20mediu_aug%202020,pdf
[113] https://www.zf.ro/zf-transilvania/primaria-oradea-a-accesat-un-proiect-european - over-18-mil-euro-21824074
[114] https://mfe.gov.ro/
[115] https://uefiscdi.gov.ro/geothermica
[116] https://ondrill.ro/fonduri-europene/
[117] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Table_4-Share_of_renewable_energy_sources_in_heating_and_cooling_2004-2016.png
[118] https://www.profit.ro/povesti-cu-profit/energie/statul-cere-din-piata-proiecte-de-productie-de-energie-geotermala-situatie-juridic-complicata-langa-bucuresti-21364978
[119] NATIONAL CONFERENCE "ENERGY CITIES ROMANIA" BRASOV 6-7 APRIL 2017 THE GEOTHERMAL ENERGY POTENTIAL OF ROMANIA AND SOME ENERGY EFFICIENT CENTRALIZED HEATING/COOLING SYSTEMS Author: Dr. Ing. Radu POLIZU Vice-president of the Romanian Geoexchange Society
[120] [www.geoexchange.ro
[121] [”Energy Poverty in European Union: Assessment Difficulties, Effects on the Quality of Life, Mitigation Measures. Some Evidence from Romania” Adrian Neacsa, Mirela Panait, Jianu Daniel Muresan and Marian Catalin Voica Sustainability (2020)
[122] https://www.researchgate.net/figure/Repartition-of-geothermal-resources-in-Romania_fig1_312284159
[123] https://geoexchange.ro/legislatie-ro/
[124] https://geoexchange.ro/wp-content/uploads/2013/12/Decisions_2013_114_UE-1.pdf
[125] https://www.afm.ro/casa_verde_pf_ghid.php
[126] https://lege5.ro/Gratuit/geztcobyguztc/legea-nr-39-2023-pentru-completarea-art-291-alin-3-din-legea-nr-227-2015-privind-codul-fiscal
[127] Mihajlović DT, Drešković N, Arsenić I, Ćirić V, Đurđević V, Mimić G, & Pap I. (2016). Impact of climate change on soil thermal and moisture regimes in Serbia: An analysis with data from regional climate simulations under SRES-A1B. Science of The Total Environment. 2016;571:398-409.

[128] Map Viewer. EGDI. [online]. [Accessed 23 April 2024]. Available from https://www.europe-geology.eu/data-and-services/map-viewer/
[129] Pešić A, Brankov J, Denda S, Bjeljac Ž, & Micić J. Geothermal energy in Serbia – Current state, utilization and perspectives. Renewable and Sustainable Energy Reviews. 2022;162: 112442.
[130] Golusin M, Munitlak Ivanovic O, Bagaric I, & Vranes S. Exploitation of geothermal energy as a priority of sustainable energetic development in Serbia. Renewable and Sustainable Energy Reviews. 2010;14:868-871.
[131] Petrović Pantić T, Atanasković Samolov K, Štrbački J, & Tomić M. Geothermal potential, chemical characteristic and utilization of groundwater in Serbia. Environmental Earth Sciences. 2021;80(22).
[132] European Commission. Joint Research Centre & European Soil Bureau. Soil Atlas of Europe; 2005.
[133] Filipović B, Krunić O, Lazić M. Regional Hydrogeology of Serbia. Faculty of Mining and Geology. University in Belgrade; 2005.
[134] Horváth F, Musitz B, Balázs A, Végh A, Uhrine A, Nádor A, Koroknai B, Pap N, Tóth T, Wórum G. Evolution of the Pannonian basin and its geothermal resources. Geothermics. 2015;53:328–352.
[135] Nádor A, Lapanje A, Tóth G, Rman N, Szőcs T, Prestor J, Uhrin A, Rajver D, Fodor L, Muráti J, Székely E. Transboundary geothermal resources of the Mura-Zala basin: joint thermal aquifer management of Slovenia and Hungary. Geologija. 2012;55(2):209–224.
[136] Rman N, Gál N, Marcin D, Weilbold J, Schubert G, Lapanje A, Rajver D, Benková K, Nádor A. Potentials of transboundary thermal water resources in the western part of the Pannonian basin. Geothermics. 2015;55:88–98.
[137] Tóth G, Rman N, Rotár-Szalkai Á, Kerékgyártó T, Szőcs T, Lapanje A, Černák R, Remsík A, Schubert G, Nádor A. Transboundary fresh and thermal groundwater ows in the west part of the Pannonian Basin. Renewable and Sustainable Energy Reviews. 2016;57:439–454.
[138] Rman N, Bălan LL, Bobovečki I, Gál N, Jolović B, Lapanje A, Marković T, Milenić D, Skopljak F, Rotár–Szalkai A, Samardžić N, Szőcs T, Šolaja D, Toholj N, Vijdea AM, Vranješ A. Geothermal sources and utilization practice in six countries along the southern part of the Pannonian basin. Environemntal Earth Sciences. 2022;79:1.
[139] Martinović M, Zlokolica-Mandić M, Vukićević Z. Geothermal atlas of Vojvodina, Autonomous province of Vojvodina - Provincial Secretariat for Energy. Republic of Serbia; 2010.
