

Feasibility study for the pilot field Mihovljan (Pannonian Basin)

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Executive Summary

This report was made as part of the TRANSGEO project. The overall objective of TRANSGEO is to investigate the potential to transform abandoned hydrocarbon wells into new sources of green geothermal energy. To reach this goal, the TRANSGEO team is providing new tools and knowledge to support communities and industries in the energy transition and to break down economic and technical barriers to well reuse. The TRANSGEO project (<https://www.interreg-central.eu/projects/transgeo/>) is co-funded by the European Regional Development Fund through the Interreg Central Europe program.

The aim of this feasibility study is to assess the possibility of using existing oil and gas wells in the Mihovljan exploitation field area for geothermal energy production. The Mihovljan oil field is located in the northern part of the Republic of Croatia, within Međimurje County, near the town of Čakovec. The area is characterized by favorable transport connectivity, developed electric power and gas infrastructure, and compliance with spatial planning documentation, which enables the potential integration of a future geothermal system into the existing energy network.

As part of this study, 15 wells were analyzed. Based on the available well documentation, the geological, petrophysical, geophysical and production characteristics of the deposit were evaluated. Out of a total of 15 wells, of which 10 are abandoned, two production-injection well pairs and two production-impression pairs were selected for further analysis. The first production-injection well consists of Mih-1 as a production well and Mih-7 as an injection well, while the second pair consists of Mih-3beta as a production well and Mih-6 as an injection well. Calculations of isothermal production and the energy potential of the geothermal reservoir were carried out for the selected well pairs, as well as a techno-economic analysis that includes an assessment of revitalization costs, investments in surface infrastructure and expected revenues.

The report reflects the views of the authors.



1. Introduction

The purpose of this study is to determine the feasibility of exploiting geothermal energy near the town of Čakovec, in the Mihovljan exploration field. For this purpose, data obtained during drilling within the mentioned area, as well as data from wells located on its peripheral parts, have been analyzed. To determine the potential for exploiting geothermal energy using any method, geothermal gradient and heat flow maps of the area in question are used. In the case of the Republic of Croatia, this area is limited to the northern part. The first to describe the thermogeological parameters of the Pannonian Basin was Jelić, who in his doctoral thesis in 1979 focused his research on the Sava and Drava depressions. The relationships obtained described the thermogeological characteristics of both depressions. Based on previous research and published geothermal maps, it can be concluded that the Pannonian Basin area in Croatia is suitable for the exploitation of geothermal energy. The Pannonian Croatia region is relatively well geologically explored. This has been contributed to by the creation of numerous research wells, the aim of which, besides geological connection of units, was to collect data on potential hydrocarbon reserves. In addition to them, many exploitation and development wells have been made, which also contributed to the degree of exploration of the mentioned area. More than 4000 wells have been drilled, and in addition to geological differentiation and location of oil and gas fields, they have enabled the determination of locations and boundaries of deep aquifers. Given the long tradition of hydrocarbon production in this area, a significant part of the wells is now decommissioned and/or abandoned. However, the data collected during the research works can be used today, and in the future, to determine the potential for geothermal water production for energy purposes.

Research work in the broader area of the Čakovec zone of the Mura depression, as well as at the site itself, was not continuous but was carried out with shorter and longer time breaks. The regional gravimetric survey of northern Croatia, carried out between 1940 and 1942, included the Mihovljan site. Regional seismic investigations date back to 1957 and 1958, and were continued on several occasions with supplementary seismic profiles of the research area until 1968. Regional and detailed gravimetric measurements were made between 1953 and 1967. The results of these measurements match the data obtained from seismic measurements. The continuation of supplementary seismic investigations was carried out from 1971 to 1974. After the reinterpretation of all collected geophysical and geological data, on March 6, 1974, the Mihovljan-1 (Mih-1) exploratory well was located, and it was drilled in the same year. The well registered oil in the Petišovci sandstones. Further testing and examination of these deposits yielded oil and gas.



2. Geographic Location and Analysis of Spatial Planning Documentation

The Mihovljan exploitation field is bounded by 8 apex points, the coordinates of which are shown in Table 1. A graphical representation of the Mihovljan exploitation field is shown in Figure 2-1. Surface Area (km²): 12,66

Apex points	Coordinates	
	HTRS96/TM	
	E	N
1	494.925,00	5.140.880,00
2	494.925,00	5.143.055,00
3	494.165,00	5.144.190,00
4	494.765,00	5.144.190,00
5	496.900,00	5.142.095,00
6	499.900,00	5.142.095,00
7	499.900,00	5.139.800,00
8	496.950,00	5.140.880,00

Table 1 Coordinates of the apex points of the exploitation field

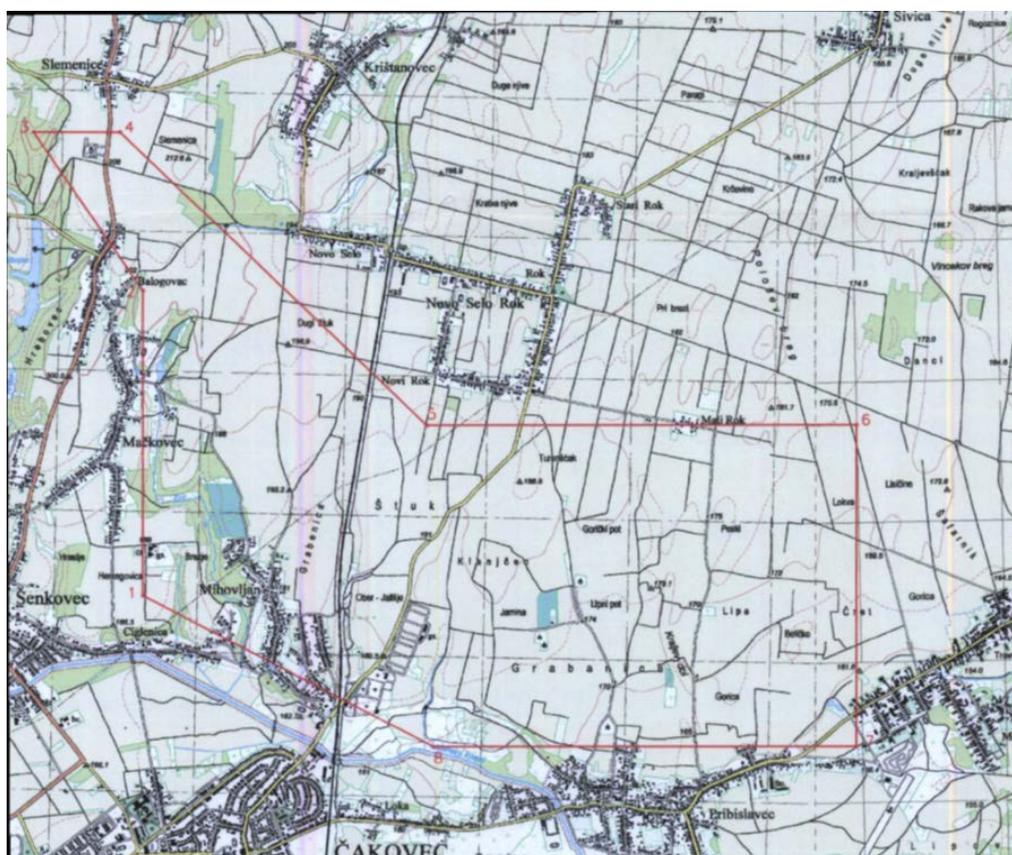


Figure 2-1 Graphical Representation of the Mihovljan Exploitation Field



In accordance with the administrative division of the area, the Mihovljan exploitation field is located in Međimurje County, specifically in the area of the town of Čakovec and the municipalities of Pribislavec and Belica, with a small part in the municipality of Šenkovec.

2.1. Location

The town of Čakovec, and the municipalities of Pribislavec, Belica, and Šenkovec are located in the north of the Republic of Croatia, within Međimurje County. The town of Čakovec comprises 14 settlements (as of 2013), which are: Čakovec, Ivanovec, Krištanovec, Kuršanec, Mačkovec, Mihovljan, Novo Selo na Dravi, Novo Selo Rok, Savska Ves, Slemenice, Šandorovec, Štefanec (since 2013), Totovec, and Žiškovec. The municipality of Pribislavec encompasses the settlement of the same name, while the municipality of Belica consists of just two settlements: Belica and Gardinovec. The municipality of Šenkovec includes two settlements: Knezovec and Šenkovec. Figures 2-2 and 2-3 are showing degree of urban development and grassland area of Čakovec and surrounding area.



Figure 2-2 Degree of urban development of Čakovec, Mihovljan, Šenkovec, Pribislavec and Belica (copernicus.eu)



Figure 2-3 Grassland in area of Čakovec, Mihovljan, Šenkovec, Pribislavec and Belica (copernicus.eu)

2.2. Transport Connectivity

The exploitation area is situated along the state road D-209, leading towards the border with the Republic of Slovenia, which represents one of the most important routes in northwestern Croatia. The road passes through the settlements of Mura-Sobot, Štrukovec, Žiškovec, Slemenice, Mačkovec, Šenkovec, the town of Čakovec, and Nedelišće. The total length of the road is 17.3 km. It is also situated along D3, a state road in Croatia with a total length of 218.4 km, passing through many major cities such as Rijeka, Karlovac, Zagreb, Varaždin, and reaching the border crossing Goričan with Hungary. The international airport in Zagreb is 98 km away.

2.3. Power Grid

Međimurje County has very good coverage with an electricity supply network that can ensure the transmission of sufficient quantities of electricity for both the population and the economy. Between 2014 and 2021, the total number of consumers in Međimurje County increased from 45.995 to 49.453, while electricity consumption rose from 202.623 to 214.900 MWh.

Lines	Length (km)
35 kV transmission line	102.57
35 kV cable	18.28
20 kV (operated at 10 kV) transmission line	226.53
20 kV (operated at 10 kV) cable	336.64
10 kV transmission line	40.65
10 kV cable	67.77

Table 2. Length of electricity transmission and distribution lines in Međimurje County by voltage level



Constant activities are carried out on the implemented electricity transmission systems for the construction and reconstruction of 110 kV substations and the improvement of connections between them. The area contains 2 110/35 kV and 12 35/10 kV transformer stations with a total installed capacity of 318.10 MVA. The electricity supply is provided by HEP with a total length of 895.29 km of power lines.

Electricity production in Međimurje County is carried out from renewable sources, utilizing the hydro potential of the Drava River and solar energy. In addition to long-standing electricity production in hydroelectric power plants HE Čakovec, HE Dubrava, and three small hydroelectric plants, in recent times, electricity production has also been carried out using solar energy. A significant number of producers use the surfaces of built structures as the basis for installing photovoltaic panels either for their own needs or for supplying electricity to the distribution system. The total power of hydroelectric plants amounts to 152 MW, and the power of installed photovoltaic panels in more than 100 registered solar power plants in Međimurje County amounts to 3.2 MW. Solar energy is also used for heat production for personal needs, which contributes to the overall use of renewable energy sources and the commitment to reducing CO₂ production in these areas.

The Lendava (Slovenia) - Virje oil pipeline from the JANAF system passes through Međimurje County over a length of 39.9 km. The pipeline route runs alongside or directly through the construction areas of the settlements Goričan and Domašinec, representing a significant limitation to the spatial development of these settlements. To remove this limitation, the pipeline route is planned to be relocated, which would bypass the settlements, increasing the length of the oil pipeline in Međimurje County to 43.03 km. In the corridor of the existing and planned relocation of the oil pipeline, a multifunctional international product pipeline for petroleum products is also planned.

The gas transmission system in Međimurje County is managed by the companies PLINACRO d.o.o. and INA d.d. PLINACRO d.o.o. is the operator of the gas transmission system of the Republic of Croatia and owns the existing main gas pipelines Varaždin II - Šenkovec, Varaždin II - Čakovec, Čakovec - Šenkovec, Šenkovec - Mihovljan, Mihovljan - Mura-Sobot, and Legrad - Donja Dubrava, with a total length of 51 km. INA d.d., the oil and gas industry company, as the holder of approvals for gas exploitation fields and associated main and connecting gas pipelines in the county, manages the existing main gas pipeline ČVOR Međimurje - MRS Lendava, pipeline routes ČVOR Vučkovec - ČVOR Međimurje, ČVOR Međimurje - CPS Mihovljan, and the pipeline routes of wells Vučkovec 1 and Vučkovec 5 - ČVOR Vučkovec, well Vukanovec-1 - ČVOR Vučkovec, and well Zebanec 2 - ČVOR Međimurje, with a total length of 25 km. For the improvement and expansion of the gas pipeline network in the county, the main gas pipeline Sotin - Mura-Sobot DN 1200/100 and the dispatch gas pipeline ČVOR Međimurje - CPS Molve DN 300/75 are planned. The routes of the planned gas pipelines are largely located along the existing JANAF route in a combined infrastructure corridor with a length of 45 km. Amendments and additions to the spatial plans of the municipalities through which the planned gas pipelines pass take into account the planned route and define measures for the protection and use of the area.

2.4. Demographic Aspects

Constant activities are carried out on the implemented electricity transmission systems for the construction and reconstruction of 110 kV substations and the improvement of connections between them. The area contains 2 110/35 kV and 12 35/10 kV transformer stations with a total installed capacity of 318.10 MVA. The electricity supply is provided by HEP with a total length of 895.29 km of power lines.

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The Lendava (Slovenia) - Virje oil pipeline from the JANAF system passes through Međimurje County over a length of 39.9 km. The pipeline route runs alongside or directly through the construction areas of the settlements Goričan and Domašinec, representing a significant limitation to the spatial development of these settlements. To remove this limitation, the pipeline route is planned to be relocated, which would bypass the settlements, increasing the length of the oil pipeline in Međimurje County to 43.03 km. In the corridor of the existing and planned relocation of the oil pipeline, a multifunctional international product pipeline for petroleum products is also planned.

The gas transmission system in Međimurje County is managed by the companies PLINACRO d.o.o. and INA d.d. PLINACRO d.o.o. is the operator of the gas transmission system of the Republic of Croatia and owns the existing main gas pipelines Varaždin II - Šenkovec, Varaždin II - Čakovec, Čakovec - Šenkovec, Šenkovec - Mihovljan, Mihovljan - Mura-Sobot, and Legrad - Donja Dubrava, with a total length of 51 km. INA d.d., the oil and gas industry company, as the holder of approvals for gas exploitation fields and associated main and connecting gas pipelines in the county, manages the existing main gas pipeline ČVOR Međimurje - MRS Lendava, pipeline routes ČVOR Vučkovec - ČVOR Međimurje, ČVOR Međimurje - CPS Mihovljan, and the pipeline routes of wells Vučkovec 1 and Vučkovec 5 - ČVOR Vučkovec, well Vukanovec-1 - ČVOR Vučkovec, and well Zebanec 2 - ČVOR Međimurje, with a total length of 25 km. For the improvement and expansion of the gas pipeline network in the county, the main gas pipeline Sotin - Mura-Sobot DN 1200/100 and the dispatch gas pipeline ČVOR Međimurje - CPS Molve DN 300/75 are planned. The routes of the planned gas pipelines are largely located along the existing JANAF route in a combined infrastructure corridor with a length of 45 km. Amendments and additions to the spatial plans of the municipalities through which the planned gas pipelines pass take into account the planned route and define measures for the protection and use of the area.

According to data from the Croatian Employment Service, the number of job vacancies in Međimurje County in 2022 is 5.921, while in 2021 it was 7.440, representing a decrease of about 1.3% over the year. The number of unemployed individuals in Međimurje County in 2022 is 1.962, which accounts for 1.7% of the total unemployment in Croatia. However, it is important to note that Međimurje County is one of the smallest in Croatia in terms of population size.

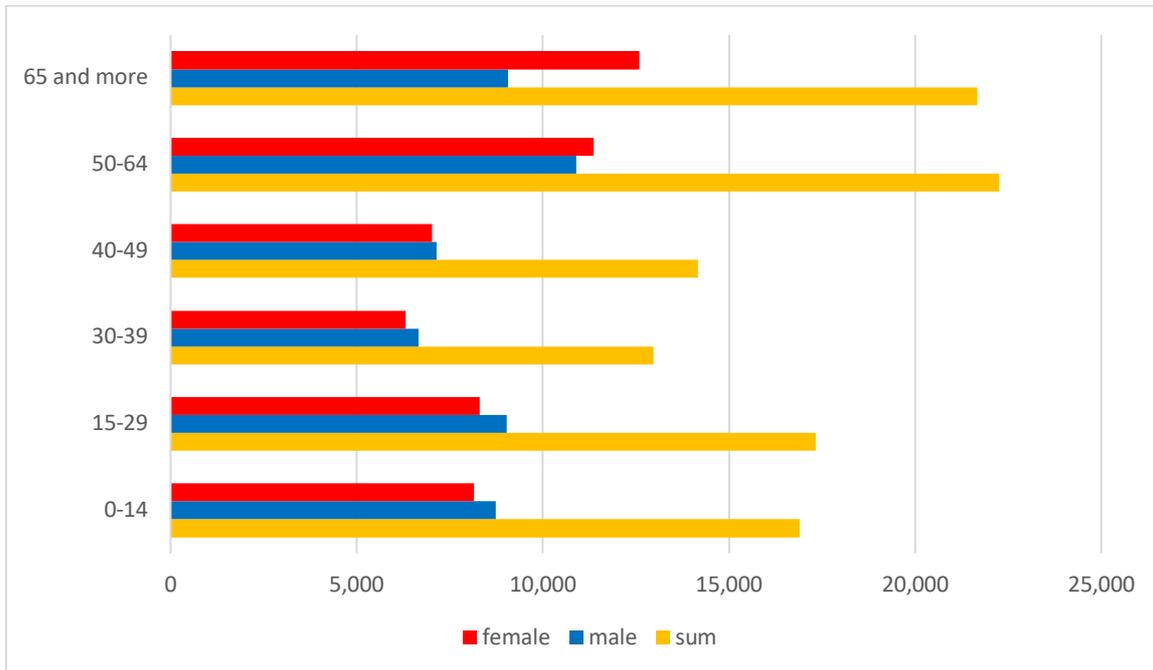


Figure 2-4 Graphical representation of the age-gender structure of the population of Međimurje County

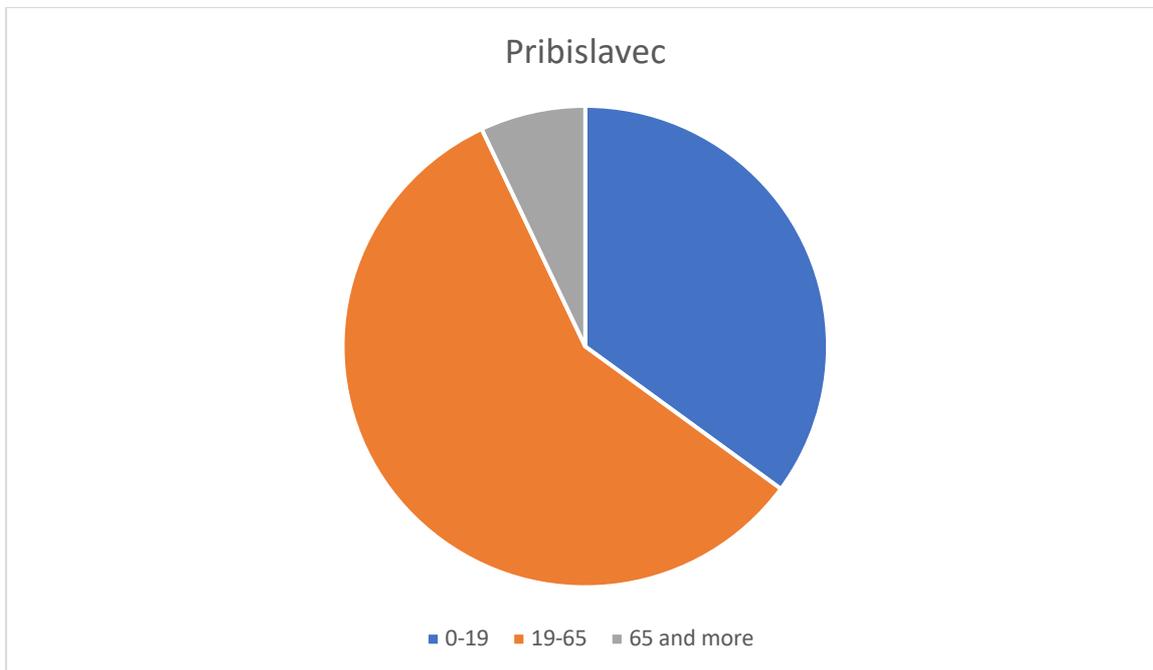


Figure 2-5 Graphical Representation of the Age Structure of the Population in the Municipality of Pribislavec (DZS, 2021)

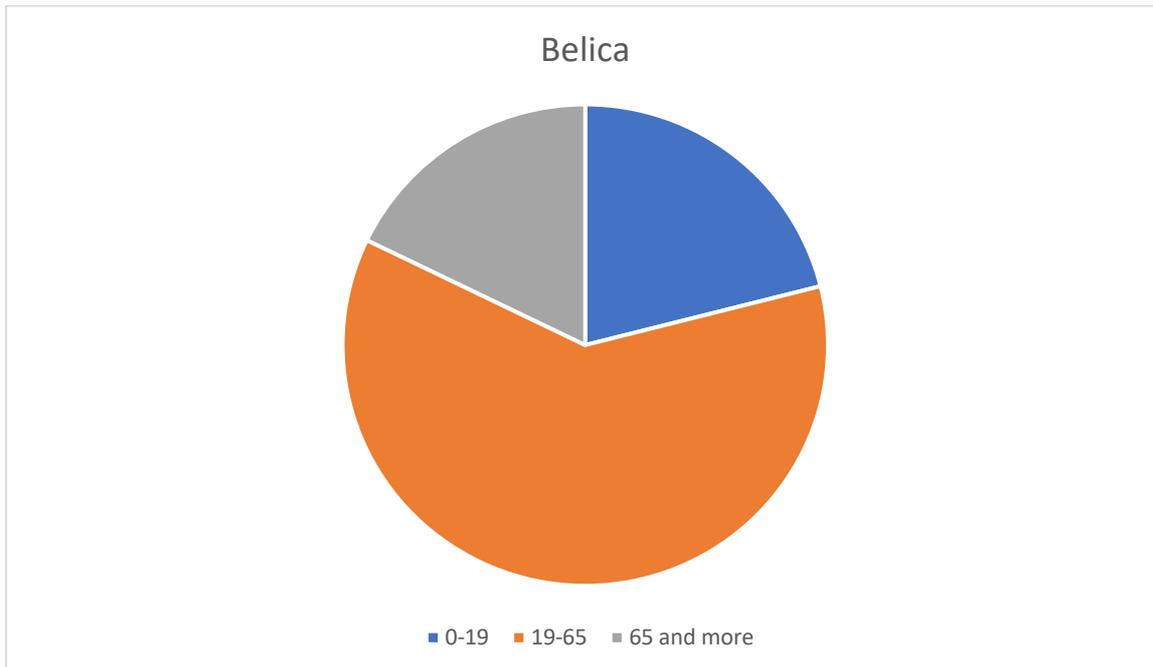


Figure 2-6 Graphical representation of the age structure of the population in the Municipality of Belica (DZS, 2021)

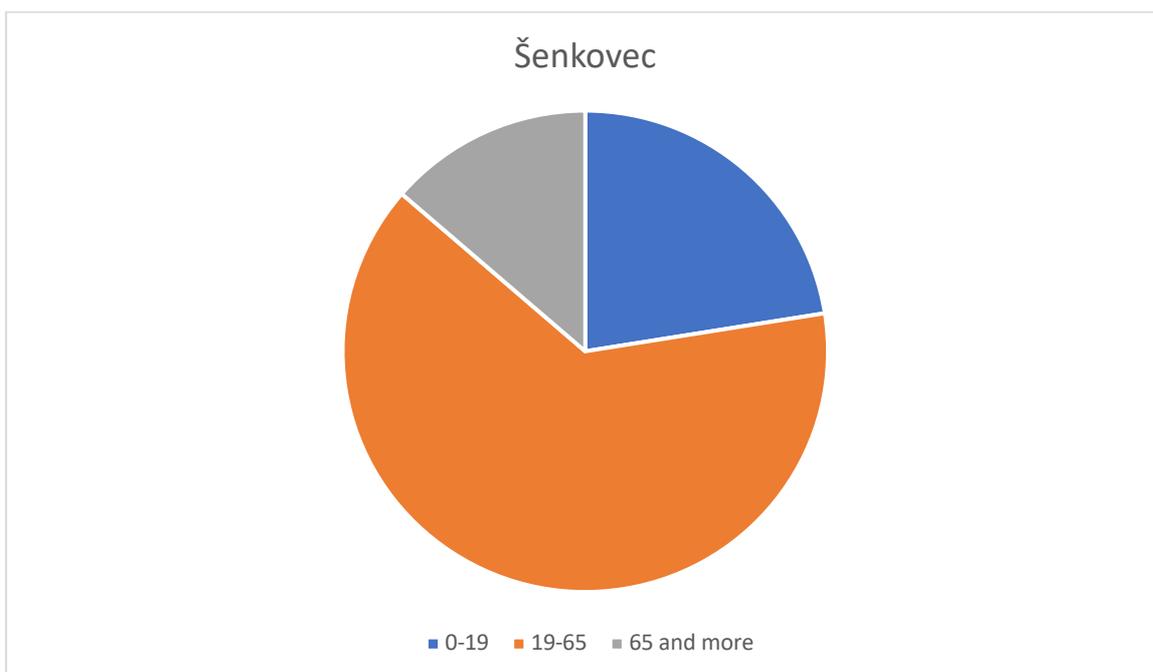


Figure 2-7 Graphical representation of the age structure of the population in the Municipality of Šenkovec (DZS, 2021)



2.5. Compliance of Interventions with Current Spatial Planning Documentation

The exploitation area of Mihovljan is covered by the following spatial plans:

- Spatial Plan of Međimurje County ("Official Gazette of Međimurje County" No. 7/01, 8/01, 23/10, 3/11, 7/19, and 12/19 - consolidated text)
- Spatial Plan of the City of Čakovec ("Official Gazette of the City of Čakovec," No. 4/03, 9/09, 06/12, 7/14, and 1/15 - consolidated text)
- Spatial Plan of the Municipality of Pribislavec ("Official Gazette of Međimurje County" No. 1/04, 2/07, 19/13, 10/15, and 24/22)
- Spatial Plan of the Municipality of Belica ("Official Gazette of Međimurje County" No. 4/04, 18/06, 7/12, 14/15, and 4/21 - consolidated text)

2.5.1. Spatial Plan of Međimurje County ("Official Gazette of Međimurje County" No. 7/01, 8/01, 23/10, 3/11, 7/19, and 12/19 - consolidated text)

EXCERPT FROM THE TEXTUAL PART OF THE PLAN

CONDITIONS FOR DETERMINING SPACE

...

Article 24.

Conditions for the location of planned potential buildings:

...

- Energy facilities for biogas production and electric energy from renewable sources may be located outside the construction area of settlements, at the point of origin or within the economic zone depending on its specific characteristics, and outside particularly valuable agricultural land P1, P2, and irrigated agricultural land

...

EXPLOITATION OF MINERAL RESOURCES

Article 39.

Exploitation of mineral resources can be carried out at locations marked on map number 1 - Land Use and Spatial Surface Areas, with the possibility of expanding existing exploitation areas. The expansion of the exploitation field will be determined by the spatial plan of the municipality/city in whose territory the exploitation is planned and according to the spatial conditions prescribed by this Plan.

...

Article 40.

After exploration works in areas where new exploitation fields and expansion of existing ones can be planned, local self-government units can plan coverage and conditions for exploitation in spatial development plans, as well as the purpose of the space after exploitation ceases. The location of new mineral resource exploitation fields cannot be planned on highly valuable agricultural land (P1) and valuable agricultural land (P2).

In accordance with the conditions specified in the conclusion of the environmental impact study, due to the natural characteristics of the area and for the purpose of preserving the landscape values of



the area, areas within the planned exploitation space can be designated that may be exempt from exploitation.

Exceptionally, expansion of existing exploitation fields cannot be planned in protected areas and on forested areas.

By determining detailed conditions for the exploitation of mineral resources in the Spatial Plan of the Area under Development (PPUO/G), there is no need to initiate the procedure for amending the Spatial Plan of Međimurje County.

EXPLOITATION OF ENERGY MINERAL RESOURCES E1 AND GEOTHERMAL WATERS E2

Article 44.

...

Exploitation of geothermal waters (E2) is carried out for tourism purposes at the Vučkovec site, while at the Draškovec site, multiple uses are planned. Exploration at the Merhatovec and Kotoriba sites has revealed a significant potential for geothermal waters that can be utilized for multiple purposes.

The scope of operations where a mining operation exists for the exploration and exploitation of hydrocarbons - drilling for the exploration and exploitation of energy mineral resources, can be located within the exploitation field, outside the construction area of settlements and areas exempted from construction at distances of at least:

- 70 m from residential buildings, sports and recreation zones, tourist zones, cemeteries, protected or registered cultural heritage,
- 100 m from protected areas,
- 50 m from categorized roads,
- 250 m from watercourses flowing into the Mura River.

...

A mining operation for the exploration and exploitation of geothermal waters may be approved subject to the restrictions listed in paragraphs 2 and 3 of this article, and exceptionally may be approved within the construction area of a settlement or in a detached construction area outside settlements, if the exploitation of geothermal waters serves the function of the zone in which it is located.

Noise generated in the vicinity of residential and working buildings during the exploitation process must not exceed the limit values prescribed by special law.

Exploration activities aimed at determining the status of hydrocarbon reserves and geothermal waters can be conducted within the designated exploration zones.

CONSTRUCTION OUTSIDE THE BOUNDARIES OF THE BUILDING AREA

Article 80.

Outside the building area, construction may be planned for:

...

5) mining facilities and installations for the exploration and exploitation of mineral resources (E3, E4), energy mineral resources (E1), and geothermal waters (E2) - conditions for their placement are determined by Article 44 of these Implementation Provisions.

...

ENERGY SYSTEM

...

Article 110a.



Buildings for the production of electricity from renewable sources, following prior investigations and studies on the selection and determination of suitable locations for their placement, must meet the spatial conditions and criteria prescribed by these provisions.

Article 111a.

In the process of planning and determining the routes of new pipeline systems - multi-purpose product pipelines for petroleum products, district heating pipelines, pipelines for the transport of geothermal water, main gas pipelines, and routes for the gas transport system from the pumping station to the gas processing station (route of connecting transport pipelines), existing infrastructure corridors should be used to the greatest extent possible. Where this is not possible, the corridors must not intersect areas of permanent vineyards and orchards, nor forests.

...

Article 112a.

The exploitation of geothermal energy can be expected at sites of geothermal wells built for oil and gas exploration where significant or substantial yields of geothermal waters have been determined. It is expected that geothermal energy can be used for multiple purposes (service sector, energy, spa tourism, agriculture).

MEASURES FOR PROTECTION OF THE ECOLOGICAL NETWORK AREAS

...

Article 127d

In protected areas and areas of the ecological network - Natura 2000 network, restrictions and prohibitions apply:

...

- *Construction of power plants (including those using renewable energy sources) is prohibited.*
- *Exploitation of mineral resources, hydraulic engineering works, and land reclamation are prohibited.*

...

CULTURAL HERITAGE

...

Article 144a.

For spatial interventions involving extensive earthworks such as infrastructure corridors of county or state significance (new routes of county roads, main gas pipelines, water supply pipelines), golf courses, surface mining of mineral resources (opening new and expanding existing exploitation fields), the investor is required, before issuing a location permit, to ensure reconnaissance of the area by a qualified person or institution for the determination of archaeological heritage in that area.

Based on the completed reconnaissance report, depending on the results, the professional service of the competent authority for the protection and preservation of cultural heritage will establish further guidelines and conditions in accordance with the Law on Protection and Preservation of Cultural Heritage.

In the procedure for approving the opening of mineral resource exploitation fields, the investor is obliged to ensure reconnaissance of the area during the preparation of the Environmental Impact Assessment Study, and based on the prepared report, the competent authority will determine guidelines, conditions, and measures in accordance with the Law on Protection and Preservation of Cultural Heritage, which the author will incorporate into the content of the Study.

If archaeological sites are encountered during the execution of all spatial interventions, work must be suspended and the competent authority for the protection of cultural heritage must be informed.



CONDITIONS FOR IMPLEMENTATION OF STATE-SIGNIFICANT SPATIAL INTERVENTIONS

...

Article 211b.

Conditions for the exploration and exploitation of energy mineral resources (geothermal waters E2) and conditions related to spatial interventions for their exploitation are contained in the preceding article and in Articles 44 and 112a of these Provisions.

...

2.5.2. Spatial plan of the city of Čakovec ("Official Gazette of the City of Čakovec", No. 4/03, 9/09, 06/12, 7/14, and 1/15 - consolidated text)

EXCERPT FROM THE TEXTUAL PART OF THE PLAN

SPACE MANAGEMENT CONDITIONS

...

Article 8.

Buildings for water use, water protection, and flood protection:

...

Borehole with potential for geothermal water exploitation - Međimurje 4 (Mđ-4).

...

Article 8a.

...

New exploratory and/or exploitation gas wells can be located within the Mihovljan gas exploitation field and the planned gas field "Međimurje - Peklenica", with micro-locations determined in accordance with special regulations, and the plot or land area they occupy, including the associated handling space, is considered a separate construction area.

Existing boreholes with freshwater findings are not planned for exploitation but only for maintenance mining operations, while the potential use of geothermal water at borehole "Međimurje 4" (Mđ-4) is planned.

...

Article 67c.

Urban building areas

Potential water exploitation in this plan is only envisaged for the borehole with geothermal potential Mđ-4.

The decision on the purpose of using the mentioned borehole (energy, tourism, or other) depends on a feasibility study that needs to be prepared for each specific purpose, with a preference for using thermal water as an energy source for agricultural purposes.

Other existing boreholes Čakovec - 1 and Mačkovec - 1 need to be remediated or maintained in a manner that does not negatively impact the environment and human health.



The existing borehole Mačkovec - 1, which is used as part of the gas production system as a saline water injection well, may be used for this purpose provided that the injection process has no negative impact on the environment and human health.

...

Renewable energy sources

Article 102b.

(1) In addition to existing and planned conventional energy systems, this Plan recommends and enables the use of supplementary energy sources from renewable sources in terms of energy efficiency, provided such opportunities are available.

(2) Supplementary energy sources include devices and facilities that use renewable sources such as solar energy, water, wind, heat from industry, environment, energy from waste, biomass, etc., or any form of energy that partially or completely replaces fossil fuels for the production of electricity and/or hot water.

(3) Energy buildings or facilities and devices intended for energy production from renewable sources for own needs or for the market can be constructed in accordance with special regulations within construction areas and outside them, provided they do not endanger the environment and the values of cultural heritage and landscape.

2.5.3. Spatial Plan of the Municipality of Pribislavec ("Official Gazette of Međimurje County", number 1/04, 2/07, 19/13, 10/15, and 24/22)

EXCERPT FROM THE TEXTUAL PART OF THE PLAN

CONDITIONS FOR SPACE ORGANIZATION

...

Article 8.

Existing buildings

...

Exploration areas and hydrocarbon exploitation fields, geothermal waters for energy purposes, underground gas storage and permanent carbon dioxide disposal, as well as facilities and installations for exploration and exploitation:

- hydrocarbon exploration area Northwest Croatia - 01 (SZH-01)

- hydrocarbon exploitation field "EP Mihovljan"

Planned buildings

Hydrocarbon and geothermal water exploitation fields for energy purposes

- area planned for exploration and exploitation of geothermal waters throughout the Municipality.

Planned - possible buildings

...

Hydrocarbon and geothermal water exploitation fields for energy purposes



- exploration potential of geothermal water *Međimurje 4*

Planned buildings

...

Hydrocarbon and geothermal water exploitation fields for energy purposes

- area planned for hydrocarbon exploitation (E1)

...

Article 49.

Construction outside the construction area

Outside the construction area, within the Municipality, the following can be built:

...

- exploration areas and hydrocarbon exploitation fields, geothermal waters for energy purposes, underground gas storage and permanent carbon dioxide disposal, as well as facilities and installations for exploration and exploitation

- buildings intended for agricultural production (greenhouses, glasshouses, storage facilities, cold storage, etc.)

...

- buildings for exploration and exploitation of mineral resources

...

EXPLORATION AREAS AND HYDROCARBON EXPLOITATION FIELDS, GEOTHERMAL WATERS FOR ENERGY PURPOSES, UNDERGROUND GAS STORAGE AND PERMANENT CARBON DIOXIDE DISPOSAL, AND FACILITIES AND INSTALLATIONS FOR EXPLORATION AND EXPLOITATION

Article 89.

Exploratory works and activities aimed at determining the reserves of hydrocarbons (E1) and geothermal waters (E2) that can be used for accumulated heat for energy purposes can be carried out throughout the County, under the conditions prescribed by the Spatial Plan of Međimurje County and in accordance with special regulations.

Article 90.

Based on the results of exploratory works, and in accordance with special regulations and provisions of the Spatial Plan of Međimurje County, it is possible to establish and form hydrocarbon and geothermal water exploitation fields. Hydrocarbon exploitation fields or geothermal water exploitation fields can only be formed within defined and selected exploration areas, and their area may be the same or smaller than the exploration area, with the possibility of forming multiple hydrocarbon or geothermal water exploitation fields within one exploration area.

Article 91.

The scope of the intervention in the space for exploration and exploitation of hydrocarbons, geothermal waters for energy purposes, underground gas storage and permanent carbon dioxide disposal, and facilities and installations for exploration and exploitation, may be located in such a way as to avoid forest land as



much as possible, and the intervention should avoid or reduce permanent occupation of endangered and rare habitat types and habitats significant for target species within the Natura 2000 ecological network, and must not be located within registered and protected archaeological zones.

Article 92.

(1) Mining operations in the space for exploration and exploitation of hydrocarbons may be located to maximally avoid forest land, and the intervention should avoid or reduce permanent occupation of endangered and rare habitat types and habitats significant for target species within the Natura 2000 ecological network, and must not be located within registered and protected archaeological zones.

(2) Mining operations in the space for exploration and exploitation of geothermal water may be approved subject to the limitations specified in paragraphs 2 and 3 of this Article, and exceptionally may be approved within the construction area of settlements or detached construction areas outside settlements, if the exploitation of geothermal water is in the function of the zone in which it is located.

(3) Geothermal power plants must not be located less than 300 m from the edge of public buildings and residential buildings.

(4) Noise that may occur in the environment of residential and work buildings during the exploitation process must not exceed the limit values prescribed by special regulations.

...

2.5.4. Spatial Plan of the Municipality of Belica ("Official Gazette of Međimurje County", number 4/04, 18/06, 7/12, 14/15 and 4/21 - consolidated text)

EXCERPT FROM THE TEXTUAL PART OF THE PLAN

CONDITIONS FOR SPATIAL PLANNING

...

Article 10.

Spatial Interventions and Areas Not Considered Construction:

...

2. Interventions for exploration and exploitation and facilities for exploitation in exploitation fields:

- for hydrocarbons and geothermal water for energy purposes:
- part of the determined EPU "Mihovljan"
- part of the determined IPU "Northwest Croatia - 01" (SZH-01)
- mineral deposits:
- location for depositing excess excavation that constitutes a mineral raw material during construction works, according to special regulations - within the designated waste management zone at the local level in the area of the settlement of Belica.

EXPLORATION AND EXPLOITATION OF MINERAL RESOURCES, HYDROCARBONS AND *GEOHERMAL WATER*



Article 102.

(1) Interventions related to the exploration and exploitation of mineral resources, hydrocarbons and *geothermal water*, as well as the remediation of areas after completed exploitation or cessation of exploitation by other means, shall be carried out directly in accordance with special laws and other regulations governing these activities and in accordance with the conditions of the Spatial Plan of the Međimurje County.

(2) All interventions must be planned and carried out in a manner that ensures environmental and nature protection measures and prevents emissions of harmful substances into the air and increases in noise towards residential construction areas.

(3) Noise that may occur during exploration and exploitation procedures in surrounding residential zones and other functional areas must not exceed the maximum permissible values established for the respective zone.

Hydrocarbons and geothermal water for using accumulated heat for energy purposes

Article 103.

(1) Within the area of the Municipality, there are:

- part of the determined exploitation field of hydrocarbons EPU "Mihovljan"
- part of the determined exploration area for hydrocarbons IPU "Northwest Croatia - 01" (SZH-01).

(2) Geothermal potential for using accumulated heat from water for energy purposes is identified in the eastern part of the Municipality, in the "Međimurje 4" area and shown on cartographic display number 3 "Conditions for Use, Planning and Protection of Areas".

(3) Activities carried out for the purpose of exploring geothermal water for energy purposes may be conducted in accordance with the geothermal potential, i.e., the determination of exploration areas for geothermal water for energy purposes is permitted within established hydrocarbon exploration areas, in accordance with special regulations.

(4) Exploration areas or parts thereof for hydrocarbons or geothermal water for energy purposes may be converted without amending this Spatial Plan into corresponding exploitation fields if the exploitation field meets the appropriate conditions prescribed by special regulations on the exploration and exploitation of hydrocarbons or geothermal water for energy purposes.

(5) Exploitation fields from the previous paragraph, which are formed within the appropriate established exploration areas, may have an area equal to or smaller than the exploration area, and multiple exploitation fields for hydrocarbons or geothermal water may be formed within the same exploration area.