[140] Milivojević M, Martinović M. Geothermal energy possibilities, exploration and future prospects in Serbia. Proceedings World Geothermal Congress, Antalya, Turkey; 2005.
[141] Petrović Pantić T, Atanasković Samolov K, Štrbački J, & Tomić M. Geothermal potential, chemical characteristic and utilization of groundwater in Serbia. Environmental Earth Sciences. 2021;80(22).
[142] Martinović M, Milivojević M. The hydrogeothermal model of Mačva. Proceedings World Geothermal Congress, Kyushu-Tohoku, Japan; 2000.
[143] Perić J, Milivojević M. Geothermal potential territory of Serbia without territory of Autonomous provinces. Faculty of Mining and Geology, University of Belgrade; 1990.
[144] Muffler LJP, Cataldi R. Methods for regional assessment of geothermal resources. Geothermics. 1978;7:53–89
[145] Dragović N, Vuković M, & Riznić D. Potentials and prospects for implementation of renewable energy sources in Serbia. Thermal Science. 2019;23:2895-2907.

[146] Oudech S, & Djokic I. Geothermal Energy Use, Country Update for Serbia. European Geothermal Congress; 2019.
[147] Hydrological processes and Geological settings over Europe controlling dissolved geogenic and anthropogenic elements in groundwater of relevance to human health and the status of dependent ecosystems (HOVER). GeoERA. [online]. [Accessed 23 April 2024]. Available from https://geoera.eu/projects/hover8/
[148] DARLINGE – Danube Region Leading Geothermal Energy. Interreg Danube Transnational Programme.
[149] Antonijević D, & Komatina M. Sustainable sub-geothermal heat pump heating in Serbia. Renewable and Sustainable Energy Reviews. 2011;15:3534-3538.
[150] Bertani R, Lund J. Geothermal in World energy resources. World Energy Council; 2013.
[151] Milivojević M, Martinović M. Geothermal energy possibilities, exploration and future prospects in Serbia. Proceedings World Geothermal Congress; Kyushu, Tohoku, Japan; 2000.
[152] Milenić D, & Vranješ A. Istraživanje i valorizacija subgeotermalnih energetskih resursa. Rudarsko geološki fakultet Beograd; 2015.
[153] Popis stanovništva, domaćinstava i stanova. Republički zavod za statistiku Srbije. [online]. [Accessed 21 May 2024]. Available from https://www.stat.gov.rs/sr-Latn/.
[154] Ritchie H, & Rosado P. Electricity Mix. Our World in Data. [online]. [Accessed 22 Paril 2024]. Available from https://ourworldindata.org/electricity-mix.
[155] CO2 emissions per kWh in Serbia. Nowtricity. [online]. [Accessed 22 April 2024]. Available from https://www.nowtricity.com/country/serbia/.
[156] Tsagarakis KP, Efthymiou L, Michopoulos A, Mavragani A, Anđelković AS, Antolini F, Bacic M, Bajare D, Baralis M, Bogusz W, Burlon S, Figueira J, Genç MS, Javed S, Jurelionis A, Koca K, Ryzynski G, Urcheguia J, Žlender B. A review of the legal framework in shallow geothermal energy in selected European countries: Need for guidelines. Renewable Energy. 2020;147:2556 – 2571.
[157] Lepotić Kovačević B, & Lazarević B. Construction of plant and electricity/heat generation from hydro-geothermal sources in the Republic of Serbia – Guide for investors. Third edition; 2016.
[158] Green Economy Financing Facility – GEFF. GEFF in Serbia. [online]. [Accessed 23 April 2024]. Available from https://ebrdgeff.com/serbia/.
[159] Ristić D, Vukoičić D, Nikolić M, Milinčić N, Kićović D. Capacities and energy potential of thermal-mineral springs in the area of the Kopaonik tourist region (Serbia), Renewable and Sustainable Energy Reviews. 2019;102: 129–138.
[160] Valjarevic A, Srećković-Batoćanin D, Valjarević D, & Matović V. A GIS-based method for analysis of a better utilization of thermal-mineral springs in the municipality of Kursumlija (Serbia). Renewable and Sustainable Energy Reviews. 2018;92:948 – 957.
[161] Milivojevic M. Geothermal map, Geological atlas of Serbia 1:2.000.000, No.11. Ministry of mining and energetics Republic of Serbia, Belgrade; 2001.
[162] Dimitrijević M. Geological map 1:2.000.000, Geological Atlas of Serbia, no 1. Republic foundation for geological investigations and Geological survey-Gemini; 2002.
[163] Karamata S, Krstić B, Stojnov R. Terranes from Adriatic to the Moesian Massif in the Central Part of the Balkan Peninsula. Terra Nova, 4, Abstract suppl. 2, Alcapa Symp., Gray, Graz. 1992;1–36.
[164] Karamata S, Krstić B. Terranes of Serbia and neighbouring areas. In: Knežević - Đorđević Vand Terranes of Serbia. The formation of the geologic framework of Serbia and the adjacent

region. Faculty of Mining and Geology, Comm. Geodynamics Serbian Academy of Science and Arts. 1996;25–40.
[165] Jelenković R, Kostić A, Životić S, Ercegovac M (2008) Mineral resources of Serbia. Geologica Carpathica. 2008;59(4):345–361.
[166] MapViewer. ThermoMap. [online]. [Accessed 23 April 2024]. Available from https://www.thermomap.eu/.
[167] Stojadinovic D, Nikic Z, & Isakovic D. Groundwater of alluvial aquifer as a significant resource for municipal water supply in Republic of Serbia. IAEG;2006.
[168] Vasilev M, & Banjac M. Thermal recovery test for determining the thermal conductivity of the soil. Thermal Science. 2024;28:425-435.
[169] Eurostat. Electricity price statistics. [online]. [Accessed 18 May 2024]. Available from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics&oldid=629427#Electricity_prices_for_household_consumers
[170] Jokić A, Nikolić N, & Lukić N. Feasibility of closed loop ground source heat pump for residential heating and cooling applications in Serbia. Thermal Science. 2019;24(279):965-976.
[171] Cvetanović L, & Šušteršič V. Proračun toplotnih gubitaka i analiza isplativosti sistema grejanja sa toplotnom pumpom tipa zemlja-voda u poredjenju sa drugim sistemima grejanja na konkretnom slučaju. Traktori i pogonske mašine. 2018;23(3/4).
[172] Kljajić M, Anđelković A, Hasik V, Munćan V, & Bilec M. Shallow geothermal energy integration in district heating system: An example from Serbia. Renewable Energy. 2020;147:2791-2800.Bartko, L., Badida, M., Horbaj, P., Komkoly, J. (2014). Využitie geotermálnej energie v podmienkach Slovenska. In: Transfer inovácií 29/2014
[173] URL: https://www.sjf.tuke.sk/transferinovacii/pages/archiv/transfer/29-2014/pdf/304-311.pdf
[174] CVTI SR (2023). Veda v CENTRE: Slovenské pramene a horúci dych sucha. URL: https://www.cvtisr.sk/aktuality-pre-siroku-verejnost/veda-v-centre-slovenske-pramene-a-horuci-dych-sucha-zaznam.html?page_id=54998
[175] EC (2024). Study on energy prices and costs: evaluating impacts on households and industry – 2023 edition. Final report. URL: https://op.europa.eu/en/publication-detail/-/publication/3b43f47c-e1c5-11ee-8b2b-01aa75ed71a1/
[176] Energia.sk (2017). Odpadové teplo. Na Slovensku cesta zarúbaná? URL: https://www.energia.sk/odpadne-teplo-na-slovensku-cesta-zarubana/
[177] Energieportal (2023). Je to ohriaty vzduch z komínov aj klimatizácií. Zmapovali potenciál odpadového tepla na Slovensku. URL: https://www.energie-portal.sk/Dokument/odpadove-zvyskove-teplo-vykurovanie-analyza-110173.aspx
[178] Energieportal (2021). Geotermálne elektrárne brzdí EIA aj náklady, projekty na výrobu tepla sú ďalej. URL: https://www.energie-portal.sk/Dokument/oto-halas-geotermalne-elektrarne-brzdi-eia-aj-naklady-projekty-na-vyrobu-tepla-su-dalej-106817.aspx
[179] Energieportal (2020). Rozvoj geotermu na Slovensku brzdia aj vysoké investičné náklady. URL: https://www.energie-portal.sk/Dokument/rozvoj-geotermu-na-slovensku-brzdia-aj-vysoke-investicne-naklady-106473.aspx
[180] Engineering (2023). S. Jacko: Potrebné je čo najširšie využitie geotermálneho zdroja pri Čižaticiach. URL: https://www.engineering.sk/aktuality/29111-sr-ksk-vrt-geotermalny-vyuzitie-jacko-eko
[181] EP (2023). Správa o geotermálnej energii.

[182] URL: https://www.europarl.europa.eu/doceo/document/A-9-2023-0432_SK.pdf
[183] EP (2024). Energia z obnoviteľných zdrojov v EÚ a na Slovensku. URL: https://www.europarl.europa.eu/topics/sk/article/20171124STO88813/energia-z-obnovitelnych-zdrojov-v-eu-a-na-slovensku
[184] EURAKTIV (2024). Novela EIA vychádza v ústrety geotermálnej energii, no chýbajú podrobnosti o vrtoch.