(6) All activities carried out for the purpose of exploring and exploiting hydrocarbons and geothermal water for energy purposes must comply with the Framework Plan and Program for Onshore Hydrocarbon Exploration and the Strategic Environmental Assessment of the Framework Plan and Program for Onshore Hydrocarbon Exploration.

Article 104.

(1) Location of boreholes:

- new exploration boreholes with associated buildings are located within appropriate established exploration areas



- new exploitation boreholes with associated buildings are located within appropriate established exploitation fields.

(2) The distance from the axis of boreholes to the land strip of watercourses and regulated channels, water retention areas, protective zones of general-purpose power lines, and all other buildings not intended for exploration and/or exploitation of gas, oil, and other geopotentials must be at least as high as the height of the drilling tower increased by 10%, but at least 90.0 m.

(3) Around a constructed borehole, the safety and fire zone extend to 30.0 m radius around the borehole axis.

(4) For permanently abandoned boreholes (the channel of the abandoned borehole is located 1.5 - 2.0 meters underground upon liquidation of the borehole), the safety-protection zone where it is prohibited to build structures for the stay and work of people is 3.0 m radius around the axis of the channel of the permanently abandoned borehole.

(5) There are currently no registered permanently abandoned boreholes in the Municipality.

Article 105.

(1) Pipelines and other structures of the hydrocarbon and geothermal water production - dispatch system may be located within the entire area of the Municipality, and it is recommended that their routes be aligned with the routes of previously constructed compatible linear infrastructure.

(2) Hydrocarbon transmission systems are addressed in Chapter: 5.3.2.1. "Systems for pipeline transport of hydrocarbons and hydrocarbon products".

Energy production from *renewable sources* (RES) and cogeneration

Article 109.

(1) Production of energy from *renewable sources* and cogeneration is possible to supplement the conventional system or independently from the conventional system.

(2) Energy from *renewable sources* and cogeneration (solar energy, systems using earth, water temperature, and others) can be produced in:

- individual energy facilities - as energy for one or several individual users, whereby it is possible, but not necessary, to connect the system to the appropriate conventional transmission and distribution network for delivery of produced energy (electric or thermal).

- commercial energy facilities, i.e., facilities primarily intended for energy (electric and thermal) production for the market.

(3) In the case where an individual energy facility produces energy exclusively for the own needs of another content on the building plot, it is considered an auxiliary building, and in case of surplus energy supply to the public energy system, it is considered an ancillary building.

(4) A commercial energy facility is considered a primary purpose building, i.e., an ancillary building if it is a commercial energy facility located on a building plot where the primary building is also a commercial energy facility of another energy source or where the primary building is of other economic, production purposes.

(5) All buildings and facilities for the production and use of energy from *renewable sources* and cogeneration must be planned in a way that complies with the Regulation on the Use of *Renewable Energy*



Sources and Cogeneration ("Official Gazette" number 88/12), other special regulations, and regulations establishing their harmlessness to human health and the environment.

(6) For the placement of buildings and facilities for the production and use of energy from *renewable sources* and cogeneration, it is necessary to:

- seek the opinion of the competent Conservation Department, in order to avoid compromising the integrity of cultural assets.
- in case of placing energy production complexes outside building areas, examine nature protection conditions.

Article 110.

(1) Individual energy facilities or plants for the production and use of energy from *renewable sources* and/or cogeneration are located directly next to the designated consumer, on the same building plot or on a separate building plot nearby.

(2) The maximum permitted total power of an individual energy facility (electric and thermal energy) is 500 kW.

(3) In the Municipality's area, it is permitted to build individual solar energy facilities, thermal systems using earth energy (water, other medium), and biomass energy facilities, while energy facilities using biogas and wind as an energy source are not permitted.

(4) Individual energy production systems based on *renewable energy sources* and cogeneration can be located:

- on building plots in all functional zones within urban building areas except in public green areas /designated Z/ (parks, playgrounds, etc.) and protective green areas /designated ZZ/.
- on building plots within isolated building areas outside urban areas.
- on a building plot of a separate (family) agricultural estate outside urban building areas.

(5) A requirement for an individual energy production system based on *renewable energy sources* and cogeneration is that the building plot where it is proposed retains a minimum of 20% of the area as green areas of natural terrain, on which and below which installation of the system production of energy is not foreseen.

(6) In addition to the conditions of paragraph 3 of this Article within urban building areas:

- it is not possible to place facilities that use surface water from watercourses for the production of electric and/or *thermal energy*.
- it is not possible to place facilities that produce noise higher than allowed for the zone in which the facility is proposed.
- on building plots where residential content is located or planned to be built, photovoltaic panels can only be placed on building roofs or integrated into facades.
- other conditions for the placement and construction of facilities for the production and use of energy from *renewable sources* and/or cogeneration are determined equally as for other buildings within the appropriate functional zone.

Article 111.



(1) As commercial types of energy facilities that use *renewable energy sources* and cogeneration for energy production for the market are provided:

- solar energy facilities
- *geothermal energy* facilities
- combinations of the mentioned types.

...

(3) The maximum permitted installed capacity of an individual commercial RES facility is determined according to a special regulation depending on the type, and based on this Plan, commercial facilities are possible with a maximum of 10.0 MW installed capacity per facility.

...

(6) Commercial *geothermal energy* facilities can be located within urban building areas with economic, production purposes /designation I/.

(7) Facilities that produce noise greater than allowed for the zone in which they are located during energy production or unpleasant odors that could negatively affect the quality of living in the settlement must be at least 250.0 m away from residential contents.

...

(9) Conditions for the placement and construction of *geothermal energy* facilities are determined equally as for other facilities provided within urban building areas with economic, production purposes.

2.6. Conclusion of compliance of the project with spatial planning documentation

The analysis of spatial planning documents has shown that the exploitation of geothermal water within the Mihovljan exploitation field area is in compliance with the current spatial planning documentation, namely the Spatial Plan of Međimurje County, the Spatial Plan of the City of Čakovec, the Spatial Plan of the Municipality of Pribislavec, and the Spatial Plan of the Municipality of Belica.

3. Mihovljan exploitation field

3.1. General Description

The Mihovljan oil and gas field is located east of the village of the same name, in Međimurje County. Its western boundary is defined by the Čakovec–Mihovljan–Novo Selo Rok asphalt road, while the southern and eastern boundaries are marked by the Čakovec–Pribislavec–Belica asphalt road. The northeastern boundary is delineated by the Belica–Novo Selo Rok line. The field itself is situated on hilly terrain with an average elevation of approximately 180 meters.



The Mihovljan structural high dominates the field, clearly expressed on structural maps for reservoirs I and II. The main axis of this structural high trends in a northwest-southeast direction. No significant tectonics have been observed in the boreholes drilled so far. The Mihovljan deposit is classified as a combined structural-stratigraphic trap type and categorized as a stratified deposit with lithological trapping and structural closure, according to I. O. Brod's classification from 1957. Reservoir rocks in this area consist of moderately to firmly bounded quartz sandstones, while cap rocks are composed of tuffs that act as effective barriers against vertical hydrocarbon migration.

The Mihovljan field was discovered in 1974 with the first exploration well, Mih-1, and a total of 15 wells have been drilled on the field to date. Stratigraphically, the Mihovljan field includes deposits from the following periods: Miocene, Lower Pannonian, Upper Pannonian, Lower Pontian, Upper Pontian, and Quaternary. The Mihovljan structural high, with its main axis trending north-south, dominates the field, without registered tectonic disturbances. Gas reservoir I is located in the Upper Pannonian deposits (Siget sandstones), discovered by well Mih-2. Oil reservoir II is located within the Lower Pannonian deposits (Petišovci sandstones) and are confirmed by wells Mih-1, Mih-3B, Mih-6, and Mih-7. According to I. O. Brod's classification, hydrocarbons at the Mihovljan field are found in structural-stratigraphic traps classified as stratified deposits with lithological trapping.

A reinterpretation of the broader structural-geological relationships of the Mihovljan area by H. Kisovar in 1975 confirmed previous structural solutions. This reinterpretation was based on data from the latest seismic profiles and deep exploration wells drilled on this structure. Structural maps based on multiple exploration key points at the Mihovljan exploration site indicated the existence of a separate structural feature, the Mihovljan anticline, formed in higher lithostratigraphic horizons. The anticline is elongated, with its longer axis trending west-east. The structure has a homogeneous construction, and the position of the anticline crest varies depending on the depth of individual lithostratigraphic units. The most prominent anticlinal form is expressed at the Petišovci sandstone roof (EL marker X). Westward, across the structural trough, the Mihovljan structure transitions into a separate structural feature, the Mačkovec anticline. The Mihovljan structure comprises sediments from the Mura, Lendava, and Mura-Sobot formations. The sandstone horizons include the Paka, Upper and Lower Ratka, Siget, and Petišovci sandstones, as well as sandstone horizons within the Međimurje member. The Petišovci and Siget sandstones are the most important. The Međimurje member of the Mura-Sobot formation is also noteworthy for the presence of tuffaceous rocks, beneath which are andesitic breccias. The lithological composition of the Tertiary substratum is assumed to be limestones, dolomites, and dolomitic limestones.

Exploration work in the broader Čakovec zone of the Mura depression, as well as at the site itself, was not continuous but conducted intermittently. Regional gravimetric measurements of northern Croatia, including the Mihovljan site, were conducted from 1940 to 1942. Regional seismic surveys date back to 1957 and 1958 and were supplemented with seismic profiles until 1968. Regional and detailed gravimetric measurements were carried out from 1953 to 1967. The results of these measurements correlate with data obtained from seismic measurements. Supplementary seismic surveys continued from 1971 to 1974. Following the reinterpretation of all collected geophysical and geological data, an exploration well, Mihovljan-1 (Mih-1), was located on March 6, 1974, and drilled the same year. Oil was registered in the Petišovci sandstones by the well, and testing and examination of these deposits yielded oil and gas. A total of 15 wellbores have been constructed on the Mihovljan exploitation field.

The deposits of the Mihovljan exploitation field have a structural nose shape with the main axis trending north-south. The dips of the layers are nearly equal on the eastern and western wings, while they are steeper to the north. No fault tectonics have been observed by current works. Deposits in the Mihovljan field include Miocene (Lower, Middle, and Upper), Pliocene, and Quaternary with associated formations: Mura-Sobot, Lendava, and Mura formations. Two hydrocarbon reservoirs have been discovered in the field: Reservoir I - gas reservoir, and Reservoir II - oil reservoir. Gas reservoir I was confirmed only by well Mih-2, while oil reservoir II was confirmed by wells Mih-1, Mih-3B, Mih-6, and Mih-7.



Reservoir II is formed in sedimentary rocks of the Lower Pannonian, Petišovci sandstones. The rocks containing accumulated oil are composed of light gray and gray, medium to firmly bounded quartz sandstone. The oil-water contact is located at a depth of -1455 meters. Cap rocks of the deposit consist of tuffs. The values of deposit parameters are as follows: porosity (ϕ) 20.9%, initial oil saturation (S_{oi}) 67.5%, effective permeability (k) $19.9 \times 10^{-3} \mu\text{m}^2$.

Reservoir I is formed in sedimentary rocks of the Upper Pannonian, Siget sandstones. The reservoir rocks are composed of gray fine-grained quartz sandstone. The gas-water contact is determined at a depth of -1408 meters. The cap, insulating rocks of the reservoir consist of tuffs. To the west and south, reservoir is constrained by a lithological barrier, i.e., an outcrop of sandstone layer. The values of deposit parameters are as follows: porosity (ϕ) 22%, initial gas saturation (S_{gi}) 70%, effective permeability (k) $25 \times 10^{-3} \mu\text{m}^2$. Gas reservoir I was exploited from 1984 to 1986 by well Mih-2. During this period, the reservoir was depleted, and the well was abandoned. According to Levorsen's classification of reservoir, Reservoirs I and II were formed in structural-stratigraphic traps and classified according to Brod as stratified reservoirs with lithological trapping.

Since the beginning of oil exploitation in 1988, all wells have been exploited using deep sucker rods. After a few months, a significant initial decline in oil production was observed in all wells, accompanied by a slight increase in water content. However, after one year, the production decline slowed down. After chemical treatments due to high oil viscosity and a high content of paraffin in the oil, oil and fluid production increased. During the exploitation period, there has been little data on reservoir pressure due to the integrated deep sucker rods. In May 1997, pumping was stopped due to unprofitability caused by low oil prices and high transportation costs. After a technical-economic assessment in 2000, oil exploitation from the Mihovljan exploitation field became profitable again due to the increase in global oil prices. The long idle period of the wells was used to measure the levels in the wells under static conditions. The results of these measurements showed that nearly initial reservoir pressure was established in wells Mih-1 and Mih-6, while pressure in wells Mih-3B and Mih-7 was slower to recover. The value of near-initial reservoir pressure indicates an oil deposit with a pressure-supported production regime. In well Mih-1, after chemical treatment in 2003, fluid inflow increased, but shortly afterward, the water cut in the produced fluid significantly increased. The well operated until January 2020 when it was closed due to low inflow. Well Mih-3B ceased operations in March 2008 due to deep sucker rod failure. It was put back into operation in November 2011, producing approximately $1.0 \text{ m}^3/\text{d}$ of oil, but operations ceased in February 2014 due to deep sucker rod failure and the decision not to undergo major completion and return to production due to low oil inflow. Well Mih-7 operated until May 2018 when it was also closed due to low inflow. Oil deposit II in the Mihovljan field is currently being exploited by only one well, Mih-6. At the end of 2019, the well underwent current equipment maintenance and deep sucker rod operation optimization, resulting in increased oil production in 2020 compared to the previous year.

3.2. Well Mačkovec-1

The location of the deep exploration well Mačkovec-1 (Mač-1) is situated between the villages of Šenkovec, Mačkovec, and Mihovljan, in Međimurje. It is approximately 1000 m east of Šenkovec, about 600 m southeast of Mačkovec, and approximately 600 m west of Mihovljan.

The approximate coordinates of the well are:

Y = 5 610 790

X = 5 141 541

Elevation (h) = 186 m



The Mačkovec exploration site is located within the Čakovec zone of the Mura Depression (west of the Mihovljan site). The deep exploration well Mač-1 penetrated the Mura, Lendava, Mura-Sobot formations, and a section of the Tertiary basement. The well was completed at a depth of 3050 m.

The Mačkovec structure is shaped like an anticline. In the Lendava formation, the Paka sandstones, Lendavčica marls, and Upper Ratka sandstones members are absent, which complicated correlation during drilling. However, deeper in the well, correlation improved significantly, and the development and thickness of members in the Mura-Sobot formation are very similar.

Recent reinterpretations of the broader structural-geological relations of the Mihovljan exploration area, based on deep drilling results from Mih-1 and Mih-2 and the interpretation of recent seismic profiles, also encompassed the Mačkovec area.

The first exploration activities in the Mačkovec area began with super-regional gravimetric surveys of northern Croatia. More extensive post-World War II investigations followed, utilizing new and the latest geophysical exploration methods. In 1958, gravimetric and magnetometric measurements were conducted. In subsequent years, geoelectric surveys were carried out in the immediate vicinity of the site. The first seismic profiling took place in 1958/59, followed by further surveys in 1965/66. The latest seismic profiles were recorded from 1971 to 1974 and digitally processed. Photogeological processing of the wider area around the site was also conducted.

The first oil and gas explorations, discoveries, and production in the Međimurje region were among the first of their kind in Europe, specifically in Selnica, Peklenica, before World War II. The nearest neighboring wells, Mih-1 and Mih-2, were drilled in 1974/75. Northeast of the Mačkovec site, Mđ-1 was drilled in 1954, followed by Mđ-2, -3, -4, -5, and -6 between 1966 and 1969. However, the Mačkovec site had not been subjected to deep drilling until now.

The first indications of gas in this well were registered in the Mura formation at depths from 990 to 1023 m. The relative concentration of gas in the effluent was recorded at 2% on the detector, with methane and hydrogen detected by chromatography. Gas occurs in sandstone layers within marls. Similar weak occurrences were noted in the Peklenica member's roof. During the drilling of Gorica-Dolina marl and Upper Ratka sandstone roof sections, a slightly higher concentration (2-4%) was detected. The composition is consistent (C1 and H2). Gas concentration in Siget sandstones reaches up to 2%. The expected increase in Petišovci sandstones did not occur (detector: 2-4%). Weak gas occurrences were also observed in Benica marl, Čentiba member, and Međimurje member's roof. These occurrences are associated with sandstone layers within marl and occasionally with fractures in marl (Benica marl, Čentiba member). In the Međimurje member, gas originates from silicified effusive rock. Gas occurrences in the Tertiary basement are associated with fractured limestones. The relative gas concentration in the effluent ranges from 1% to 3%, with one stronger manifestation (d = 2995 m, detector - 5%; chromatography - C1 0.95%).

The results indicate that gas occurrences at Mač-1 are insignificant in terms of quantity and composition. No oil was found. These poor results during drilling are confirmed by analyses of the reservoir properties of the most significant sandstone layers. Unlike the Petišovci sandstones, which yielded oil at Mih-1 (permeability 259 mD, porosity 22.5%), the Petišovci sandstones at Mač-1 are impermeable (core no. 1, interval 1572.0 - 1575.0, permeability 0 mD, porosity 5.1 - 6.0%)

3.2.1. Well Construction

The length of the Mač-1 wellbore is 3050 meters.

Casing:

Surface casing (13 3/8") installed to 247 m and cemented to surface.



I intermediate casing (9 5/8") installed to 1639 m and cemented to surface.

II intermediate casing (7") installed to 2704 m and cemented to 1500 m.

3.2.2. Drill Stem Test

At the deep exploration well Mačkovec-1, three Drill Stem Testing (DST) operations were conducted. The first test was performed at a depth interval of 2546 - 2556 m, and the second at 3039 - 3050 m. However, in both cases, despite using a 9 1/4" tool size, the packers did not hold. The third test was conducted from the 9 5/8" casing interval from 1639 to 3050 m, corresponding to the Mura-Sobot formation and likely the Tertiary Basement according to the lithostratigraphic profile. The test spanned such a large interval to ascertain the presence of any fluids and potentially obtain a layered fluid sample. Testing was performed, as mentioned above, from the 9 5/8" casing, and sealing was successfully achieved with a single BOCL 45A packer.

Test durations were controlled using a CIP valve, with pressure recorded using a downhole gauge. Flow rate measurement was accompanied by significant gas venting at the surface. Flow was measured over 468 minutes under maximum pressure, recorded at 141.44 atp on the downhole gauge's chart. However, this data was deemed inaccurate, likely due to operator error where a 12-hour mechanism was mistakenly set instead of a 24-hour one, resulting in incomplete recording of the flow measurement and omission of static pressure plot. During flow measurement, 9000 dm³ of fluid entered the empty drill pipes. Unfortunately, due to the absence of a static pressure plot on the downhole gauge chart, no calculation can be made, but it can be noted that approximately 9000 dm³ of water likely entered the annular space below the packer or within the casing, displacing fluid into the drill pipes.

Based on the pressure plot's shape, which is uniformly rounded and shows no sign of flattening, it can be inferred that the reservoir has limited extent, and pressure would start declining sharply after a short time. Despite the results from the DST testing, the well was subsequently completed with a 7" production casing from surface to 2700 m and handed over for further testing by the Repair Department

3.2.3. Geological-Geophysical Works and Special Operations

Deep exploration well Mač-1 penetrated the Mura, Lendava, Mura-Sobot formations, and a part of the Tertiary Basement. The well reached a depth of 3050 m. Within the Lendava formation, members such as Paka sandstones, Lendavčica marl, and Upper Ratka sandstones are absent, contrasting with neighboring wells (Mđ-6 and Mih-1) where these members are well-developed, posing challenges for correlation during drilling. In deeper sections of the well, correlation is good, with similar development and thickness of members in the Mura-Sobot formation. The Tertiary Basement was only penetrated by Mač-1.

Regarding hydrocarbon potential, Mač-1 was non-productive. Sand layers such as Lower Ratka, Siget, and Petišovci sandstones contained minor gas quantities (up to 5%), but no oil was found. Surrounding wells showed higher hydrocarbon presence. Upper Ratka sandstones, Lendavčica Gorice marl, and Peklenica members in Mđ-6 exhibited traces of hydrocarbons (oil and gas), though not economically viable. Significant oil reserves were discovered in Petišovci sandstones in Mih-1.

During drilling, continuous geological monitoring was conducted. Sieve material samples were taken every 5 meters, examined under UV light and using the LKT method. An operational geological diagram was created. Eight mechanical cores totaling 21.8 meters were extracted, yielding 18.2 meters (83%). All cores were meticulously examined for hydrocarbon content and described. Core samples were sent for physical (19), sedimentological (34), micropaleontological (23), and bitumen analyses (29).



At a depth of 1055 meters, a gas station was installed, and continuous gas logging was performed to the bottom of the well. Instruments used included a speedograph, chromatograph, and detector. Preliminary WL measurements were taken before installing the technical column to a depth of 1643 meters, with final WL measurements taken after drilling completion at 3051 meters (by WL). A Drill Stem Test (DST) was conducted over the interval from 1659 to 5050 meters, yielding 9 m³ of fluid recovery. Two DST attempts were unsuccessful. The final depth of the well according to drill rods was 3050 meters, and 3051 meters according to WL. The well terminated in limestone forming the Tertiary Basement. At the request of the Development Department, the well was cased with a 7" production casing to a depth of 2700 meters for water testing purposes.

3.2.4. Conclusion of Drilling at Mačkovec-1

The Mačkovec-1 (Mač-1) well is located in the Čakovec zone of the Mura Depression, approximately 1100 m east of the village Šenkovec and about 600 m southeast of the village Mačkovec. It was drilled in 1975 at the top of the structure. The primary objective of the well was to investigate Miocene deposits and assess hydrocarbon saturation on the Mačkovec structure. The well reached a depth of 3050 m and was cased with a production string down to 2704 m. However, due to very low gas quantities observed during drilling, the well has a negative status regarding hydrocarbon exploration.

Since 1986, Mačkovec-1 has been used as an injection well for technological/layer waters. Following unsuccessful operations in 2007, there is a need to create a directional channel, Mač-1R, from the existing borehole. This is intended to prepare the well for injecting layer water from the Zebanec, Vukanovec, and Vučkovec exploitation fields.

3.3. Well Mačkovec-1R

The task of the Mač-1 well was to investigate Miocene deposits and determine hydrocarbon saturation in the Mačkovec structure. The well has a depth of 3050 meters and is cased with a production string up to a depth of 2704 meters. However, due to the very small quantities of gas detected during drilling, the well has been classified as a non-commercial hydrocarbon well. Since 1986, the Mačkovec-1 well has been used as an injection well for technological/formation water. Given that the KRS operations in 2007 were unsuccessful, it was decided to create a sidetrack from the existing wellbore to prepare the well for the injection of formation water from the Zebanec, Vukanovec, and Vučkovec exploitation fields.

Drilling commenced on March 22, 2015, by opening a window in the 9 5/8" casing in the interval between 776.2 and 780.9 meters. The directional drilling was conducted using a PDM (positive displacement motor) and MWD (measurement while drilling) system. Continuous geological monitoring of the Mačkovec-1R (Mač-1R) well was performed using the LNB-01 drilling control laboratory from 776 meters to the final depth of 1642 meters. Rock cuttings samples were collected in accordance with the project task, examined, and analyzed. Upon completion of drilling, the collected samples were stored in the well material storage facility at Mramor Brdo.

3.3.1. Well Construction

The length of the Mač-1R wellbore channel is 1642 m.

Casing:

Surface casing (13 3/8") installed to 247 m and cemented to surface.

I Intermediate casing (9 5/8") installed to 781 m and cemented to surface.



II Intermediate casing (5 ½") installed to 1640 m.

Directional drilling components:

MD=1602,13 m

Hv= 1600

Azi=360°

Inc=0°

VS=39,05 m

3.3.2. Geological-Geophysical Works and Special Operations

Continuous geological monitoring of the Mačkovec-1R wellbore (Mač-1R) was conducted using the Drilling Surveillance Laboratory (LNB-01) from 776 m to the final depth of 1642 m. Rock cuttings samples were collected in accordance with the project requirements, examined, and analyzed. Upon completion of drilling, the collected samples were stored in the Mramor Brdo well material warehouse. The results of geological monitoring are depicted in the Operational Geological Diagram.

To record, collect, and process all geological data, occurrences of hydrocarbons, and drilling parameters, geological monitoring of the Mačkovec-1R wellbore was performed continuously using the Drilling Surveillance Laboratory (LNB-01) throughout the drilling process to the final depth of 1642 m.

During the drilling of the exploration wellbore Mačkovec-1R, five occurrences of new gas were recorded with relative concentrations ranging from 0.8% to 1.9%, lasting from 10 to 25 minutes, with a chromatographic composition of C₁-C₃. In the Lendava Formation layers, three occurrences of new gas were registered with relative concentrations from 1.1% to 1.9%. These occurrences are associated with sandstones and mainly contain methane (C₁) with lesser amounts of ethane (C₂) and propane (C₃), indicating gas dissolved in water. In the Mura-Sobot Formation layers, two occurrences of new gas were recorded with relative concentrations of 0.9% and 0.8%, chromatographically consisting of C₁-C₃ gases. The gases are associated with sandstones and are also dissolved in water.

Background gas started appearing from a depth of 980 m and was almost continuously registered down to the bottom of the wellbore. Concentrations remained below 1%, occasionally reaching up to 2.8%. The gas is associated with the Mura, Lendava, and Mura-Sobot formation sandstones. During the drilling of the wellbore to 1642 m, only minor tripping gases (up to 0.7%) were recorded, mainly occurring after tool composition changes. There were no connection gas occurrences noted.

3.3.3. Conclusion of Drilling Mač-1R

Drilling commenced on March 22, 2015, with the opening of a window in the 9 5/8" casing at intervals from 776.2 to 780.9 m (KOP=776.2 m). All formations specified by the project were drilled through. Due to looseness in certain intervals, part of the sandstones were not recovered in the samples. Five new gases were registered with concentrations of 0.8% to 1.9%, and all samples tested negative for UV and CHCl₃. After reaching the target depth of 1601 m (TD=1600 m), it was decided to deepen the wellbore to the Petišovci sandstones. Drilling was completed on April 1, 2015, with the final depth of the wellbore reaching 1642 m (TD=1640 m). During the concluding meeting held in Zagreb on April 3, 2015, it was determined that the project objectives had been met, and it was decided to cement the well with a 5 ½" diameter casing (0.140 m) in preparation for injecting technological/layer water. Based on the interpretation of the WL log and



geological monitoring results, the following intervals were perforated: 1440 - 1437.5 m, 1383 - 1365.5 m, 1356.5 - 1349 m, 1334 - 1324 m, 1319 - 1318 m.

3.4. Well Međimurje-4

The deep exploratory well Međimurje-4 (Mđ-4) is located 250 m southeast of the village of Mali Rok, and can be accessed via a soft road from the Čakovec - Rok gravel road, approximately 1400 m in length.

Coordinates:

y = 5 614 614.65

x = 5 142 460.69

h = 178.53 m

The Međimurje region is renowned for its discovery and production of oil, making it the oldest oil field not only in Croatia but also in Europe (Selnica, Peklenica). Initial explorations involved digging wells to discover oil. Later, drilling methods such as percussion and rotary systems were employed. These explorations were pioneering in nature, with more serious drilling activities occurring during World War II. Deep wells like Mur-1,2, Sit-1, and Peklenica-1 were drilled during this period. Despite minor hydrocarbon manifestations, significant commercial quantities were not found in these wells.

On the gravimetric map, the area east of Čakovec is depicted as a large syncline parallel to the course of the Drava River. Interpretation of regional seismic profiles within this syncline area has identified positive regional elements extending from Čakovec towards Hungary. A deep exploratory well drilled in the vicinity of Čakovec confirmed these seismic interpretations, revealing a shallower structural development than previously assumed, with Tertiary series developed in marl facies and sandy marl without sand horizons, lacking reservoir properties and hydrocarbon traces.

After the abandonment of this well in 1959, no further exploration activities were conducted in this area until 1965, except for deep exploratory wells drilled by Nafta Lendava on the summit of the Selnica - Peklenica anticline. In 1964, exploratory work was reactivated, supplementing existing regional seismic surveys with a detailed network of seismic profiles. Enhanced seismic interpretation provided a more comprehensive understanding of the structural relationships in the Međimurje region. Surface operations and deep drilling were both resumed.

Međimurje-2 well was drilled to verify sedimentological conditions and physical properties of potential reservoir rocks. The well revealed thick sandstone developments equivalent to Lower, Middle, and Upper Ratka sandstones and Petišovci sandstones in the northern part of the Mura Depression, along with relatively thick layers of marl as cap rocks. Apart from minor gas traces indicated by specific gravity drops in the drilling mud, no other occurrences were observed during drilling. Due to favorable development of isolator and collector rocks in Međimurje-2, Međimurje-5 encountered significantly reduced sandstone development, and Ča-1 well only encountered isolator rock development, indicating a gradual thinning and western inclination of sandstones.

Geological interpretation of covered terrains in northern Croatia, including the area between Čakovec and the Mura River, revealed structural features resembling horst structures bounded by faults. This uplifted block gradually descends eastward, with Tertiary deposits periclinally overlain on paleorelief, gently sloping towards the east. Comparison of photogeological structural maps with residual gravity maps indicated significant correspondence. Additional seismic measurements were conducted last year to verify these alignments, as previous seismic profiles largely bypassed this intriguing area. Interpretation of all existing



results from surface testing methods and deep drilling produced multiple structural maps at various levels, identifying a structural dome north of Mihovljan and south of Rok.

To investigate these relationships further based on supplementary seismic surveys, the deep exploratory well Md-4 was located near Mali Rok, positioned at nearly the highest structural elevation. The primary objective of the well is to drill through the entire Tertiary sediment complex. Positive results in neighboring Hungary near Budafa in limestone rocks likely of Triassic age suggest that Md-4 should penetrate a significant portion of the Tertiary substrate profile. Based on results from Md-1, which encountered Triassic brecciated limestone likely of Triassic age, similar Triassic sediment development is expected in this area, potentially with hydrocarbon saturation. The well will examine lithofacial relationships and serve as a valuable reference point for correlation and resolving tectonic relationships on a regional scale.

3.4.1. Well Construction

Length of the borehole Md-4 channel is 3007.7 m.

Casing:

Surface casing (13 3/8") installed to 101.5 m and cemented to surface.

I Intermediate casing (9 5/8") installed to 1034.8 m and cemented to surface.

3.4.2. Drill Stem test

During the drilling of a deep exploration well, nine layers were subjected to testing operations were conducted using the Drill Stem Test (DST) method. Seven open-hole intervals were tested, with two intervals undergoing repeated testing. Two operations technically failed.

The first testing operation was conducted in the interval from 1369.5 to 1393 m. The tested sandstones belong to the upper part of the sand layers of the middle part of the Lendava Formation (middle Ratka sandstones), based on lithostratigraphic unit identification in the borehole profile. The lithology of the tested interval comprises fine-grained, poorly to moderately cemented sandstone with interbeds of marl. Hydrocarbon presence was not detected under UV light or in the fluorescence drop analysis (based on the Mechanical Core Description from a depth of 1381-1387 m and crushed rock samples description from R. Ferenčak). As lapora was obtained from the mechanical core, no physical analyses were conducted to provide insights into the reservoir properties of the tested sandstones. Formation water salinity measurements were not performed prior to the testing operation. The packer setting depth was determined based on the drilling progress chart and crushed rock samples. The formation temperature, derived from the temperature gradient between neighboring wells Md-3 and Md-21, is approximately 65 °C. The effective thickness of porous sandstones in the tested interval, determined from a subsequent micro-log diagram, is 11.0 m. The testing operation was technically successful. The packer was activated normally at the desired depth and provided a good seal. During the open tester phase, air exited intensively through the tester head nozzle at the surface. No hydrocarbon was observed on the surface. Saltwater (5.6 m³) entered the empty drill pipes, from which some gas was separated. The recorded diagram is sufficiently clear to extract all necessary data for extrapolating the pressure buildup curve and calculating parameters characterizing the reservoir and exploitation properties of the tested sandstones. The pressure curve shape indicates good permeability of the tested sandstones with significant layer damage. Initial pressure at the start of main flow was considerably distant from the baseline, although no water cushion was used. The pressure buildup during flow increases rapidly due to the low viscosity of water, leading to rapid recompression of the space below the packer when the tester opens. The final pressure buildup curve shape suggests the presence of a barrier (fracture) near the wellbore channel, visible on the extrapolated final pressure buildup curve as well. The volumetric water factor $B_w = 1.0165 \text{ m}^3/\text{m}^3$ and compressibility $C_w = 42.2 \times 10^{-6} \text{ atm}^{-1}$, derived



from the Standig and Dodson diagram as functions of temperature and pressure, while the water viscosity of 0.44 cp is defined from the Burcik diagram as a function of temperature and salinity. The calculated values for reservoir and exploitation parameters of the sandstones include a flow rate of 124.1 m³/d and a skin factor of 11.5. The damage ratio DR = 3.72 indicates the presence of skin, which has taken a significantly positive value. The effects of damage and skin are evident in the reduction of permeability in the drainage zone around the wellbore. Effective permeability decreased during drainage from K = 91.5 mD to K₁ = 28.7 mD. The theoretical potential of the tested sandstones would significantly increase if the damage were eliminated, resulting in Q₁ = Q*DR = 461.65 m³/d. The productivity index shows the formation's inherent ability to produce a relatively low value (PI = 2.56 m³/d/at). The calculated drainage radius appears unusually large (r_d = 304 m). However, if there is a barrier (fracture) near the wellbore, as discussed earlier, the drainage radius value should be smaller. The reflection of pressure buildup from an impermeable barrier account for this peculiarity. The nature and orientation of the barrier cannot be defined precisely, but it is assumed to lie within the radius of investigation. Analysis of layer water samples taken from drill pipes upon tool retrieval yielded salinities of 11.9, 12.8, 12.3, and 12.4. According to Palmer's classification, the layer water falls into Class 1 - alkaline. Gas chromatography analysis of the gas sample was also performed.

The second attempt of the next testing operation was conducted in the previously drilled interval from 1224 to 1241 m. In the lithostratigraphic profile of the borehole, the tested interval encountered sandy layers in the upper part of the Lendava Formation. Lithologically, the interval consisted of poorly cemented fine-grained sandstones with clayey interbeds. Positive hydrocarbon saturations were detected under UV light, and tests with organic solvents confirmed the presence of hydrocarbons. No mechanical core was retrieved from this interval; thus, no physical analyses were available to indicate reservoir and exploitation properties of the tested layers. The testing operation followed informative Formation Integrity Tests (FIT) measurements when the bottom of the well was at 1618 m. The packer setting depth was determined based on the diameter progress chart at the most favorable locations. The effective thickness of permeable sandstones estimated from micro-log diagrams was 16 m. The maximum temperature at the bottom of the well was 66 °C, while the temperature opposite the tested sandstones, calculated from the temperature gradient, was 49.3 °C. The testing operation employed two packers and side wall anchor jaws ("open hole straddle packer test with side wall anchor"). However, the operation technically failed. The jaws did not firmly engage the wellbore wall over a length of 30 m, preventing the required loading for packer activation. After several unsuccessful attempts, further efforts to conduct the testing operation satisfactorily were abandoned. It is regrettable that a series of unforeseen circumstances delayed testing the sand layers with positive hydrocarbon saturations soon after drilling, significantly later.

The third tested interval was at a depth of 1646.45-1670 m. According to lithostratigraphic unit identification, the tested interval encompassed the uppermost part of the sandstones in the lower Lendava Formation (Lower Ratka sandstones). The lithology of the tested interval consisted of gray fine-grained sandstones with marl interbeds at the base of the interval. No positive hydrocarbon saturations were detected within the porous sandstones (based on crushed rock samples description and mechanical core description from a depth of 1661.6 - 1665.3 m). Physical analyses of mechanical core samples provided several data points indicating relatively good porosity (19.3 and 14.4), but permeability varied (38 and 9.3). WL were not conducted immediately before the testing operation but had been performed earlier (52 m above the current bottom at 1670 m). The packer setting depth was determined based on the drilling progress chart and crushed rock samples. The temperature of the tested sandstones, determined from the temperature gradient, was 66.7 °C. The effective thickness of permeable sandstones was estimated at 11 m from subsequently logged micro-log diagrams. The testing operation only partially succeeded technically. The packer was activated normally and provided a good seal. During the open tester phase (78 min), 7.56 m³ of saltwater entered the drill pipes, from which a more significant amount of gas than usual was separated. The partial success of the operation was due to the lack of a pressure diagram. A situation similar to the Dobrovnik-1 well occurred where the hour hand mechanism jammed, preventing movement of the plate drum used to register the measured pressure. Therefore, apart from estimating that the tested



sandstones exhibit good permeability (as seen from the produced saltwater), no further conclusions can be drawn. Analysis of layer water samples taken from 37 passes of drill pipes during tool retrieval yielded a salinity of 9.5 g/l NaCl, and according to Palmer's classification, the water falls into Class 3 - hard. Gas chromatography analysis of three gas samples taken from drill pipes was also performed.

The fourth interval tested by the DST method is located at a depth of 1775.3 - 1805.0 m. It encompasses the lower slope of Lenti marl of the Lendava Formation and the uppermost part of Petišovci sandstones of the Mura-Sobot Formation. Lithologically, the interval consists of interbedded medium-hard sandy marl and moderately cemented fine-grained sandstone with thin intercalations of marl. No positive hydrocarbon saturations were observed (according to the mechanical core description from a depth of 1787.3 - 1788.7 m and the description of crushed rock samples from the cuttings). Physical analyses of the sandstones retrieved from the mechanical core were not conducted due to the destruction of samples in a traffic accident. WL were not performed before the operation. The packer setting depth was determined using drilling progress charts and crushed rock samples. The formation temperature determined by temperature gradient was 72 °C. The effective thickness of the permeable layer was estimated at 10.0 m from micro-log diagrams. The testing operation was technically successful. Tools were deployed to the bottom, and the packer was activated at the desired depth, providing satisfactory sealing. During the open tester phase (60 min), a negligible influx of saltwater (5.28 m³) entered the empty drill pipes. Upon retrieving the tools to the surface, it was found that the pipes contained 580 l of cuttings slurry, likely mixed with infiltrate. No gas was observed. The recorded diagrams were clear, indicating sufficient data for extrapolating the pressure buildup curve and calculating other parameters characterizing reservoir and exploitation properties of the tested sandstones. The shape of the pressure buildup curves suggests that the Petišovci sandstones tested have significant permeability. Due to the sharp pressure increase upon closure, it can be concluded that the drainage zone was damaged. Extrapolated pressure buildup curves indicate slight overpressure (bottom gauge 0.7 atp, top gauge 1.3 atp). Extending the first flow phase by a few minutes could have eliminated this overpressure. Formation volumetric water factor $B_w = 1.0156 \text{ m}^3/\text{m}^3$ and water compressibility $C_w = 42.2 \times 10^{-6} \text{ at}^{-1}$ were determined from Dodson and Standig diagrams as functions of temperature and pressure. Viscosity determined from Burcik diagrams as a function of salinity and temperature was $\mu = 0.39 \text{ cp}$. The analysis yielded a flow rate of 126 m³/d and a skin factor of 18.4. Earlier noted formation damage along the borehole channel zone is confirmed by a damage ratio $DR = 2.85$, indicative of a skin effect. The skin size ($S = 18.4$) indicates altered reservoir properties near the borehole channel. The permeability of the tested sandstones decreased from 78.4 to 27 mD. (Whether this reduction is due to drilling operations or formation flow is difficult to ascertain). It is likely that damage occurred due to slurry infiltrate entering the formation, creating a cake on the borehole walls, possibly exacerbated by solid particles from the slurry and cuttings. It is possible that damage to the tested sandstones occurred due to increased clay content from slurry filtration. The calculated drainage radius is significantly large ($r_d = 290 \text{ m}$). Given that earlier tested sandstones had similar large testing radii ($r_d = 304 \text{ m}$), it can be concluded that these values reflect good reservoir and exploitation properties of the tested deposits. The theoretical potential of the Petišovci sandstones tested would be substantial if no damage had occurred, amounting to $Q_1 = Q \cdot DR = 360 \text{ m}^3/\text{d}$. Analysis of layer water samples from 12 passes yielded a salinity of 21.85 g/l NaCl, classified as Class 3 - hard water by Palmer's analysis. Gas chromatography analysis was also conducted, indicating a significant presence of air due to poor sealing of the gas trap.