[185] URL: https://euractiv.sk/section/energetika/news/novela-eia-vychadza-v-ustrety-geotermalnej-energii-no-chybaju-podrobnosti-o-vrtoch/
[186] EURAKTIV (2022). Geotermálnej energii v Európe aj na Slovensku pomáha energetická kríza. URL: https://euractiv.sk/section/energetika/linksdossier/geotermalnej-energii-v-europe-aj-na-slovensku-pomaha-energeticka-kriza/
[187] EURAKTIV (2022). Geotermálne vrty nedostávajú podporu z eurofondov. Rezort hospodárstva sľubuje nápravu. URL: https://euractiv.sk/section/energetika/news/geotermalne-vrty-nedostavaju-podporu-z-eurofondov-rezort-hospodarstva-slubuje-napravu/
[188] Eurostat (2024). Electricity price statistics. URL: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics#Electricity_prices_for_household_consumers
[189] Fendek et al. (1999). Geothermal energy utilization in Slovak Republic. In: Slovak Geol. Mag., 5,1-2 (1999), 131-140
[190] Ferenc, Š. (2015). Geotermálna energia a jej využitie. Vydavateľstvo Univerzity Mateja Bela v Banskej Bystrici Belianum. ISBN 978-80-557-0955-0
[191] Fleiter, T., Manz, P., Neuwirth, M., mildner, Felix, Persson, U., Kermeli, K., Crijns-Graus, W., Rutten, C. (2020). Documentation on excess heat potentials of industrial sites including open data file with selected potentials. Published June 16, 2020, Version Version 2
[192] URL: https://zenodo.org/records/4785411#.YnTziuhBxaQ
[193] Franko, O. (1995) Atlas of geothermal energy in Slovakia. URL: https://www.geothermal-energy.org/pdf/IGAstandard/WGC/1995/1-franko.pdf
[194] Franko, O., Fusán, O., Král, M. (1999). Hydrogeothermics of Slovakia. In: Bulletin d'Hydrogdologie No 17 (1999), Centre d'Hydrogeologie, Universitd de Neuchatel. URL: https://www.geothermal-energy.org/pdf/IGAstandard/EGC/1999/Franko2.pdf
[195] Fričovský, B., Černák, R., Marcin, D., Blanárová, V., Benková, K., Pelech, O., Fendek, M. (2019). Geothermal Energy Use, Country Update for Slovakia. . In: European Geothermal Congress 2019. URL: https://europeangeothermalcongress.eu/wp-content/uploads/2019/07/CUR-25-Slovakia.pdf
[196] Geotermalnaenergia.sk. (2020). Geotermálna voda patrí všetkým. Kto ju môže ťažiť a za akých podmienok? URL: https://geotermalnaenergia.sk/legislativa/geotermalny-vrt-patri-vsetkym-zakon/
[197] GrantUP (2022). Potenciál geotermálnej energie na Slovensku? Vrt pri Košiciach vyzerá nádejne. URL: https://grantup.sk/potencial-geotermalnej-energie-na-slovensku-vrt-pri-kosiciach-vyzera-nadejne/
[198] Gregor, M., Remšík, A., Černák, R. (2015). Regional geological database for deep geothermal – Slovakia.
[199] URL: http://www.geoelec.eu/wp-content/uploads/2012/03/Regional-geological-database-for-deep-geothermal-Slovakia.pdf

[200] GreenTalk (2023). ANALÝZA: Poklad, ktorým mrháme. Nevyužité zvyškové teplo môže znížiť závislosť na fosílnych palivách. URL: https://greentalk.sk/blog/analyza-poklad-zvyskove-teplo/
[201] Grexová, S. (2008). New methode of measurement of temperature flow. In: Acta Montanistica Slovaca. 13(1) URL: https://www.researchgate.net/publication/26503963_New_methode_of_measurement_of_temperature_flow
[202] Hók, J., Pelech, O., Teťák, F., Németh, Z., Nagy, A. (2019). Outline of the geology of Slovakia W. Carpathians. In: Mineralia Slovaca, Web ISSN 1338-3523, ISSN 0369-2086 51 (2019)
[203] URL:https://www.researchgate.net/profile/Jozef-Hok/publication/334987613_Outline_of_the_geology_of_Slovakia_W_Carpathians/links/5d490ccf92851cd046a573d7/Outline-of-the-geology-of-Slovakia-W-Carpathians.pdf
[204] IEA (2024). Energy system of Slovak Republic. URL: https://www.iea.org/countries/slovak-republic
[205] International Atomic Energy Agency. Slovakia Geology General – IEA INFCIS (2024). URL: https://infcis.iaea.org/udepo/Resources/Countries/Slovakia.pdf
[206] https://euractiv.sk/section/energetika/news/eurofondy-podporia-geotermalnu-energiu-neskoro-a-len-naoko/
[207] Majcin, D., Král, M., Bilčík, D., Šujan, M., Vranovská, A. (2017). Deep geothermal sources for electricity production in Slovakia: thermal conditions. In: Contributions to Geophysics and Geodesy.Vol. 47/1, 2017 (1–22)
[208] URL: https://www.academia.edu/48606495/Deep_geothermal_sources_for_electricity_production_in_Slovakia_thermal_conditions?auto=download&email_work_card=download-paper