The fifth tested interval is at a depth of 1984.3 - 2008.0 m. According to lithostratigraphic unit identification, the interval belongs to the Mura-Sobot Formation and microfossil findings indicate it is part of the Miocene. Lithologically, it is represented by weathered limestone and medium-hard sandy marl interspersed with calcite veins. No hydrocarbon presence was noted (based on description of cuttings samples and mechanical core description from a depth of 1989 - 1993.5 m). As these are rocks with secondary porosity, no physical analyses were conducted. WL were performed prior to the testing operation. The measured temperature at the bottom of the well was 82 °C. The effective thickness of permeable rocks was estimated at 8.0 m from micro-log diagrams. The packer setting depth was also determined based on WL



measurement diagrams. The testing operation was technically successful. Tools were lowered to the bottom and the packer was activated at the desired depth. The sealing was satisfactory. During the open tester phase (60 min), a negligible influx was observed in the empty drill pipes. Upon retrieval, it was found that the pipes contained only 580 l of cuttings slurry, likely mixed with infiltrate. No gas was observed. The recorded diagram was clear, but it showed that the pressure buildup curves, ICIP and FCIP, did not stabilize. The characteristics of the diagram indicate that the pressure at the first closure increased rapidly but did not stabilize. The inflow was very small, and the pressure at the second closure increased slowly and would stabilize for a much longer time than measured. Overall, the pressure measurement times should have been longer than normal for rocks with primary porosity. The small pressure increase during the inflow measurement suggests that the formation has very low permeability. This is also indicated by the calculated values, from which the formation volumetric factor for water, $B_w = 1.033 \text{ m}^3/\text{m}^3$, and compressibility, $C_w = 42.2 \times 10^{-6} \text{ at}^{-1}$, were determined from Standig and Dodson diagrams. The viscosity was determined from Burcik diagrams as $\mu = 0.37 \text{ cp}$. The entire calculation is an approximation because the influx was negligible (580 l of cuttings slurry mixed with infiltrate), and this quantity was taken as the inflow from the layer, which is not realistic. L. F. Maier in the article "Recent developments in interpretation and application of formation test data using the DST method" recommends in such cases to consider the filtrate as hydrocarbons rather than formation water, as this would likely yield more accurate values for effective permeability. However, this recommendation was not followed this time because there was no trace of hydrocarbons in the influx. The calculated values yielded a flow rate of $14.65 \text{ m}^3/\text{d}$ and a skin factor of 48. A very high damage ratio $DR = 15.87$ indicates the presence of a skin effect, which has taken on a very high positive value of $S = 48$. The skin value indicates that the properties of the collector near the borehole channel have been altered, resulting in reduced permeability. Since these are collectors with secondary porosity, it is likely that the damage occurred during drilling, when slurry infiltrated into fractures, carrying with it cuttings particles. This filled the fractures of the collector in the damaged zone along the borehole channel. The theoretical potential of the tested deposits would have been significant if no damage had occurred, amounting to $Q_1 = 232.5 \text{ m}^3/\text{d}$. The drainage radius is a small value, measuring only 6.4 m.

The sixth test was conducted after the well was deepened by 35.7 m. The interval tested ranged from 1981.7 to 2043.7 m. Lithologically, there were no significant changes observed. This marked the first recent testing of a 62 m interval in the Pannonian Basin using the conventional method of tool reliance at the bottom of the well. Sealing was achieved with a single packer and was satisfactory. The packer's placement was determined based on previously recorded microlog data. Electrical conductivity (WL) logs estimated the effective thickness of the tested interval's permeable layers to be 19.5 m. During the open-hole test (150 min), there was a very small inflow into the blank drill pipes. Apart from the drilling mud (650 l), approximately 600 l of slightly saline water, likely infiltrated drilling mud, also entered the pipes. No hydrocarbons were detected. Recorded pressure diagrams were clear, containing all necessary data for extrapolating the pressure buildup curve. However, due to the use of the "CIPV" tool instead of "DUAL," initial flow and initial reservoir pressure data were absent. Despite a slight pressure increase during flow, visual inspection of the diagrams suggests that the pressure buildup curve did not stabilize within the measurement period (60 min). From known diagrams by Standig and Dodson, the formation water volumetric factor $B_w = 1.033 \text{ m}^3/\text{m}^3$ and compressibility $C_w = 43 \times 10^{-6} \text{ at}^{-1}$ were determined, with viscosity $\mu = 0.36 \text{ cp}$ from the Burcik diagram. Calculations yielded flow parameters of $5.76 \text{ m}^3/\text{d}$ and skin of 29.21. These values indicate that the reservoir pressures in the previous and current intervals were very close. The damage here was nearly 50% less than previously, suggesting partial recovery of the formation from damage. However, this was insufficient to significantly alter permeability, and despite being more open (effective thickness 19.5 m compared to earlier 8 m), the formation did not yield a higher inflow. The increased drainage radius also supports this conclusion. The nature of the damage remains consistent with previous intervals, likely due to drilling operations and mud infiltration. Water sample analysis during drainage indicated a salinity of only 4.4 g/L NaCl.



The seventh and eighth tests were conducted at depths of 2689.75 - 2713.7 m, repeated due to inadequate sealing during the first attempt. After wellbore cleaning, the same interval was tested again after being deepened by 4 m (2693.35 - 2717.7 m). This interval also belongs to the Mura-Sobot formation (based on lithostratigraphic identification). Lithologically, it consisted of light gray chert intercalated with thin layers of dark gray marl. UV examination of cuttings from the 2712.5 - 2713.7 m depth revealed the presence of hydrocarbons, fluorescing orange to golden yellow. However, physical analyses were not performed due to the secondary porosity of the rocks. WL measurements were taken (10 m before interval, but 15 days earlier) prior to the DST operation. The bottomhole temperature calculated from the temperature gradient was 108.7 °C. Packer placement was determined using drilling progress diagrams and cuttings samples from the drilling mud. The operation was technically successful on the second attempt using two packers, achieving satisfactory sealing. During initial flow, there was a minimal release of air through the surface choke. No air was observed after ICIP measurement during the main flow. Approximately 800 l of drilling mud entered the blank drill pipes, with a few gas bubbles noted. Pressure diagrams clearly showed no pressure increase during flow, suggesting that registered pressures were not actual reservoir pressures but likely due to mud invasion through fractured zones outside the packers. If the registered pressures were real reservoir pressures, there would have been an inflow into the pipes with pressure buildup observed during flow. In any case, pressure diagrams were unreliable and could not be correctly interpreted. Attempts to analyze the liquid sample failed due to its gel-like state, making filtration for analysis impossible. The tested interval can be considered unproductive – "dry".

The final test investigated an interval at depths of 2962 - 2985.0 m, belonging to the Mura-Sobot formation. Lithologically, the interval comprised fine-grained, tightly cemented but fractured quartz sandstones. Some fractures were filled with calcite, and hydrocarbons were observed under UV light fluorescing pale to golden yellow. Luminescent-droplet analysis confirmed the presence of hydrocarbons (according to mechanical core descriptions from depths 2978.3 - 2980.3 m and 2980.3 - 2981.9 m). Physical analyses of the mechanical core were not conducted for known reasons. WL measurements were not taken immediately prior to the DST operation but were conducted earlier (10 m prior and 15 days earlier). The temperature at the bottomhole was calculated to be 119 °C using the temperature gradient. Packer placement was determined based on drilling progress diagrams and cuttings samples from the drilling mud. The operation was technically successful using two packers stacked one above the other, achieving satisfactory sealing. During initial flow, a few air bubbles exited through the surface choke. After ICIP measurement, no surface manifestations were observed during the main flow. Over the 102-minute open-hole test, approximately 20 l of drilling mud entered the blank drill pipes due to packer rubber compression. Recorded pressure diagrams were completely clear, showing no increase in either static or flow pressure. The upper pressure gauge showed a flat line, aligning with the zero line. The lower gauge showed a shift from the base line, attributable to the column of drilling mud. There was no pressure increase, indicating that the tested interval was "dry," unlike any observed previously in practice.

3.4.3. Geological-Geophysical Works and Special Operations

Thanks to the previously mentioned results in Selnica and Peklenica, surface exploration activities were focused in these areas as well as neighboring regions in Hungary. Initially, the area was surveyed using gravimetric measurements. A prominent gravimetric maximum was indicated on the gravimetric map at Selnica - Peklenica. From there, towards Mura-Sobot and Petišovci, a distinct gravimetric anomaly separated, which was investigated by the deep well Pt-1 confirming positive saturations in the Ratka and Petišovci sandstones. During the war, Pt-2 and Pt-3 were drilled, both also proving positive. After the war, work resumed with deep drilling activities primarily in the Petišovci area. However, apart from drilling in the already discovered Petišovci oil and gas field, extensive exploration efforts were not pursued. Existing gravimetric maps were supplemented with measurements in initially unexplored areas, namely the Lendava Hills and Murski Gozd. Geological mapping was also conducted in Lendava Hills and Urban - Selnica. Until



the introduction of seismic methods in 1955, in addition to the aforementioned surface exploration activities, deep drilling was also carried out at Sitnica (1955) and Mđ-1 (1955 - 1954).

The introduction of seismic surveys as a new exploration method marked a new era in oil and gas exploration in the Međimurje region. By 1957, Nafta Lendava conducted the first seismic surveys mainly in the Selnica - Peklenica anticline area. The following year, in 1958, gravimetric measurements and regional seismic profiling were conducted east of Čakovec.

During the deep exploratory well Mđ-4, continuous geological supervision was maintained during drilling. Samples were taken from the drilling mud starting from 200 to 3007.7 m, every 5 m down to the final depth. Mechanical core samples were taken 27 times and retrieved successfully 24 times. Sedimentary rock cores were analyzed based on drilling progress and changes in lithological composition of cuttings, aiming to study reservoir rocks and shale for their cap rock properties and determining conductive fauna. After examination and description, the core material was sent to relevant departments for the following analyses:

- a) physical testing
- b) micropaleontological testing
- c) sedimentological testing
- d) petrographic testing
- e) luminescence-bitumen testing

Well logging was conducted five times. The first measurements were made in 1967 down to a depth of 1043 m, preceding the installation of the 9 5/8" technical casing. The second measurements were carried out on January 22, 1968, down to a depth of 1618 m, serving an informative purpose. The third measurements were made in 1968 down to a depth of 2009.5 m. The fourth measurements were taken to a depth of 2679 m, and the fifth and final measurements were completed in 1968 to a depth of 3010 m.

3.4.4. Conclusion of Drilling Mđ-4

The deep exploratory well Mđ-4 successfully fulfilled its mission. The following formations were drilled through: Mura Formation, Lendava Formation, and Mura-Sobot Formation, where drilling was halted. All pertinent layers were drilled through and their lithological composition as well as reservoir properties were examined. However, no economically significant hydrocarbon saturations were discovered in well Mđ-4. Only traces of gas were detected, which separated from saline water during the Drill Stem Test (DST) in the G. and D. Ratka sandstones.

3.5. Well Mihovljani-1

The location of the deep exploratory well Mihovljan-1 (Mih-1) is approximately 1500 m north of the Čakovec - Pribislavec asphalt road. It is approximately 1400 m southwest of the nearest deep exploratory well Mđ-4.

The approximate coordinates of the well are:

$$y = 6,613,650$$

$$x = 5,141,470$$

$$h = 175 \text{ m}$$

The exploration site Mihovljani is situated in the Čakovec zone of the Mura Depression. Based on structural maps obtained through reinterpretation of old data and interpretation of the latest seismic profiles (S. Miše,



M. Kisovar, 1974), as well as results from deep exploratory wells such as Ča -1, Mđ -1, -3, -4, and -6, Si -2, Se -1, the current structure of Mihovljani has been determined. The structure forms an anticline oriented with its longer axis running northwest-southeast, with some deviations bending towards the southeast.

The Mihovljani site was covered by superregional gravimetric surveys of northern Croatia conducted between 1940-1942. These were the initial exploration efforts in this area. Post-World War II, more extensive exploratory work was carried out using newer geophysical methods. Gravimetric measurements were conducted in 1959. Photogeological interpretation also covered the area between Čakovec and the Mura River. The first seismic profiling was done in 1958/59. The seismic network was expanded with profiles recorded during 1965/66, including those directly over the Mihovljani site. The latest seismic profiles were recorded and processed using digital techniques in 1971 and 1973.

The Međimurje region is renowned for its oil and gas discoveries, marking it as one of the oldest petroleum fields not only in Croatia but also in Europe (Selnica, Peklenica). Initial exploration efforts in this region involved digging wells as the primary method for discovering hydrocarbons, starting in 1880. Drilling methods evolved from well digging to percussion drilling and eventually rotary systems. These drilling activities continued intermittently until 1939.

Adjacent to the Mihovljani site, northeast, a series of supportive deep exploratory wells were drilled. The first of these was Mđ-1 in 1954. Later, Ča-1 was drilled southwest of this site in 1959. Deep exploratory drilling was reactivated in 1966 with Mđ-2, followed by Mđ-3 in the next year. Mđ-4 and -5 were drilled in 1968, and Mđ-6 in 1969. Mđ-1 and -2 did not show significant hydrocarbon presence, except for minor gas traces in the Ratka sandstones of the Mura-Sobot Formation. Mđ-3 indicated only traces of oil in the Tertiary Substrate, as did Mđ-4 in the Petišovci sandstones. No hydrocarbons were found in Mđ-5, while Mđ-6 detected gas traces.

The closest well to the Mihovljani site is Mđ-4, which was tested using the Drill Stem Test (DST) method during drilling. Seven intervals were tested during this operation.

At the Mihovljani site, prospective gas deposits have been identified in the Paka sandstones, as well as in the Upper Ratka and Lower Ratka sandstones. There are presumptions of hydrocarbon formations in the Petišovci sandstones, and potentially in the Čentiba and Međimurje members of the Mura-Sobot Formation. The cap rocks of these potential hydrocarbon reservoirs consist of marl from the mentioned formations. The prospective hydrocarbon deposits are of an anticlinal-lithological type.

3.5.1. Well Construction

The length of the borehole Mih-1 is 1990.6 meters.

Casing:

Surface casing (13 3/8") installed to 120 m and cemented to surface.

I intermediate casing (9 5/8") installed to 1259 m and cemented to surface.

II intermediate casing (5 1/2") installed to 1790 m

3.5.2. Drill Stem Test

Deep exploration well Mihovljan-1 (Mih-1) underwent a Drill Stem Test (DST) in the interval 1615.00 - 1625.30 m, which belongs to the Petišovci sandstones of the Mura-Sobot formation according to lithostratigraphic classification. The tested reservoir consists of gray sandstone with millimeter-scale laminations, moderately to poorly cemented, fine to medium-grained. Physical analyses indicated



permeability ranging from 0.0 to 711.9 mD and porosity from 7.3 to 29.7%. Upon entry into the layer, gas concentration in the flow increased to 0.7% (GD-11), accompanied by detection of lighter and heavier hydrocarbon homologues (C3, C4) on the chromatograph.

The testing aimed to gather pressure data from the formation, assess reservoir quality, and obtain formation fluid samples. Tools were set at the wellbore bottom with a single packer, based on data from the "Operational Geological Diagram". Testing times were regulated by a Dual cip valve, and pressure was recorded using a single downhole gauge due to lack of steel tapes. Both flows were characterized by a significant intensity: initially air, followed by combustible gas after 7 minutes, reaching a maximum surface pressure ahead of the choke of 9.52 mm from 40 PSI (2.81 atm). After 49 minutes of flow measurement, oil surfaced at a maximum pressure of 170 PSI (11.95 atm), yielding approximately 10.5 m³ of heavy paraffinic oil.

Five gas samples were taken and analyzed at the Central Laboratory, revealing a composition dominated by C₁ (59.9 - 71.3%), with significant amounts of N₂ (5.145 - 5.668%) and higher hydrocarbons (0.525-1.045%).

The entire operation was accurately recorded on the depth gauge chart. Pressure reduction was observed during initial and subsequent gas inflows. During the lower flow measurement, pressure increased after initial decline, concurrent with oil eruption. The reservoir pressure attained maximum values within minutes during both flow tests, facilitating robust extrapolation. Based on diagrams and a calculated well production rate of 240 m³/day, additional values were computed. The average effective permeability was determined at 211.7 mD, correlating well with physical analyses.

During the 64-minute flow, the formation was drained within an approximate radius of 2057 m, without barriers except for observed damage inferred from a calculated damage factor of 0.525, indicating significant formation impairment. Considering all data and calculations, the tested oil-saturated sand horizon exhibits favorable reservoir properties. Consequently, the well is recommended to be completed with a 5 ½ " production casing to 1790 m depth and transferred to OOUR Remont for further evaluation.

3.5.3. Geological-Geophysical Works and Special Operations

The exploration site Mihovljani had not been previously explored by deep drilling. The first exploration well, Mihovljani-1 (Mih-1), was located in the central part of the Mihovljani anticline. Its primary task was to drill and test the sequence of Tertiary deposits, including a significant portion of the Mura-Sobot formation, to determine the potential presence of hydrocarbons. The well successfully accomplished its task and was completed with a production casing.

During drilling, continuous geological supervision was conducted with the presence of a field geologist. Samples were taken every 5 meters, examined under UV light and with the use of LKT (Litho-Kaleidoscope-Tomography). An operational geological diagram was prepared. Ten mechanical cores were retrieved, totaling 60.2 meters, with a recovery rate of 50.9 meters or 80.50%. All cores were thoroughly examined for hydrocarbon content. Core samples were sent for physical, sedimentological, micropaleontological, macropaleontological, and bitumen analyses. At approximately 680 meters depth, a gas station was installed, and gas logging was performed down to the bottom of the well using instruments such as a speedograph, chromatograph, and detector. Electric logging measurements were conducted before installing the technical casing at 1262 meters depth, informative electric logging measurements at 1688.0 meters, and final logging after completion of drilling at 1987.0 meters depth. The Drill Stem Test (DST) method was applied to test the interval 1615.0 - 1625.5 meters, yielding 10.5 cubic meters of oil and substantial quantities of combustible gas.

The deep exploration well Mih-1 on the Mihovljani structure discovered commercial oil reserves in the Petišovci sandstones of the Mura-Sobot formation, as well as slight traces of oil and gas in the Međimurje member of the same formation. The Petišovci sandstones consist of fine-grained, moderately cemented,



tuffaceous sandstones interbedded with thin layers of moderately hard sandy marl (continuous core intervals: 1612.0 - 1619.0; 1619.0 - 1625.0; 1625.0 - 1634.0). The gas station recorded weak gas manifestations, with a maximum 0.7% relative gas concentration detected on the detector, and heavier hydrocarbon homologues C₃ and nC₄ were observed on the chromatograph.

3.5.4. Conclusion of Drilling Mih-1

The deep exploration well Mih-1 has successfully fulfilled its objectives. It penetrated through the Mura Formation, Lendava Formation, and a segment of the Mursko-Sobotska Formation where drilling was halted. Based on sieve samples, mechanical cores, and interpretation of electric log diagrams, several sandstone series were identified: Paka Sandstones, Lower Ratka Sandstones, Siget Sandstones, and Petišovci Sandstones. The Petišovci Sandstones are identified as hydrocarbon-bearing reservoirs. The correlation between deep exploration well Mih-1 and Mđ-4 is strong. Stratigraphically, the development at Mih-1 is shallower compared to Mđ-4, with deeper lithostratigraphic units recorded. Through the drilling of deep exploration well Mih-1, which correlates with nearby wells such as Mđ-4, Ma-5, and Ma-6, a complex sequence of Pliocene-age deposits was penetrated, likely reaching into Miocene sediments before drilling was halted. The results from well Mih-1 confirm significant hydrocarbon accumulation in the Petišovci Sandstones within the central part of the Mihovljani anticline. Further evaluations during the well's production phase and subsequent exploration activities will determine the site's prospectivity.

3.6. Well Mihovljani-2

The location of the deep exploration well Mihovljan-2 (Mih-2) is situated east of the road leading from the village of Pribislavec to M. Rok in Međimurje. It is approximately 950 m southeast of the first deep exploration well Mihovljan-1. The approximate coordinates of the well are:

$$y = 5,614,568$$

$$x = 5,141,365$$

$$h = \text{approximately } 170 \text{ m}$$

The Mihovljan exploration site is located in the Čakovec zone of the Mura Depression. The structure is an anticline with its longer axis trending generally west-east, with some deviations dipping towards the southeast. The first exploration well, Mihovljan-1, is located on the western part of the anticline summit, while Mihovljan-2 is situated on the actual crest of the anticline. The primary objective of the well was to drill and examine the Tertiary sediment profile, including a significant portion of the Mura-Sobot Formation (potentially penetrating the Međimurje Member) and to determine the development of pre-Tertiary rocks. Additionally, it aimed to assess the presence of hydrocarbons in the Mihovljan structure and to ascertain the extent of the identified oil field from well Mih-1 towards the east.

The structural and geological relationships of the Mihovljan locality were first analyzed in the regional study "Tectonic Structure of the Mura Basin" and later in the geological survey for well Mđ-4, including reinterpretations using recent seismic profiles and data correlations from WL diagrams of wells Ča-1, Mđ-1, -3, -4, and -6, Si-2, and Sel-1. The anticlinal structure of Mihovljan has a predominant west-east axis with some southeastward dips. The anticlinal shape is not consistently formed in all lithostratigraphic units according to structural maps, with distinct occurrences in the Peklenica Member of the Lendava Formation, as well as within the roof of the Paka Sandstones of the same formation and in the roof of the Petišovci Sandstones. The summit part of the anticline is located in its central part. The Mihovljan structure comprises Tertiary sedimentary deposits identified in the Ormoško-Selnička Zone, specifically the Mura, Lendava, and Mura-Sobot Formations. It was observed that some sandstone layers are absent. Based on the results from the first well Mih-1, formations such as Paka, Lower Ratka, Siget, and Petišovci Sandstones were developed.



Notably, the Upper Paka Sandstones were not identified, but the development of the Međimurje Member was significantly thicker than previously assumed. There was no presence of Benica marl and Čentiba Member of the Mura-Sobot Formation, instead of which the mentioned Međimurje Member was developed.