[209] Malcho, M. (2011). Možnosti spätného získavanie tepla z technologických procesov. Žilinská univerzita v Žiline. Vysoké Tatry, 29. 11. 2011
[210] Malík, P., Bím, M. (2009). Regionálne hydrogeologické štúdie na území Slovenska v prvej dekáde 21. Storočia. In: Podzemná voda XV 1/2009. URL: http://www.sah-podzemnavoda.sk/cms/e107_plugins/content/content.php?content.71
[211] Mašek, M. (2022). Čo Slovensku ponúka geotermálna energia? Možnosti sú široké. URL: https://dennikn.sk/blog/2824123/co-slovensku-ponuka-geotermalna-energia-moznosti-su-siroke/
[212] MHSR (2015). Ekonomicko-technické hodnptenie uplatnenia CZT v SR a komplexné posúdenie národného potenciálnu pre uplatnenie CZT. Komplexné posúdenie národného potenciálu pre uplatnenie vysoko účinnej kombinovanej výroby. URL: https://energy.ec.europa.eu/document/download/050a12cb-f724-4e1a-bb03-5b1c6f879f99_en?filename=SlovakiaReport.pdf
[213] MHSR (2020). Komplexné posúdenie potenciálu efektívneho vykurovania a chladenia v Slovenskej republike podľa článku 14 smernice 2012/27/EÚ
[214] URL: https://energy.ec.europa.eu/system/files/2022-01/SK%20CA%202020%20sk.pdf
[215] Ministry of Environment of the Slovak Republic (2024). Geothermal energy. URL: https://www.minzp.sk/en/areas/renewable-energy-sources/geothermal-energy/
[216] Ministry of Environment of the Slovak Republic. Geothermal energy. URL: Greener Slovakia. URL: https://www.minzp.sk/files/iep/greener-slovakia-2030,pdf
[217] Ministry of Environment of the Slovak Republic (2007). Koncepcia geologického výskumu a prieskumu územia Slovenskej republiky na roky 2007 – 2011. URL:

https://www.minzp.sk/files/sekcia-geologie-prirodnych-zdrojov/koncepcia-geologickeho-vyskumu-geologickeho-prieskumu.pdf
[218] Ministry of Environment of the Slovak Republic (2017). Koncepcia geologického výskumu a geologického prieskumu územia SR. URL: https://www.minzp.sk/geologia/koncepcia-geologickeho-vyskumu-geologickeho-prieskumu-uzemia-sr.html
[219] Ministry of Education, Research, Development and Youth of the Slovak Republic (2014). Nový spôsob využitia odpadového tepla. URL: https://www.minedu.sk/novy-sposob-vyuzitia-odpadoveho-tepla/
[220] Plán obnovy (2024). Obnoviteľné zdroje energie v REPower EU. URL: https://www.planobnovy.sk/repowereu/oze/
[221] Podnikajte.sk (2023). Zastropovanie cien elektriny a plynu pre malé firmy v roku 2023. URL: https://www.podnikajte.sk/financny-manazment/zastropovanie-cien-elektriny-a-plynu-pre-male-firmy-v-roku-2023
[222] Potocký, E. (2023). Odpadové teplo Ako využiť energiu, ktorú dnes do okolia vypúšťame bez úžitku. URL: https://www.postoj.sk/137343/ako-vyuzit-energiu-ktoru-dnes-do-okolia-vypustame-bez-uzitku
[223] Slovenské elektrárne (2024). Produkcia emisií do ovzdušia. URL: https://www.seas.sk/o-nas/zivotne-prostredie/ochrana-ovzdusia/produkcia-emisii-do-ovzdusia
[224] SFÉRA (2023). Successful completion of research project on waste heat utilization. URL: https://industry.sfera.sk/en/news/successful-completion-of-research-project-on-waste-heat-utilization/
[225] SIEA (2021). Geotermálna energia 2021. URL: https://www.siea.sk/wp-content/uploads/odborne_o_energii/Dokumenty/Geotermalna-energia.pdf
[226] SLOVGEOTERM (2024).. Geothermal Project in Kosice. URL: https://www.slovgeoterm.sk/en/kosice
[227] SME (2007). Geotermálnu energiu využívame v 38 lokalitách. URL: https://domov.sme.sk/c/3615390/geotermalnu-energiu-vyuzivame-v-38-lokalitach.html
[228] STATISTA (2024). Average monthly electricity wholesale price in Slovakia from January 2019 to April 2024. URL: https://www.statista.com/statistics/1314560/slovakia-monthly-wholesale-electricity-price/
[229] STATISTA (2024). Non-household prices of electricity in Slovakia 2008-2022. URL: https://www.statista.com/statistics/596296/electricity-non-household-price-slovakia/
[230] Sura, M. (2022). Názor: Aký je potenciál geotermálnej energie pri náhrade zemného plynu? URL: https://energoklub.sk/sk/clanky/nazor-aky-je-potencial-geotermalnej-energie-pri-nahrade-zemneho-plynu/
[231] Štátny geologický ústav Dionýza Štúra (1995). Atlas geotermálnej energie Slovenska
[232] URL: https://www.geology.sk/geoinfoportal/mapovy-portal/atlasy/atlas-geotermalnej-energie/