The first deep exploration well Mih-1 at the Mihovljan site confirmed the presence of significant quantities of oil in the Petišovci Sandstones. Oil occurrences were also identified in the Međimurje Member. Prospective gas reservoirs are anticipated in the Paka, Lower Ratka, and Siget Sandstones. The hydrocarbon deposits in the Mihovljan structure are of anticlinal-lithological type. The cap rock isolating the established and prospective hydrocarbon reservoirs comprises marl from the aforementioned formations.

At well Mih-2, two hydrocarbon-bearing members can be distinguished: the Siget and Petišovci Sandstones. Physical analyses yielded permeability values (up to 107.8 mD) and porosity (up to 28.3%), which do not represent favorable reservoir properties.

3.6.1. Well Construction

The length of the borehole channel of well Mih-2 is 2967 meters.

Casing:

Surface casing (13 3/8") installed to 308,33 m and cemented to surface.

I Intermediate casing (9 5/8") installed to 1786 m and cemented to surface.

3.6.2. Drill Stem Test

The initial test in the open channel of well Mihovljan-2 was conducted in the interval 1571.80 - 1579.50 m. According to lithostratigraphic classification, this interval belongs to Siget sandstones (rather than Petišovci sandstones as previously assumed before WL measurements). The tested sandstones are poorly to moderately cemented, exhibiting good reservoir properties, with thin horizontal layers of shale. No traces of positive saturations were detected under UV light. Upon encountering the layer, the relative gas concentration in the mud log peaked at 64%, with an absolute concentration of 4.3% confirmed by VMS analysis, indicating a potentially gas-bearing horizon. Prior to testing, no WL measurements were conducted, thus packer placement was determined based on operational geological diagrams. Testing was performed with bottomhole packer support using a DUAL valve. Immediately upon packer activation, a strong air flow erupted to the surface, followed by the appearance of gas within 4 minutes. The gas flow pressure at the surface rose sharply within the first 15 minutes, then gradually decreased, stabilizing at 71.73 atm after 55 minutes of flow measurement. During the first flow, intermittent small amounts of gasoline were observed. After initial static pressure measurement, the rods were pulled out, and the DUAL valve was opened for the second flow measurement. The pressure buildup at the surface was faster compared to the first measurement, reaching 70% of the final value within 10 minutes and stabilizing at 79.47 atm after 50 minutes, which was 7.74 atm higher than the first flow. Only 100 dm³ of mud log mixed with gasoline was recovered from the rods during retrieval. Upper and lower depth gauge charts were recorded accurately, showing well-developed initial and final static pressure curves. The formation temperature was not directly recorded but was calculated from the temperature gradient (67.4 °C). Gas flow parameters were computed using gas influx formulas, excluding the gasoline as it was recovered in negligible amounts. Gas samples were taken at the surface during the first flow measurement, revealing significant variability in CO₂ content affecting gas specific gravity. Pressure extrapolation indicated non-intersecting static pressure gradients during the first flow, suggesting the formation did not fully unload the overpressure caused by the hydrostatic pressure of the mud log. Calculations based on extrapolating the final static pressure of the lower depth gauge resulted in a gradient with a slight inclination of 3.11 atm per cycle. Assuming production stabilized by the end of the second flow, the well calculated to deliver 76,354 Nm³/day at a 9.52 mm choke.



The average effective permeability of the tested horizon was determined as 20.4 mD, aligning well with physical core analysis results showing an average permeability of 31 mD from 18 samples. Slightly higher permeability in physical analysis reflects preferential sampling of more permeable sections of the sandstones. The zone within a 14.1 m radius around the borehole was assessed during 110 minutes of flow measurement, showing no observable barriers. Based on the damage ratio calculation ($DR = 8.02$), the formation appears significantly damaged; if remedied, the well could potentially yield a minimum of 822,970 Nm³/day. The calculated potentiometric surface based on hydrostatic gradient indicates a minor overpressure, enhancing its petroleum geological prospects. Due to observed gasoline dispersion, calculated productivity may be overestimated by approximately 10%, warranting adjustment for a more accurate estimation. The neighboring well Mih-1 did not exhibit positive saturations in the tested sandstone layer. At its current exploration stage, certainty regarding whether this sandstone interval exclusively contains gas or represents a gas cap over an oil layer cannot be determined. Nonetheless, the tested interval presents an economically attractive prospect, with potential for oil saturation in deeper parts of the structure.

The second testing interval at well Mihovljan-2 covered depths from 1665.8 to 1679.0 m, which, according to lithostratigraphic classification, belongs to Petišovci sandstones. Within this interval, the reservoir comprises medium to poorly cemented grayish-tinted sandstones of medium grain size. Physical analyses indicate permeability ranging from 0.0 to 107.8 mD and porosity from 9.2% to 28.3%. Under UV light, the sandstones generally exhibited negative fluorescence, except for sporadic positive saturation intervals up to several centimeters thick. Upon entering the layer, gas in the mud log increased to a maximum of 4.6%. At a neighboring well, Mih-1, a hydrocarbon-bearing sand layer was encountered at 1614.5 m depth. In this well, the same layer was drilled structurally deeper, leading to the assumption, based on all indications, that the sandstone was water-saturated. Testing was conducted to gather data on layer pressures, reservoir quality, and to obtain fluid samples. Anchored at the bottom with a single packer, unfortunately using a CIP valve, only one flow measurement was taken, manifesting moderate air discharge intensity at the surface. After 20 minutes, air discharge intensity significantly decreased, with only occasional bubbles towards the end of flow, prompting closure of the CIP valve to prevent equalizing flow and static pressures. No gas appeared at the surface during flow. Upon retrieving the tool, there was no obstruction, and the driller's meter indicated eight load lines higher than before. During the 59-minute flow measurement into empty drilling rods, 50 passes of fluid were recovered, with the first two passes being mud log and the rest being gas-saturated formation water. Water samples were taken at 20, 11, and 1 pass, and gas samples separated from water were taken at 37, 26, and 1 pass. Given the significant water volume of 8.8 m³, the sample was sufficiently clean for a representative analysis. The water had a moderate salinity of 23.55 g/l NaCl and specific gravity of 1.018. The dissolved gas composition was dominated by C1 (83-85%) and CO₂ (4.7-9.5%), with higher fractions represented in smaller percentages. Both upper and lower depth gauges recorded the entire operation accurately. The inflow into the rods was initially intense and uniform but later encountered backpressure from the water column, causing a slight curvature in the inflow line. Consequently, pressure differences in the first 35 minutes of flow, when inflow was mostly uniform, were used in the well capacity calculation. After 54 minutes, the static pressure curve fully developed, facilitating excellent extrapolation. Based on the diagram and calculated well production of 192 m³/d, other values were derived: The average effective permeability is 16.64 mD, which aligns well with physical analysis results. The layer was drained within an approximate radius of 9.55 m during the 59-minute flow. Unfortunately, due to the use of a CIP, the presence of any barriers (either lithological or tectonic) within this radius cannot be determined. Based on extrapolated static pressure values, a potentiometric surface of 202 m was calculated. However, this value is not entirely accurate due to uncertainty regarding the presence of overpressure caused by mud log action on the layer. With a calculated damage factor of 1.47, indicating minor formation damage, remedying this would increase well capacity to 282.24 m³/day. Based on all obtained and calculated data, it can be concluded that the tested sand horizon at this well is water-saturated and structurally part of the watered-out section of the oil layer in the Mihovljan structure. The sandstone exhibits good reservoir properties, suggesting potential future use of this well as an injection well for water flooding operations.



3.6.3. Geological-Geophysical Works and Special Operations

During drilling, continuous geological monitoring was conducted. Samples were taken every 5 meters, examined under UV light and with the LKT tool. An operational geological diagram was constructed. Ten mechanical cores were retrieved, totaling 45.7 meters in length, with 91% recovery (41.57 m). All cores were thoroughly examined for hydrocarbon content. Core samples were sent for physical (51), sedimentological (49), micropaleontological (36), macropaleontological (8), and bitumen (93) analyses. At a depth of 928 meters, the gas station was activated, and gas logging was performed to the bottom of the well. Instruments including a speedograph, chromatograph, and detector were operational. Informative electrical logs were conducted before installing the production casing at 1790 meters, and final electrical logs were conducted after completing the well to a depth of 2967 meters. DST testing was performed on intervals 1571.8 - 1579.5 meters (yielding 76,354 Nm³/day of gas) and 1665.7 - 1679.2 meters (yielding 8.8 m³ of water and traces of gas).

3.6.4. Conclusion of Drilling Mih-2

Deep exploration well Mihovljan-2 penetrated the Mura, Lendava, and part of the Mura-Sobot formations. The well reached the Međimurje member of the Mura-Sobot formation at a depth of 2967 meters. The Mihovljan structure is an anticline with a normal sequence of Tertiary deposits. Two sandstone layers were drilled, which are hydrocarbon-bearing reservoirs: Siget and Petišovci sandstones. Testing in the Siget sandstones indicated significant gas accumulation. However, no oil was obtained from this well despite expectations and good correlation with Mihovljan-1. The extent and size of the oil reservoir discovered by Mihovljan-1 will only be determined after studying and interpreting data from drilling new exploration wells at the Mihovljan site.

3.7. Well Mihovljani-3

The location of the deep exploration well Mihovljan-3 is on the west side of the road leading north from the village of Pribislavac towards well Mih-1. It is approximately 1000 meters south of the Mih-1 well. The approximate coordinates of the well are:

Y = 5,613,700

X = 5,140,450

h = approximately 170 meters

The exploration site Mihovljan is situated in the Čakovec zone of the Mura Depression. The structure is shaped like an anticline, with its longer axis generally trending west-east, with some deviations veering towards southeast. The first exploration well, Mih-1, is located on the western part of the anticline crest of Mihovljan, while Mih-2 is positioned at the very top of the anticline. Mih-3 is located on the southern flank of the anticline. This flank is slightly depressed compared to the northern part along faults that run parallel to the anticline.

The objective of well Mihovljan-3 was to drill and examine the profile of Tertiary deposits up to and including a significant portion of the Mura-Sobot formation. Additionally, it aimed to determine the potential presence of hydrocarbons and to investigate the horizontal extent of the discovered oil reservoir from well Mih-1 towards the south.

3.7.1. Well Construction

The length of the borehole channel of well Mih-3 is 1862.4 meters.



Casing:

Surface casing (13 3/8") installed to 84,9 m and cemented to surface.

I Intermediate casing (9 5/8") installed to 502,5 m and cemented to surface.

3.7.2. Geological-Geophysical Works and Special Operations

During drilling, continuous geological monitoring was conducted. Samples were taken every 5 meters, examined under UV light and with LKT. An operational geological diagram was created. Three mechanical cores were extracted with a total length of 18.0 meters, yielding 17.8 meters, i.e., 98%. All cores were thoroughly examined for hydrocarbon content. Core samples were sent for sedimentological (19), micropaleontological (9), and bitumen (18) analyses.

- Core J-1 (1276.5 – 1285.5 m), UV shows no traces, CHCl₃ negative.
- Core J-2 (1624 - 1632 m), UV shows no traces, CHCl₃ negative.
- Core J-3 (1861.5 – 1862.4 m), UV shows no traces, CHCl₃ negative.

At a depth of 164 meters, a gas station was activated, and gas logging was performed to the bottom of the well. Instruments used included a spidograph, chromatograph, and detector.

Indicative WL measurements were conducted before installation of the production casing to a depth of 505.5 meters, and final WL measurements were taken after completion of the well to a depth of 1863.5 meters. DST testing was not performed. The final depth of the well is 1862.4 meters as per drilling rods, or 1863.5 meters according to WL measurements.

3.7.3. Conclusion of Drilling Mih-3

The deep exploration well Mih-3 penetrated the Mura, Lendava, and part of the Mura-Sobot formations. Drilling was completed in the Međimurje member of the Mura-Sobot formation at a depth of 1862.4 meters according to drilling rods. The Tertiary deposits are in normal succession up to and including the Petišovci sandstone equivalent of the Mura-Sobot formation. There is a unconformity between this member and the Međimurje member, where the Benica marl and Čentiba member are missing. The bottom of the Međimurje member was not penetrated. The sandstone series, which are hydrocarbon-bearing units at Mih-1 (Petišovci sandstones - oil) and at Mih-2 (Siget sandstones - gas), exhibit a shaly development here and contain only small amounts of gas (up to 0.7% relative gas concentration in the mud gas). The well deviates approximately 60 meters from the planned profile shallower. It was decided to deviate the well at a depth of 600 meters to achieve a lateral distance from the vertical wellbore of 400 - 450 meters at a depth of 1600 meters.

3.8. Well Mihovljan-3 α and Mihovljan-3 β

The deep exploration well Mihovljan-3 (Mih-3) is located on the western side of the road leading from the village of Pribislavec northwards towards well Mih-1.

Approximate coordinates of the well are:

Y = 5,615,700

X = 5,140,450

h = approximately 170 m



Well Mih-3 α is oriented at a depth of 591 m with a specified azimuth of N 15° E.

Well Mih-3 β is oriented at a depth of 515 m with a specified azimuth of N 38° W.

The exploration site Mihovljan is located within the Čakovec zone of the Murska Depression as a separate structural feature - the Mihovljan anticline. It has an elongated shape, with the longer axis of the anticline trending predominantly west-east across most horizons. The position of the anticlinal crest shifts depending on the depth of burial of individual lithostratigraphic horizons, ranging from west to east or in some cases from north to south.

The objective of directional wells Mih-3 α and Mih-3 β was to penetrate the Siget and Petišovci sandstones, which are expected to have more favorable lithological development compared to Mih-3. At Mih-3, the Siget sandstones are shale-prone, while the Petišovci sandstones are shaly and are separated as the equivalent of the Petišovci sandstones.

3.8.1. Well Construction

The length of the Mih-3 α wellbore is 1780.4 meters.

Casing:

Surface casing (13 3/8") installed to 84,9 m and cemented to surface.

I Intermediate casing (9 5/8") installed to 502,5 m and cemented to surface.

L= 485 m

A=26°15'

The length of the Mih-3 β wellbore is 1822.4 meters.

Casing:

Surface casing (13 3/8") installed to 84,9 m and cemented to surface.

I Intermediate casing (9 5/8") installed to 502,5 m and cemented to surface.

II Intermediate casing (5 1/2") installed to 1820 m.

L= 599,3 m

N=35°29' , angle 23°

3.8.2. Drill Stem Test

During the deep exploration well Mihovljan-3 α , a single Drill Stem Test (DST) operation was conducted to evaluate the reservoir characteristics of sandstone and the overlying andesite roof (based on Core Description No. 2 retrieved from 1697.00 - 1706.00 m). The testing interval ranged from 1700.20 to 1708.00 m, encompassing the lower Lenti shale and the entire development of Petišovci sandstones of the Lendava formation and the roof of the Međimurje member of the Mura-Sobot formation. The operation was performed in an open hole with one packer and a CIP valve, activating the packer by setting the tool at the bottom of the well. The maximum temperature in the well, measured by a downhole thermometer at 1706.20 m, was 93.3 °C. From the onset of measurement, gas flow manifestation was very weak, with air bubbling ceasing 2 - 3 cm below the water surface in the vessel. Over the 52-minute measurement period, only 35 liters of fluid were recovered into the empty drill pipes. No hydrocarbon inflow was observed.



Pressure gauges on the downhole pressure recorders depicted well-defined curves characteristic of formations with negligible permeability and good stratigraphic energy. The flow curve indicated no inflow. While the static pressure curve did not fully develop, a slight "S" shape suggested the presence of vertical permeability. Due to the absence of fluids during measurement and no pressure increase at the surface, no calculation of formation characteristics could be performed. Results from the test suggest that the formations tested have negligible permeability but relatively good stratigraphic energy, making them uninteresting from a petroleum geological perspective.

In another DST operation, the interval from 1764.65 to 1776.50 m was tested in gray fine-grained shale of the Petišovci sandstones in well Mihovljan-3B. During drilling, hydrocarbon traces in the sieve samples were not observed, nor was there a significant increase in gas content in the flow (from 1.9% to 2.1%). However, the sandstone in the core showed partial "positive" results, prompting further testing of its uppermost section due to the potential of the Petišovci sandstones. The operation utilized a CIP 1 packer, two 6000 psi pressure gauges with 12 and 24-hour mechanisms, and an HT-500 thermometer. Initially, gas flow manifestation was very good but began to diminish after 10 minutes. Gas appeared at the surface after 31 minutes, though the pressure did not reach measurable levels. Gas samples were taken at 33 and 54 minutes. In the drill pipes, 600 liters of emulsion (oil-water mixture) were obtained. Considering the volume below the packer was approximately 390 liters, the amount of oil influx was estimated at around 200 liters. The emulsion sample taken was not suitable for analysis. Extrapolated pressure reached 162 atm, indicating the existence of a "SUPER CHARGE," which due to the low sandstone permeability during the 53-minute flow, was not completely eliminated. Consequently, the reservoir pressure was 15 atm lower than the hydrostatic pressure of the water column. Based on available data, it is concluded that the Petišovci sandstones in their uppermost part have negligible permeability and are thus primarily unpromising. However, with appropriate processing, better results could potentially be achieved due to the relatively strong stratigraphic energy.

3.8.3. Geological-Geophysical Works and Special Operations

During the drilling operations, continuous geological monitoring of the wells was conducted. Samples were taken every 5 meters, examined under UV light, and described. An operational geological diagram was created, and gas logging was performed throughout the entire drilling process. Three mechanical cores were extracted (2 from Mihovljan-3 α and 1 from Mihovljan-3B), from which samples were selected for sedimentological, micropaleontological, and bitumen analyses.

At well Mihovljan-3 α , a total of 18 meters were cored, yielding 18 meters of core (100% recovery):

- Core J-1 (1605.8 – 1614.8 m), UV traces absent, CHCl₃ negative.
- Core J-2 (1697 - 1706 m), UV traces absent, CHCl₃ negative.

At well Mihovljan-3B, a total of 9 meters were cored, yielding 9 meters of core (100% recovery):

- Core J-1 (1762-1771.5 m), UV positive, CHCl₃ reactive.

Testing was conducted twice:

- At Mihovljan-3 α (1700.2 - 1708.0 m), 35 liters of fluid were recovered.
- At Mihovljan-3 β (1764.65-1776.5 m), 600 liters of emulsion (oil-water mixture) along with traces of gas were recovered.

Final well log (WL) measurements were performed at both wells (Mihovljan-3 α and Mihovljan-3B).



3.8.4. Conclusion of drilling

The deep exploration well Mih-3 penetrated the Mura, Lendava, and a portion of the Mura-Sobot formations. Drilling was halted within the Međimurje member. Given that the sand series known for hydrocarbons at Mih-1 (Petišovci sandstones - oil) and Mih-2 (Siget sandstones - gas) predominantly occur in shale-laden development, directional wells Mihovljan-3 α and Mihovljan-3 β were drilled. At well Mih-3 α , the Siget sandstones encountered were thicker than at Mih-3 but similarly shale-laden, resulting in only weak traces of gas detected during drilling. The Petišovci sandstones were also shale-laden and identified as the shale-laden equivalent of Petišovci sandstones. No hydrocarbons were confirmed, leading to the well being categorized as non-commercial.

At well Mih-3 β , the Siget sandstones were reduced to just 10 meters and were non-commercial. However, hydrocarbons were identified in the Petišovci sandstones (J-1 1762.5 - 1771.5 m). Testing (1764.65 - 1776.5 m) yielded 600 liters of oil-water emulsion and traces of gas. The well was plugged and prepared for production following remediation testing.

3.9. Well Mihovljan-4

The coordinates for well Mihovljan-1 are:

Y = 5,615,470

X = 5,140,690

H = 156 m

The deep exploration well Mih-4 is located between the villages of Pribislavec and Belica, northeast of Čakovec, and approximately 1200 meters southeast of well Mih-2. The objective of well Mih-4 was to drill and investigate the profile of Tertiary deposits, including the Mura-Sobot formation, and to penetrate the Međimurje member. Additionally, the goal was to determine the potential presence of hydrocarbons on the eastern part of the Mihovljan exploration site.

3.9.1. Geological Research

The first deep exploratory well, Mih-1, tested the northwest part of the Mihovljan anticline, while the well Mih-2 tested its northern part. The third well, Mih-3, tested the southern part of the Mihovljan exploration area. Since these well yielded negative results, a directional well, Mih-3 α , will be drilled from the Mih-3 wellbore, oriented towards the north-northeast (towards the central part of the anticline). Based on this, it has been decided that the exploratory well Mihovljan-4 will test the eastern part of the Mihovljan anticline.

3.9.2. Well Construction

The length of the Mih-4 wellbore is 1665 meters.

Casing:

Surface casing (13 $\frac{3}{8}$ "") installed to 75,5 m and cemented to surface.

Intermediate casing (9 $\frac{5}{8}$ "") installed to 500 m and cemented to surface.