[233] Štátny geologický ústav Dionýza Štúra (2024). Zdroje plytkej geotermálnej energie – plánovanie, hodnotenie a stratégie mapovania v strednej Európe. Projekt Interreg CE: GeoPLASMA-CE (2016-2019). URL: https://www.geology.sk/zdroje-plytkej-geotermalnej-energie-planovanie-hodnotenie-a-strategie-mapovania-v-strednej-europe/
[234] TASR (2022). Geotermálna voda by podľa zámerov Košického samosprávneho kraja (KSK) mala slúžiť budúcemu akvaparku. URL: https://www.teraz.sk/priame-prenosy-a-videa-tasr-tv/ksk-pri-cizaticiach-dosiahne-geoterm/608671-clanok.html

[235] TASR (2024). Trebišov čiastočne vykúria z vrtov po ťažbe zemného plynu. URL: https://dolnyzemplin.korzar.sme.sk/c/23279773/trebisov-ciastocne-vykuria-z-vrtov-po-tazbe-zemneho-plynu.html
[236] TREND (2022). Košická samospráva investuje do geotermálnej energie. URL: https://www.trend.sk/spravy/cizaticiach-vrta-velka-vrtna-veza-dostane-stovky-metrov-zem
[237] Urban, F., Ridzoň, F., Mlynár, P., Šustek, J., Jankovský, J., Katina, J. (2008). Porovnanie centralizovaného zásobovania teplom z hľadiska energetickej, ekonomickej efektívnosti a dopadov na životné prostredie v lokalite zásobovania teplom. Výskumná správa. URL: https://www.mhsr.sk/uploads/files/BkF0rmEa.pdf
[238] URSO (2023). Vývoj cien elektriny a plynu v roku 2023 a odhad na rok 2024 so zameraním na domácnost. URL: https://www.urso.gov.sk/data/files/625_odhad-vyvoja-regulovanych-cien-energii-2024-28072023.pdf
[239] Ústav materiálov a mechaniky strojov SAV (2023). Výskum možnosti využitia odpadového tepla z priemyslu na kúrenie vo verejnom a komerčnom sektore na Slovensku. Projekt SFÉRA.
[240] URL: https://www.sfera.sk/sk/o-nas/novinky/uspesne-ukoncenie-vyskumneho-projektu-pre-vyuzitia-odpadoveho-tepla/
[241] Rajver D., Ravnik D., Žlebnik L., Čebulj A. 1995: Utilization of geothermal energy in Slovenia. Proceedings of the World Geothermal Congress1995, Florence, Italy, IGA, 321-327.
[242] Rajver, D., Pestotnik, S., Rman, N., Hribernik, K., Srša, A., Lapanje, A., Prestor, J., Adrinek, S., 2023: Pregled rabe geotermalne energije v Sloveniji v letu 2022 in način pridobivanja podatkov o trgu geotermalnih toplotnih črpalk - Overview of the use of geothermal energy in Slovenia in 2022 and the method of obtaining data on the geothermal heat pump market. In: Senegačnik A. (ed.), Mineralne surovine v letu 2022 (Bulletin), GeoZS, Ljubljana, 154-173 (in Slovene).
[243] Internet 1: GEO.POWER web site. Available on: https://keep.eu/projects/506/Geothermal-energy-to-address--EN/ (Accessed on 8. 5. 2024).
[244] Giambastiani, B.M.S., Tinti, F., Mendrinos, D., Mastrocicco, M., 2014: Energy performance strategies for the large-scale introduction of geothermal energy in residential and industrial buildings: The GEO.POWER project. Energy Policy 65, 315-322.
[245] Prestor, J., Rajver, D., Pestotnik, S., Lapanje, A., 2012a: Nizkotemperaturna geotermalna energija: Neizčrpen vir energije neposredno pod našo hišo. Project GEO.POWER in Slovenia. GeoZS, Ljubljana, 31 p. (in Slovene).
[246] Prestor, J., Pestotnik, S., Rajver, D., Lapanje, A., 2012b: The Action plan of Slovenia. In: Meggiolaro M., Giambastiani B.M.S., Carr T. (eds.), Regional strategies for the large-scale introduction of geothermal energy in buildings. The results of GEO.POWER project. Provincia di Ferrara, 54 p.
[247] Internet 2: LEGEND web site. Available on: https://keep.eu/projects/4888/Low-Enthalpy-Geothermal-ENer-EN/ (Accessed on 8. 5. 2024).
[248] Rajver, D., Prestor, J., Tinti, F., 2015: Comparison of geological and shallow geothermal characteristics of some Adriatic regions in the Circum–Adriatic countries (LEGEND project). Proc. World Geothermal Congress 2015, Melbourne, Australia, 15 p.
[249] Prestor, J. (ed.) et al., 2014: Zbornik predavanj iz cikla seminarjev za krepitev usposobljenosti na področju izkoriščanja nizkotemperaturne geotermalne energije v Sloveniji. Iz Zemlje ljudem – From Earth to people. GeoZS, Ljubljana, 120 p. (in Slovene).
[250] Rajver, D., Casasso, A., Capodaglio, P., Cartannaz, C., Maragna, C., Prestor, J., Jež, J., 2020+1: Shallow geothermal potential with borehole heat exchangers (BHEs): three case studies in the Alps. Proc. World Geothermal Congress 2020, Reykjavik, Iceland, 13 p.