3.9.3. Drill Stem Test



Testing in the interval 1552.5 - 1538.68 m revealed rare, very thin layers of sandstone initially thought to belong to the Petišovci sandstones. However, subsequent wireline logging measurements identified these as Petišovci shale. During drilling at 1539 m, there was a notable increase in drilling progress accompanied by a rise in the relative gas concentration in the mud returns. The recovered core was minimal and did not adequately represent the interval due to its shale-dominated nature compared to the observed drilling progress change. Water cushioning was not utilized for the testing, and the measurement was conducted in a single string configuration. Flow was measured for 50 minutes, while pressure buildup continued for 59 minutes. Despite weak surface manifestations, 2 m³ of mud returns were obtained in the drill pipes. Initial and final flow pressures measured at the upper gauge (H=1533.7 m) were 2.63 bar, with a static pressure of 12.36 bar. The temperature recorded at the bottom during testing was 91.7 °C.

The testing results align completely with the lithological development of the tested interval, indicating it is impermeable to fluid flow.

3.9.4. Geological-Geophysical Works and Special Operations

Geological monitoring of well Mih-4 was conducted using LNB laboratory, with all data collected, described, and interpreted throughout drilling to the final depth of 1665 m.

Based on the results of geological monitoring and analysis of the well log (WL) diagrams, it was determined that all planned formations including Mura Formation, Lendava Formation, and Mura-Sobot Formation were penetrated.

The gas station commenced operation at a depth of 565 m, but gas shows were not registered until 1352 m depth. The maximum relative gas concentration recorded was 1.5% at 1380 m depth. No oil shows were registered in sieve samples. During drilling through the Lower Ratka Member sandstones, gas shows with a maximum relative concentration of up to 1.7% were noted, while hydrocarbon traces in sieve samples were not identified. An interesting increase in drilling rate accompanied by a slight rise in gas concentration in mud returns was observed at 1539 m depth. Coring in the interval from 1550 to 1552.5 m yielded samples of tuffaceous fine-grained sandy shale. Gas shows with a maximum relative concentration of 1% were also recorded during drilling through the Siget sandstones, though no hydrocarbons were detected in sieve samples. The Lower Lenti shale member exhibited highly shale-dominated development with very thin and rare layers of gray fine-grained tuffaceous sandstone. This member lies discordantly over the Međimurje Member of the Mura-Sobot Formation, indicating a stratigraphic gap between them.

A total of 7.4 m was cored, yielding 2.9 m (39.3% recovery):

- Core J-1 (1453-1456 m), UV shows no traces, CHCl₃ negative.
- Core J-2 (1550-1552.5 m), UV shows no traces, CHCl₃ negative.
- Core J-3 (1626-1627.9 m), UV shows no traces, CHCl₃ negative.

Well log measurements were conducted before installing the production casing down to 500.5 m, with final measurements extending to 1667.5 m depth. The maximum temperature recorded at the bottom of the well was 83 °C.

3.9.5. Conclusion of Drilling Mih-4

The eastern part of the Mihovljan anticline was explored by the deep exploration well Mih-4. The objective of the well was to drill and evaluate the Tertiary formations up to the Mura-Sobot Formation and to determine the possible presence of hydrocarbons in this part of the anticline. It was determined that the Tertiary formations in this exploration area are in a normal sequence up to and including the Lenti marl of



the Lendava Formation, which discordantly overlies the Međimurje Member of the Vukovar Formation. The main hydrocarbon-bearing units, the Siget sandstones, are of reduced thickness and predominantly shale development, while the Petišovci sandstones are not developed. No hydrocarbon traces were identified in the Međimurje Member. It was decided to drill a directional well from the wellbore to explore the area north of Mih-4.

3.10. Well Mihovljan-4 α and Mihovljan-4 β

Coordinates of wells Mihovljan-4 α and Mihovljan-4 β are:

Y = 5,615,470

X = 5,140,690

H = 156 m

Well Mih-4 α is oriented at a depth of 604 m with an azimuth of N 12°00'W. At a depth of 1743 m (TVD = 1600.5 m), the deviation is 529.4 m with an average azimuth of N 02°05'W.

Well Mih-4 β is oriented at a depth of 576 m with an azimuth of S 14°00'W. At a depth of 1952 m (TVD = 1600.5 m), the deviation was 819.8 m with an average azimuth of S 05°59'E.

The task of the wells was to drill and evaluate the Siget and Petišovci sandstones and to penetrate the Međimurje Member of the Mura-Sobot Formation.

3.10.1. Well Construction

The length of the Mih-4 α wellbore is 1774 meters and length of the Mih-4 β is 2022 m.

Casing:

Surface casing (13 3/8") installed to 75,5 m and cemented to surface.

Intermediate casing (9 5/8") installed to 500 m and cemented to surface.

3.10.2. Geological-Geophysical Works and Special Operations

Geological monitoring of wells Mih-4 α and Mih-4 β was conducted by LNB laboratory from the onset of deviation until final depths, with all data systematically collected, described, and interpreted during drilling. Based on the results of geological monitoring and analysis of the WL diagrams, it was determined that all targeted formations including Mura Formation, Lendava Formation, and Mura-Sobot Formation have been drilled through.

Gas detection commenced at deviation depths, and gas traces were registered upon entering the Peklenica Member, specifically on well Mih-4 β , reaching up to 5% relative concentration. On well Mih-4 α , the Gorice Shale Member is markedly shale-dominated with a thickness of only 14 m, whereas on Mih-4 β , the thickness of the Gorice Shale Member is much greater at 61 m (net thickness = 42 m). Minimal gas occurrences (up to 1.6% relative concentration) were detected on the gas detector. Portions of formations at Mih-4 β , which are shale-dominated (Gorice Shale), are classified as Paka Sandstones at Mih-4 α , with a thickness of 48 m (net thickness = 42 m). The Lendavčica Shale Member at Mih-4 α , unlike Mih-1, is combined with Dolina Shale due to the absence of Upper Ratka Sandstones, occurring between depths 1504 - 1581 m (TVD = 1387 - 1455 m). Gas concentrations detected on the gas detector were minimal, up to 1.1%. Upper Ratka Sandstones were not encountered at Mih-4 and Mih-4 α ; however, at Mih-4 β , they appeared as a 7 m thick layer with very thin shale interbeds. The Dolina Shale at Mih-4 α , similar to Mih-1, is combined with Lendavčica Shale



as Dolina-Lendavčica Shale. In this member, gas concentration of 2.8% was recorded, which is the maximum observed in this formation. Lower Ratka Sandstones at Mih-4B are predominantly shale-bearing; maximum gas concentrations detected by the gas detector were 2.6% at Mih-4α and 2.1% at Mih-4B. No hydrocarbon occurrences were registered in sieve samples. Despite Siget Sandstones being gas-bearing at Mih-2 and nearly structurally equivalent at Mih-4α, they were non-productive at this well, likely due to significantly more shale-dominated lithology. Upon entering Siget Sandstones, gas concentration of 3.3% was recorded in the outflow, marking the maximum concentration observed at this well. Towards the south, where well Mih-4B is oriented, the thickness of Siget Sandstones decreases, with a more shale-dominated lithology compared to Mih-4α.

Petišovci Sandstones, which are hydrocarbon-bearing at wells Mih-1 and Mih-3B, are absent here. In the Međimurje Member, bitumen analysis revealed a relatively low concentration of bitumen not exceeding 0.022%. Extracted bitumen are predominantly of epigenetic origin, representing a mixture of oil-tar and tar types.

At well Mih-4α, 2.1 m of coring yielded 0.75 m of core (recovery rate = 0.36%):

- Core J-1 (1709-1710 m), UV traces absent, CHCl₃ negative.
- Core J-2 (1770.9-1772 m), UV traces absent, CHCl₃ negative.

At well Mih-4B, 4.6 m of coring yielded 1 m of core (recovery rate = 21.7%):

- Core J-1 (1950-1954.6 m), UV traces absent, CHCl₃ negative.

DST testing was not conducted, and final well log measurements were performed on both wells. Maximum temperatures measured at the bottom of well Mih-4α reached 73.3 °C, while at well Mih-4B, the maximum temperature reached 81.1 °C.

3.10.3. Conclusion of Drilling Mih-4α and Mih-4B

Deep exploratory well Mih-4 penetrated the Mura and Lendava formations and drilled through the Mura-Sobot formation. No hydrocarbon occurrences were identified during drilling. Siget Sandstones, which are hydrocarbon-bearing at Mih-2, were non-productive here, while Petišovci Sandstones were undeveloped. Directional wells Mih-4α and Mih-4B were drilled to target these layers in more favorable lithological conditions. Well Mih-4α penetrated the Mura and Lendava formations. Drilling was halted in effusive rocks (andesite) of the Međimurje member of the Mura-Sobot formation. Weak traces of gas were detected only in Siget Sandstones during drilling. Petišovci Sandstones were undeveloped (as observed in Mih-4). The well was abandoned as non-productive.

Well Mih-4B also ended in the Međimurje member. No hydrocarbons were identified during drilling. Siget Sandstones were non-productive, while Petišovci Sandstones were undeveloped. The well was abandoned as non-productive.

3.11. Well Mihovljan-5

The coordinates of the Mihovljan-5 deep exploratory well are:

Y = 5,614,120

X = 5,141,555

H = 178 m



The location of the deep exploratory well Mihovljan-5 is approximately 2000 m east of the village Mihovljan and about 1300 m north of the village Pribislavec, in Međimurje. It is approximately 450 m east of the Mih-1 well and about 490 m west-northwest of the Mih-2 well. The primary objective of well Mih-5 was to drill and examine the profile of Tertiary deposits up to a significant portion of the roof of the Međimurje member of the Mura-Sobot formation. The goal also included determining the potential presence of oil and gas in this area, as well as studying the structural and petroleum geological relationships within the Mihovljan exploration area.

3.11.1. Geological Research

On exploration site Mihovljan, oil deposits were discovered in the Petišovci sandstones confirmed by well Mih-1 and further verified by well Mih-3B. Gas deposits were identified in the Siget sandstones of the Lendava formation through well Mih-2. Additionally, small quantities of oil were found in the Međimurje member of the Mura-Sobot formation. These hydrocarbon reservoirs (Petišovci and Siget sandstones) are either undeveloped or are confined in certain parts of the structure. For instance, on well Mih-3, the Petišovci sandstones are absent, and the Siget sandstones are heavily confined. A similar situation is observed in the area affected by well Mih-4.

3.11.2. Well Construction

The length of the Mih-5 wellbore is 1898 meters.

Casing:

Surface casing (13 3/8") installed to 87 m and cemented to surface.

Intermediate casing (9 5/8") installed to 498 m and cemented to surface.

Geological-Geophysical Works and Special Operations

During drilling, continuous geological monitoring was conducted at exploration site Mihovljan-5. Samples were taken every 5 meters, inspected under UV light, described, and sent for micropaleontological analyses. Gas logging was performed from a depth of 865 m to the bottom of the well. Four coring operations were carried out, resulting in the retrieval of three cores. Core samples were subjected to physical (9 samples), sedimentological (10 samples), bitumen (12 samples), micro and macropaleontological analyses (2 samples each). No Drill Stem Tests (DST) were conducted during drilling, with Electrical Conductivity (EC) logging performed post-drilling. The deep exploration well Mihovljan-5 penetrated the Mura, Lendava, and Mura-Sobot formations.

Initial gas shows in the well were detected at a depth of 1150 m in the Mura formation, with gas concentrations not exceeding 1.65% relative concentration. Through the Lendava formation, gas concentrations in the gas shows did not exceed 1.8%. In the Petišovci sandstones of the Mura-Sobot formation, gas concentration in the gas shows increased from 1.4% to 7.4%. Chromatographic analysis indicated the gas composition as 2.3% C1, 0.21% C2, 0.3% C3, 0.098% C4, and 0.084% nC4. Trace fluorescence under UV light was observed in sieve samples, and the core extracted from the sandstone roof in the interval of 1639 - 1644.8 m showed positive characteristics for the first meter, while the rest was waterlogged. Due to unfavorable apparent resistivity trends from EC logging, DST measurements were not conducted. Further drilling through the Mura-Sobot formation did not reveal hydrocarbon saturation. Bitumen analyses of core samples showed extremely low concentrations of bitumen, primarily of epigenetic oil type in the Mosti member.

A total of 13.8 m was cored, yielding 7 m of cores (50.7%):



- Core J-2 (1639-1644.8 m), UV positive, CHCl₃ positive (first 20 cm)
- Core J-3 (1730-1734 m), UV negative, CHCl₃ negative.
- Core J-4 (1895-1898 m), UV negative, CHCl₃ negative.

The maximum temperature measured at the bottom of the well was 88 °C. EC logging at well Mihovljan-5 was conducted four times, initially before casing and technical column installation, informally to a depth of 1645 m, and finally to a depth of 1898 m, capturing EL, MCL, LL-7, and AL-BHC logs. The EC diagram analysis covered the interval from 1475.9 - 1579.2 m, including D. Ratka sandstones, Siget sandstones, and an unnamed layer within the Lenti marl formation, and specifically for the Petišovci sandstone series from 1634.7 - 1675.1 m.

I interval: 1475.9 - 1579.2 m

The analysis of this interval shows that porosity ranges from 18-25%, with predominant values of 21-22%. Water saturation (Sw) results indicate that Sw exceeds 50% in all layers of this interval, therefore indicating non-hydrocarbon bearing zones.

II interval: 1634.7 - 1675.1 m

Porosity values for this interval range from 13-22%, with predominant values of 20-21%. Saturation calculations indicate that all layers within this series are waterlogged, suggesting no potential influx of hydrocarbons from these zones.

The EC diagram analysis of both intervals confirms that well Mih-5 penetrated the projected reservoirs in expected sandy formations, but these are saturated with water. Additionally, chemical water analysis yielded approximately 8 g NaCl/L for the interval from 1475.9 - 1579.2 m, and around 10 g NaCl/L for the Petišovci sandstone series.

3.11.3. Conclusion of Drilling Mih-5

Deep exploratory well Mih-5 penetrated the Mura, Lendava, and Mura-Sobot formations. The well terminated in silicified andesite of the Međimurje member within the Mura-Sobot formation. Tertiary deposits are in normal sequence up to and including the Benica shale of the Mura-Sobot formation, which is unconformably overlain by the Međimurje member of the same formation. Hydrocarbon deposits of anticlinal lithological type were identified in the Siget and Petišovci sandstones in wells Mih-1, Mih-2, and Mih-3. However, significant oil and gas saturations were not detected in well Mih-5, despite its location between these wells. Therefore, it was decided to abandon the well as non-commercial. Cement plugs were set at depths of 1675 - 1525 m and 550 - 450 m.

3.12. Well Mihovljan-6

The coordinates of the well Mihovljan-6 are:

Y = 6,382,790.65

X = 5,141,149.67

H = 177.55 m

The location of well Mih-6 is on the same foundations as wells Mih-7 and Mih-8. It is approximately 550 m southwest from well Mih-1 and approximately 700 m southeast from well Mih-3. The task of the well was to



confirm the accumulation of oil in the Lower Pannonian in the "II" reservoir, ensure production from it, and define the productive area and thickness of the "II" reservoir.

3.12.1. Well Construction

The final depth of well Mih-6 is 1734 m, and the well is directionally drilled with the following elements:

A = 65°21'

L = 338,27 m

Hv = 1659,12 m.

Casing:

Surface casing (13 3/8") installed to 87 m and cemented to surface.

Intermediate casing (9 5/8") installed to 574 m and cemented to surface.

Production casing (5 1/2") installed to 1730 m and cemented to surface.

Geological Research

In the Mihovljan field, the dominant structural feature is the Mihovljan ridge, prominently expressed on the structural map over the "I" and "II" reservoir caps. The general orientation of the main axis of the structural ridge is north-south. Tectonics have been identified solely by well Mih-8, which intersected a 25 m normal fault, thereby separating this well into a tectonically shallower block from the wells previously drilled in the field.

3.12.2. Drill Stem Test

First DST testing was conducted on the Lower Pannonian sandstones within the interval of 1649.28 - 1675 m. No water cushion was used for testing, and measurements were performed in a single stage with flow measured for 120 minutes and pressure buildup for 150 minutes. Upon packer activation, slight gas emissions occurred at the surface lasting up to 10 minutes of flow measurement. Traces of drilling fluid were observed during testing. The temperature measured at 1671.5 m depth was 88 °C, indicating a temperature gradient of 5.3 °C/100 m. The static pressure recorded on the downhole gauge was 6.9 bar, while the final flow pressure was 5.2 bar, suggesting a practically impermeable formation based on pressure readings.

Second DST testing targeted the Lower Pannonian sandstones within the interval of 1676.56 - 1688 (Hv=1613.8 - 1624.4 m). Testing was performed using standard tool configuration with a single packer, distributor, and bottom anchor in an uncased wellbore. No prior WL measurement was conducted, and packer placement was determined from operational geological diagrams in the weakest drilling progress. No water cushion was used for testing, and measurements were performed in a single stage with flow measured for 120 minutes and pressure buildup for 150 minutes. Upon packer activation, initial gas emissions were observed at the surface, becoming progressively more vigorous, with surface pressure gauge reading 0 bar. Combustible gas appeared at the surface within 30 minutes of flow measurement, with pressure still registering 0 bar. Gas was flared throughout the flow measurement period. Reverse circulation (via dual valve) was performed during static pressure measurement, recorded on downhole gauge diagrams. Results from the downhole gauge diagrams yielded the following values: final pressure of the first flow period (FFP1) = 14.6 bar, first static pressure (FCIP) = 146.8 bar. The second flow period's final pressure (FFP2) was briefly measured to activate the dual valve for reverse circulation, resulting in 19.7 bar, with the second static pressure (FCIP) at 155.3 bar. Extrapolating from the well-developed FCIP curve provided an extrapolated pressure (Pext) of 160.7 bar (gp=0.98 bar/10 m). This extrapolated static layer pressure value was used to



calculate reservoir characteristics, yielding: volumetric flow rate $Q=14.92$ m³/d, permeability $K_{he}=11.94 \times 10^{-3}$ μm^2 (12.1 mD), average effective permeability $K=1.19 \times 10^{-3}$ μm^2 (1.2 mD) with an effective layer thickness of approximately 10 m. Reservoir damage was assessed at $EDR=1.80$, indicating realistic damage, with potentiometric surface $PS=204.56$ m and drainage radius $r_i=16.27$ m. Temperature measured at 1686 m depth was 92.8 °C, resulting in a temperature gradient of 5.5 °C/100 m. The data indicates that the tested sandstone section has low permeability, and the static layer pressure is within hydrostatic limits. Considering the observed damage, an increase in volumetric flow rate ($Q_t=26.8$ m³/d) can be expected.

3.12.3. Geological-Geophysical Works and Special Operations

Geological monitoring of well Mih-6 commenced at 1000 m, with shallow formation descriptions based on neighboring well data and resistivity logs. Well Mih-6 penetrated Quaternary, Upper and Lower Pontian, Upper Pannonian, and partially Lower Pannonian formations. Drilling ceased at a depth of 1754 m ($H_v=1659.12$ m).

Within the Lower Pontian formations, two sandstone reservoirs, A and B, were encountered. Based on rock fragment samples from the flow and resistivity log analysis, the sandstone interval from 1390 to 1987 m was found to be water-bearing, while the remaining part of the reservoir was tight. In the Upper Pannonian formations, reservoirs C and I were encountered. Analysis of rock fragments from the flow and resistivity logs indicated that both reservoirs are water-bearing.

A total of 4.4 m of core was recovered, with 100% recovery:

- Core J-1 (1675-1679.4 m), UV positive, CHCl_3 positive.

Permeability measured in core J-1 ranged from $0.04-0.12 \times 10^{-3}$ μm^2 (0.04-0.12mD) and porosity from 5.4-11%.

The maximum temperature measured at the bottom of the well was 95 °C. Only final WL measurements were conducted on well Mih-6.

3.12.4. Conclusion of Drilling Mih-6

The well fulfilled its objective by penetrating the "II" reservoir as expected, confirming oil saturation. It was completed with a production casing of 5 ½" to 1730 m depth. Subsequently, it was prepared for testing and development by the Repair Department. The well Mih-6 was tested and developed in 1986 and brought into production in 1988, marking the commencement of operations at the Mihovljan oil field. Due to high oil viscosity and significant paraffin content, chemical treatments and acid perforation washes were conducted (1988, 1992, 1993). These measures contributed to increased oil and fluid production.

3.13. Well Mihovljan-7

The coordinates for well Mihovljan-7 are as follows:

$Y = 6,382,792.04$

$X = 5,141,159.57$

$H = 177.57$ m

The location of the well falls on agricultural land near a field road. Adjacent wells, Mih-6 and Mih-8, are situated on the same foundations. The distance from the wellhead of Mih-1 to the wellhead of the planned well is approximately 550 m southeast, while the distance from the wellhead of Mih-3B to the wellhead of



the planned well is approximately 700 m southeast. The objective of the well was to define productive areas and thicknesses of hydrocarbon-saturated reservoir rocks west of wells Mih-1 and Mih-3B, within the II reservoir on the western part of the structure, and to bring this reservoir into production.