[251] Prestor, J., Rajver, D., Jež, J., Pestotnik, S., 2018: Geothermal educational trail Cerkno. GeoZS, Ljubljana, Publ. by ICRA d.o.o., Idrija, 47 p.
[252] Internet 3: Greta project web site. Available on: https://www.alpine-space.eu/project/greta/ (Accessed on 8. 5. 2024).
[253] Internet 4: GeoPLASMA-CE project web site. Available on: https://programme2014-20.interreg-central.eu/Content.Node/GeoPLASMA-CE.html (Accessed on: 8. 5. 2024).
[254] Internet 5: MUSE project web site. Available on: https://geoera.eu/projects/muse3/ (Accessed on 8. 5. 2024).
[255] Internet 6: PanAfGeo project web site. Available on: https://panafgeo.eurogeosurveys.org/ (Accessed on 8. 5. 2024).
[256] SI-STAT, 2024a. Energy balance (TJ) by supply and consumption, year and energy source. Ljubljana, Statistical Office of the Republic of Slovenia. Available on: https://pxweb.stat.si/SiStatData/pxweb/en/Data/Data/1817903S.px/ (Accessed on 10. 5. 2024).
[257] SI-STAT, 2024b. Energy indicators by indicator and year. Ljubljana, Statistical Office of the Republic of Slovenia. Available on: https://pxweb.stat.si/SiStatData/pxweb/en/Data/Data/1817902S.px/ (Accessed on 10. 5. 2024).
[258] SI-STAT, 2024c. Renewable energy and waste use (TJ) by energy source, year and type of use. Ljubljana, Statistical Office of the Republic of Slovenia. Available on: https://pxweb.stat.si/SiStatData/pxweb/en/Data/Data/1822303S.px/ (Accessed on 10. 5. 2024).
[259] Jožef Stefan Institute, 2023. Emisijski faktor za električno energijo in toploto za obdobje 2002-2022. Ljubljana, Center za energetsko učinkovitost, Institut "Jožef Stefan". Available at: https://ceu.ijs.si/izpusti-co2-tgp-na-enoto-elektricne-energije/ (accessed on 10. 5. 2024), (in Slovene).
[260] SI-STAT, 2024d. Final energy consumption by end use and energy source for households. Ljubljana, Statistical Office of the Republic of Slovenia. Available on: https://pxweb.stat.si/SiStatData/pxweb/en/Data/Data/1815406S.px/ (Accessed on 10. 5. 2024).
[261] Zakon o vodah (UL RS, št. 67/02, 2/04 – ZZdrI-A, 41/04 – ZVO-1, 57/08, 57/12, 100/13, 40/14, 56/15, 65/20, 35/23 – odl. US in 78/23 – ZUNPEOVE), 2023. Ljubljana. Available on: https://pisrs.si/pregledPredpisa?id=ZAKO1244 (in Slovene).
[262] Pravilnik o evidentirani posebni rabi vode (UL RS, št. 178/20), 2020. Ljubljana. Available on: https://pisrs.si/pregledPredpisa?id=PRAV14096 (in Slovene).
[263] Water right database, 2024. Available on: http://www.evode.gov.si/index.php?id=59 (Accessed 8. 5. 2024), (in Slovene).
[264] Water protection areas, 2024. Available on: http://kazalci.arso.gov.si/en/content/water-protection-areas-1 (Accessed 8. 5. 2024).
[265] Brenčič, M., Prestor, J., Kompare, b.,Matoz, M., Kranjc, S., 2009: Integrated approach to delineation of drinking water protection zones. Geologija 52/2, 7.
[266] Eco Fund, 2024. Available on: https://www.ekosklad.si/english (Accessed on 8. 5. 2024).
[267] Prestor, J., Rajver, D., Pestotnik, S., Benček, R. et al., 2021: Smernice za vrtanje v plitvi geotermiji do globine 300 m. Posodobljen izvod – V5 (29. 1. 2021), Ministry of Infrastructure, Ljubljana, 2021, p. 82.
[268] Novak, M., 2018: Lithological Composition. In Geological atlas of Slovenia, 2nd ed.; Novak, M., Rman, N., Eds.; Geological Survey of Slovenia: Ljubljana, Slovenia.
[269] Prestor, J., Meglič, P., Janža, M., Bavec, M., Komac, M., 2018. Hydrogeological Map. In Geological Atlas of Slovenia, 2nd ed.; Novak, M., Rman, N., Eds.; Geological Survey of Slovenia: Ljubljana, Slovenia.

[270] Groundwater Archive, 2024. Available online: https://vode.arso.gov.si/hidarhiv/pod_arhiv_tab.php (Accessed on: 8. 5. 2024).
[271] Energietechnik, V.F., 2001. VDI 4640 Part 2: Thermal Use of the Underground—Ground Source Heat Pump Systems; VDI-Gesellschaft Energie und Umwelt: Dűsseldorf, Germany, p 43.
[272] Internet 7: Portal Trajnostna energija (in Slovene). Available on: https://borzen.maps.arcgis.com/apps/webappviewer/index.html?id=756ad50afb9240c58e95fc29d6f09170 (Accessed on 8. 5. 2024).
[273] Rajver, D., Pestotnik, S., Prestor, J., 2019: Primeri ocene temperatur na površini trdnih tal pri projektiranju zajetij plitve geotermalne energije – Examples of the assessment of temperatures on the surface of solid ground in the design of the shallow geothermal energy extractions. Geologija 62/1, 103-122 (in Slovene with English abstract).
[274] Rajver, D., Adrinek, S., 2023: Overview of the thermal properties of rocks and sediments in Slovenia. Geologija 66/1, 125-150.
[275] SI-STAT, 2024e. Energy prices by energy source. Ljubljana, Statistical Office of the Republic of Slovenia. Available on: https://pxweb.stat.si/SiStatData/pxweb/en/Data/Data/H028S.px/ (Accessed on 10. 5. 2024).
[276] Chen, S., Hwang, C., 2012. Fuzzy Multiple Attribute Decision Making. Springer Berlin, Heidelberg
[277] Taherdoost, H., Madanchian, M. 2023. Multi-Criteria Decision Making (MCDM) Methods and Concepts, Encyclopedia 2023, 3, 77–87. https://doi.org/10,3390/encyclopedia3010006
[278] Benković, M., Keček, D., Munđar, D., 2015. Matematičke osnove AHP metode odlučivanja (in Croatian). Hrvatski matematički elektronički časopis, 28(1)
[279] Olson, D. L., 1996. Decision Aids for Selection Problems. Springer-Verlag New York, Inc.
[280] Vargas, L.G., 1990, An overview of the Analytic Hierarchy Process and its applications. European Journal of Operational Research, 48(1), 2-8.
[281] Schmoldt, D. L., Kangas, J. (auth.), Schmoldt, D. L., Kangas, J., Mendoza, G. A., Pesonen; M. (eds.), 2001. The Analytic Hierarchy Process in Natural Resource and Environmental Decision Making. Springer Dordrecht
[282] Forman, E., Gass, S., 2001. The Analytic Hierarchy Process: An Exposition. Operations Research , 49 (4), 469-486.
[283] Saaty, T.L., 1987. The analytic hierarchy process - what it is and how it is used. Mathematical Modelling, 9(3–5), 161-176.
[284] Marjan Hummel, J., Bridges, J., IJzerman, M., 2014. Group Decision Making with the Analytic Hierarchy Process in Benefit-Risk Assessment: A Tutorial. Patient, Springer. doi: 10,1007/s40271-014-0050-7
[285] Saaty, T.L., 2008. Decision making with the analytic hierarchy process. Int. J. Serv. Sci. 1(1). https://doi.org/10,1504/IJSSCI.2008.017590
[286] Saaty, T.L., 1980, The analytic hierarchy process: planning, priority setting, resource allocation, 1st ed. McGraw-Hill International Book Co., New York; London
[287] T.L. Satty:, 2003. Decision-making with the AHP: Why is the principal eigenvector necessary. European Journal of Operational Research, 145(1), 85-91.
[288] Stevens, S.S., 1968. Measurement, Statistics and The Schemapiric View. Science, 161(3844), 849-856.
[289] Saaty, T.L., 1990, How to make a decision: The analytic hierarchy process. Eur. J. Oper. Res. 48, 9–26. https://doi.org/10,1016/0377-2217(90)90057-I
[290] Saaty, T.L., 1977. A scaling method for priorities in hierarchical structures. Journal of Mathematical Psychology, 15(3), 234–281. https://doi.org/10,1016/0022- 2496(77)90033-5

[291] T.L. Satty, M.S. Ozdemir, 2003. Why the Magic Number Seven Plus or Minus Two. Mathematical and Computer Modelling, 38, 233-244.
[292] Shiraishi, S., Obata, T., Daigo, M.: Properties of a positive reciprocal matrix and their application to AHP. Journal of the Operations Research Society of Japan 41(3), 404-414.
[293] Pant, S., Kumar, A., Ram, M., Klochkov, Y., Kumar Sharm, H., 2022. Consistency Indices in Analytic Hierarchy Process: A Review. Mathematics 2022, 10, 1206. https://doi.org/10,3390/math100812
[294] Lin, C., Kou, G., 2021. A heuristic method to rank the alternatives in the AHP synthesis. Applied Soft Computing, 100, 106916.
[295] Srdjević, B., 2005. Combining different prioritization methods in the analytic hierarchy process synthesis. Computers & Operations Research, 32, 1897–1919.
[296] T.L. Satty, 2001. Decision Making with Dependence and Feedback: The Analytic Network Process, 2nd ed.; RWS: Pittsburgh, PA, USA
[297] Millet, I., Saaty, T. L., 2000, On the relativity of relative measures - accommodating both rank preservation and rank reversals in the AHP. European Journal of Operational Research 121, 205-212.
[298] Forman, E., Peniwati, K., 1996. Aggregating Individual Judgments And Priorities With The Analytic Hierarchy Process, ISAHP 1996, Vancouver, Canada, July 12-15, 1996