3.13.1. Well Construction Mih-7

The final depth of well Mih-7 is 1734 m, and the well is deviated with the following elements:

$$A = 356^{\circ}52'$$

$$L = 225,01 \text{ m}$$

$$H_v = 1693,27 \text{ m.}$$

Casing:

Surface casing (13 $\frac{3}{8}$ ") installed to 84 m and cemented to surface.

Intermediate casing (9 $\frac{5}{8}$ ") installed to 574 m and cemented to surface.

Production casing (5 $\frac{1}{2}$ ") installed to 1710 m and cemented to surface.

3.13.2. Geological Research

In the current phase of understanding the Mihovljan field, the productive area and thickness of hydrocarbon-bearing reservoir rocks west of wells Mih-1 and Mih-3B have not been defined. This well aims to confirm the accumulation of oil in the "II" reservoir of the western part of the structure and bring it into production.

3.13.3. Drill Stem Test

The DST (Drill Stem Test) was conducted in an open hole section of the well in the interval: 1654.55 - 1662.8 m to determine the saturation of the Lower Pannonian sandstones (II reservoir). A conventional testing tool with a single packer and anchor at the bottom was used. No water cushion was employed for testing, and the measurement was carried out single-run, with flow measured over 115 minutes and pressure buildup over 155 minutes. The test proceeded with weak indications of inflow into the drill pipes, manifested by very low-intensity gas seepage. No gas was observed, and approximately 0.2 m³ of emulsion of oil was recovered in a ratio of approximately 4:1 from the drill pipes. From the depth gauge diagram, a slight rise in the flow curve of only 1.887 bar is visible. The static reservoir pressure curve was not fully closed after 155 minutes of measurement. The recorded reservoir pressure was 139.9 bar, and its extrapolated value should not be taken as exact due to the incomplete development of the pressure buildup curve. For this reason, the McKinley method was used, which indicated slightly better permeability characteristics considering the distance from the wellbore. Layer parameters were not calculated due to the lack of oil sample analysis. The measured temperature at a depth of 1661.58 m was 96 °C (temperature gradient = 5.8 °C/100 m).

Based on the obtained data, it is evident that the reservoir is oil-saturated and of low permeability. The slight "S" shape of the pressure buildup curve is attributed to gas re-dissolution.

3.13.4. Geological-Geophysical Works and Special Operations

Well Mih-7 penetrated Quaternary, Upper and Lower Pontian, Upper Pannonian, and partially Lower Pannonian formations, reaching a final depth of 1743 m (MD=1693.27 m). In the Lower Pontian formations, two sandstone reservoirs, A and B, were drilled. Based on rock cuttings and log analysis, both sandstone



reservoirs A and B were found to be water-bearing. In the Upper Pannonian formations, reservoirs C and I were drilled, and according to rock cuttings and log analysis, both reservoirs were also water-bearing. In the Lower Pannonian formations, reservoir II was drilled, which is saturated with oil and water, with an oil-water contact determined at a depth of 1475 m.

A total of 2.9 m of core was recovered, with 100% recovery:

- Core J-1 (1647-1649 m), UV negative, with weak yellow stains of CHCl_3 .

The maximum temperature measured at the bottom of the well is 95 °C. Well logging was performed prior the installation of surface casing and final WL of the well Mih-7.

3.13.5. Conclusion of Drilling Mih-7

The well has fulfilled its task by drilling into the partially oil-saturated reservoir "II" and was completed with a production casing down to 1710 m. Subsequently, it was handed over to the OOUR Remont for further testing. Following additional evaluations, the well was equipped for oil production and commenced operations in 1988.

3.14. Well Mihovljan-8

The coordinates of well Mihovljan-8 are:

Y = 6,382,780

X = 5,141,150

H = 177.57 m

The location of the well, according to the given coordinates, is situated on agricultural land near a dirt road. The platform with three wellheads for wells Mih-6, Mih-7, and Mih-8 is positioned precisely at the specified coordinates. Wells Mih-6 and Mih-7 are on the same foundation, spaced 10 meters apart. Well Mih-1 is approximately 550 meters northeast of the planned wellhead, while well Mih-5 is about 700 meters southeast. The objective of well Mih-8 was to define the productive area and thickness of hydrocarbon-saturated reservoir rocks west of wells Mih-1 and Mih-3B, as well as to address structural and lithostratigraphic relationships in this part of the field.

3.14.1. Well Construction

The final depth of well Mih-8 is 1761 m, and the well is deviated with the following directional elements:

A = 240°45'

L = 402,3 m

Hv = 1668,98 m.

Casing:

Surface casing (13 3/8") installed to 85,59 m and cemented to surface.

Intermediate casing (9 5/8") installed to 501 m and cemented to surface.

3.14.2. Geological-Geophysical Works and Special Operations



Well Mih-8 penetrated the Quaternary, Upper and Lower Pontian, Upper Pannonian, and stopped in the Lower Pannonian formations at a depth of 1761 m (TVD=1668.98 m).

In the Lower Pontian formations, two sandstone reservoirs, beds A and B, were drilled. Based on rock cuttings and analysis of the logging charts, sandstone bed A is water-bearing, while bed B is shale-sealed. In the Upper Pannonian formations, reservoirs C and I were drilled. According to rock cuttings and logging chart analysis, reservoir C is water-bearing, while reservoir I is water-bearing in the interval 1585 - 1597.5 m, with the lower part shale-sealed. In the Lower Pannonian formations, reservoir II was drilled and found to be water-bearing as well

The maximum temperature measured at the bottom of the well is 98 °C. Well Mih-8 underwent well logging before installation of surface casing and final well logging after the completion of the well.

3.14.3. Conclusion of Drilling Mih-8

Well Mih-8 intersected a normal fault at a depth of 1296.5 m with a throw of 25 m. The projected reservoir was drilled in the second tectonic block, structurally shallower but water-saturated. Core sampling and testing as per the program were not conducted due to sticking and breakage of drill pipes during the installation of the production casing. The well was permanently abandoned according to mining and oil industry regulations, with cement plugs set at depths of 1761-1650 m and 550-450 m.

4. Geological Structure of the Geothermal Reservoir at the Potential Location and Broader Locations from Available Data

4.1. Geological Description

4.1.1. Lithology description for well Mačkovec-1

The Mačkovec-1 borehole penetrated deposits of the Mura Formation, Lendava Formation, Mura-Sobot Formation, and Tertiary Basement. Based on observations of sieve samples, calcimetry, coring tests, gas manifestations, mud, and mechanical drilling speed, lithostratigraphic formations were determined, with the geological description of each formation provided in Table 3.

Formation	Interval, m	Description
Mura formation	0-1100	It is characterized by gravel, clay, sand, sandstone, coal, and marl.
Lendava formation Paklenica member	1100-1149	It is composed of marl and sandstone. The marl is gray to dark gray in color and of medium hardness. It occasionally contains clay and sandy components. Sandstone is significantly less



			represented. It contains a lot of mica, is fine-grained, and moderately cemented.
	Gorice dolina marl	1149-1299	According to the sieve samples and WL diagrams, this member is represented by marl and sandstone. The marl is gray to light gray in color. In terms of hardness, it ranges from medium hard to hard. In the upper part of the member, it is clayey and sandy. The sandstone is fine-grained and moderately cemented. It is significantly less abundant than marl and appears in layers 1 to 3 meters thick.
	Lower Ratka sandstones	1299-1384	It is the same type of marl as in the previous member. In the deeper part, micaceous sandstones were drilled. In the interval from 1355 to 1365 meters, the sandstone is conglomeratic and firmly cemented. At the base of the member, fine-grained, moderately cemented sandstone is deposited again.
	Pince marl	1384-1427	An extremely marly member is represented by gray to dark gray hard marl. The sandstone layers are very thin (up to 1 meter) and were drilled only at the base of the member.
	Siget sandstones	1427-1438	In terms of lithology, the member does not differ from the previous one. In the operational geological diagram, a slightly higher presence of sandstone and an increase in drilling speed are recorded, but here too, the sandstone layers in the marl are very thin (up to 1 meter thick).
	Lenti marl	1438-1531	It is developed in facies of gray to dark gray, medium hard marl with very thin and rare layers of fine-grained micaceous sandstone.
	Petišovci sandstone	1531-1616	The member is composed of marl and sandstone. The marl is of medium hardness. The sandstone is light gray, fine-grained, and moderately cemented. It contains a lot of mica.
Mura-Sobot formation	Benica marl	1616-1703	The member shows distinctly marly development. In the upper part, there are several sandstone layers up to 1 meter thick. The marl is of medium hardness, partially sandy.
	Čentiba member	1703-1827	The described marl was drilled another 50 meters in this member. Then, the borehole entered silicified volcanic rock (andesite?) at a depth of 1750 meters. It consists of biocalcareous sediment. In the last 10 cm of the core, the biocalcareous



		sediment is conglomeratic, and the crown of the core is silicified volcanic rock.
Međimurje member	1827-2481	In the upper part of the member, we find an exchange between the described silicified volcanic rock and dark gray, hard, partially sandy marl. After 100 meters, the marl disappears, and for the rest of the member, the lithological composition is uniform - silicified volcanic rock, with characteristics varying with increasing depth. The color changes from gray to gray-greenish to green, and at the base of the member, it is almost white. The structure is fine-grained, and the hardness is medium to high.
Tertiary basement	2481-3050	Those are deposits of fractured cataclastic limestone. Numerous cracks are filled with calcite. The limestone is gray to dark gray in color, with occasional bright, almost white patches. Near the bottom of the borehole, there is a layer of silicified volcanic rock within the limestone, approximately 12 meters thick.

Table 3 Geological description of the stratigraphic units on well Mač-

4.1.2. Lithology description for well Međimurje - 4

The Međimurje-4 borehole penetrated deposits of the Mura Formation, Lendava Formation, Mura-Sobot Formation, and Tertiary Basement. Based on observations of sieve samples, calcimetry, coring tests, gas manifestations, mud, and mechanical drilling speed, lithostratigraphic formations were determined, with the geological description of each formation provided in Table 4

Formation	Interval, m	Description
Mura formation	0-1173	It consists of sandy-clay marls, clayey sands and quartz sandstones, marly clays containing thin layers of lignite coal, shale-like gray-green clays, and gray sandy clays containing sand.
Paklenica member	1173-1241	It is represented by clayey-sandy marls, while the lower part is characterized by marls with thin layers of fine-grained, clayey sandstones.
Lendava formation	Equivalent Paka sandstone and Lendavčica marl 1241-1379	In the lower part, it is represented by dark gray clayey marls, while the middle part is composed of marls interspersed with thin layers of fine-grained sandstones. The upper part is characterized by fine-grained, clayey sands interspersed with thin layers of marly clay.



	Upper Ratka sandstones	1379-1413	The member is composed of moderately cemented grayish sandstone and dark gray clayey marl, with the assumption that marls occur in the form of thin layers.
	Dolina marl	1413-1516	This member is composed of dark gray, quite clayey-sandy marls.
	Lower Ratka sandstones	1516-1607	Gray, moderately to firmly cemented sandstone, marls in the form of thin layers.
	Pince marl	1607-1651	Medium-hard sandy marl with thin layers of sandstone.
	Siget sandstones	1651-1709	Gray fine-grained cemented sandstone and gray to dark gray medium-hard marl. The sandstones are interbedded with thin layers of marl.
	Lenti sandstones	1709-1785	The member is developed in facies of light gray and gray, quite hard marls. In the samples, 1-2% of quartz grains have been noted, along with a few pieces of whitish calcite, while at the lower part, a few pieces of light gray sandstone are observed.
Mura-Sobot formation	Petišovci sandstone	1785-1875	Present are light gray and gray moderately cemented sandstones interbedded with thin layers of dark gray, sandy, medium-hard marls.
	Benica marl	1875-2050	It is represented in the lower part by lithothamnium marl and dark gray, finely sandy, quite hard marls, while in the upper part by dark gray, quite sandy, medium-hard marls.
	Čentiba member	2050-2330	It is represented in the upper part by dark gray, very hard, finely sandy marls, while in the middle and lower part by marly siltites.
	Međimurje member	2330-3010	The member is represented by silicified sediments and pyroclastics that alternate with each other.

Table 4 Geological description of the stratigraphic units on well Mđ-4

4.1.3. Lithology description for well Mihovljan-1

The Mihovljan-1 borehole penetrated the deposits of the Mura Formation, the Lendava Formation and the Mura-Sobot Formation. Based on the observation of sieve samples, calcimetry, coring testing, gas manifestations, mud and mechanical drilling speed, lithostratigraphic formations were determined, while the geological description of individual formations is given in Table 5.

Formation	Interval, m	Description
Mura formation	0-1122	Heterogeneous gravel, gray sandy clay, gray coarse-grained sand in the upper part, with layers of coal.



Lendava formation	Paklenica member	1122-1239	Gray soft to medium-hard marl, in the upper part with layers of light gray, fine-grained, loosely cemented sandstone.
	Gorice marl	1239-1260	Gray soft to medium-hard loosely cemented marl.
	Paka sandstone	1260-1311	Dark gray soft to medium-hard marl, slightly clayey, with layers of light gray fine-grained loosely cemented marly sandstone.
	Dolina-Lendavčica marl	1311-1434	Gray soft marl in the lower part. In the central and upper parts, alternation of marl with fine-grained, loosely cemented micaceous sandy marls.
	Lower Ratka sandstones	1434-1474	Gray medium-hard sandy marl with layers of fine-grained, loosely cemented micaceous sandy marl.
	Pince marl	1474-1520	Gray, moderately hard sandy marl with interbeds of fine-grained, loosely cemented micaceous sandstone.
	Siget sandstones	1520-1545	Gray, moderately hard sandy marl with thicker layers of fine-grained, loosely cemented micaceous sandstone.
	Lenti marl	1545-1615	Gray, moderately hard marl with very thin and sparse layers of fine-grained, loosely cemented micaceous sandy marl.
Muraska-Sobot formation	Petišovci sandstones	1615-1654	In the upper part, there are sandstones with very rare and thin layers of hard, sandy marl. In the lower part, there are sandstones with thick layers of hard, sandy marl.
	Međimurje member	1654-1990.6	In the upper part, there is alternation between quartz sandstones and gray, moderately hard marl, while the rest is composed of gray to dark olive-green silicified volcanic rock with calcite veins (andesite?).

Table 5 Geological description of the stratigraphic units on well Mih-1

4.1.4. Lithology description for well Mihovljan-2

The Mihovljan-2 borehole penetrated the deposits of the Mura Formation, the Lendava Formation and the Mura-Sobot Formation. Based on the observation of sieve samples, calcimetry, coring testing, gas manifestations, mud and mechanical drilling speed, lithostratigraphic formations were determined, while the geological description of individual formations is given in Table 6.

Formation	Interval, m	Description	
Mura formation	0-1211	Heterogeneous gravel, clay with occasional layers of lightly carbonized coal and fine-grained, cemented sand, gray fine-grained quartzitic micaceous sandstone, and gray to bluish-gray soft clayey marl.	
Lendava formation	Paklenica member	1211-1313	Soft to medium-hard, loosely sandy marl, fine-grained, loosely cemented sandstone.
	Gorice marl	1313-1336	Soft to medium-hard, loosely sandy marl, fine-grained, loosely cemented sandstone.



	Paka sandstone	1336-1364	Soft to medium-hard weakly sandy marl, finely grained loosely cemented sandstone.
	Lendavčica marl	1364-1397	Gray soft to medium-hard sandy marl and loosely cemented sandstone.
	Upper Ratka sandstone	1397-1400	Loosely cemented sandstone.
	Dolina marl	1400-1444	Gray medium-hard silty marl.
	Lower Ratka sandstones	1444-1506	Gray medium-hard silty marl.
	Pince marl	1506-1557	Gray medium-hard sandy marl with layers of fine-grained, loosely cemented micaceous sandy marl.
	Siget sandstones	1557-1598	Gray medium-hard sandy marl with layers of fine-grained, loosely cemented marly sandstone.
	Lenti marl	1598-1661	Gray medium-hard sandy marl.
Murska-Sobot formation	Petišovci sandstone	1661-1701	Medium-hard sandy marl and gray fine-grained sandstone with abundant mica and quartz.
	Benica marl	1701-1730 (?)	Gray fine-grained sandstone with abundant mica and quartz.
	Čentiba member	1730 (?) - 2967	Medium-cemented sandstone with calcareous cement and traces of pyrite, with thin layers of gray to brown medium-hard marl.
	Međimurje member	1654-1990,6	Gray hard chert containing occasional pyrite.

Table 6 Geological description of the stratigraphic units on well Mih-2

4.1.5. Lithology description for well Mihovljan-3

The Mihovljan-3 borehole penetrated the deposits of the Mura Formation, the Lendava Formation and the Mura-Sobot Formation. Based on the observation of sieve samples, calcimetry, coring testing, gas manifestations, mud and mechanical drilling speed, lithostratigraphic formations were determined, while the geological description of individual formations is given in Table 7.

Formation	Interval, m	Description	
Mura formation	0-1146	Colorful coarse-grained gravel with abundant quartz, thick layers of clay which is sandy in shallower parts and marly in deeper parts, and the lower part is composed of clayey marls with layers of lightly carbonized coal.	
Lendava formation	Paklenica member	1146-1252	Gray highly clayey marl, fine-grained, loosely cemented sandstone.
	Gorice marl	1252-1268	Gray highly clayey marl, fine-grained, loosely cemented sandstone.
	Paka sandstones	1268-1322	Soft to medium-hard marl with layers of fine-grained sandstone.
	Lendavčica marl	1322-1355	Gray soft to medium-hard sandy marl and loosely cemented micaceous sandstone.



	Upper sandstones	Ratka	1355-1362	Loosely cemented sandstone.
	Dolina marl		1362-1408	Gray medium-hard silty marl with several thin layers of fine-grained sandstone.
	Lower sandstones	Ratka	1408-1475	Gray medium-hard silty marl with several thin layers of fine-grained sandstone.
	Pince marl		1475-1538	Gray medium-hard marl.
	Siget sandstones		1538-1546	Gray medium-hard marl with several thin layers of sandstone.
	Lenti marl		1546-1585 (?)	Gray medium-hard marl.
	Equivalent Petišovci sandstones		1585 (?) - 1621 (?)	Gray medium-hard marl.
Mura-Sobot formation	Stratigraphic gap		1621 (?) - 1721 (?)	
	Međimurje member		1621 (?) - 1541,4	Silicified volcanic rock (andesite?).

Table 7 Geological description of the stratigraphic units on well Mih-3

4.1.6. Lithology description for well Mihovljan-3a

The Mihovljan-3a borehole penetrated the deposits of the Mura Formation, the Lendava Formation and the Mura-Sobot Formation. Based on the observation of sieve samples, calcimetry, coring testing, gas manifestations, mud and mechanical drilling speed, lithostratigraphic formations were determined, while the geological description of individual formations is given in Table 8.

Formation		Interval, m	Description
Mura formation		0-1208	Light gray fine to coarse-grained loosely cemented sandstones with layers of clay.
	Paklenica member	1208-1337	Soft to medium-hard sandy clayey marl with thin layers of light gray fine-grained moderately cemented micaceous sandstone.
	Gorice marl	1337-1359	Gray hard marl.
	Paka sandstones	1359-1435	Light gray fine-grained micaceous sandstones with medium cementation, underlain by marl (gray medium-hard marl).
Lendava formation	Lendavčica marl	1435-1460	Gray medium-hard marl.
	Upper sandstones	Ratka 1460-1469	Light gray fine to medium-grained loosely to moderately cemented micaceous sandstone, gray medium-hard marl.
	Dolina marl	1469-1482	Gray medium-hard marl with layers of light gray fine-grained moderately cemented micaceous sandstone.
	Lower sandstones	Ratka 1482-1560	Gray medium-hard marl with layers of light gray fine-grained loosely to moderately cemented micaceous sandstone.



	Pince marl	1560-1602	Gray medium-hard marl.
	Siget sandstones	1602-1649	Fine-grained loosely to moderately cemented micaceous sandstone alternating with gray medium-hard marl.
	Lenti marl	1649-1690	Gray medium-hard marl with occasional sandy patches.
Mura-Sobot formation	Equivalent Petišovci sandstones	1690-1702	Gray medium-hard marl with very thin layers of sandstone.
	Međimurje member	1702-1780,4	Light gray to greenish-gray rock with quartz and clusters of pyrite (silicified effusive andesite?).

Table 8 Geological description of the stratigraphic units on well Mih-3α

4.1.7. Lithology description for well Mihovljan-3B

The Mihovljan-3B borehole penetrated the deposits of the Mura Formation, the Lendava Formation and the Mura-Sobot Formation. Based on the observation of sieve samples, calcimetry, coring testing, gas manifestations, mud and mechanical drilling speed, lithostratigraphic formations were determined, while the geological description of individual formations is given in Table 9.

Formation	Interval, m	Description	
Mura formation	0-1205	Light gray fine to coarse-grained loosely cemented sandstones with layers of clay.	
Lendava formation	Paklenica member	1205-1350	Soft to medium-hard sandy clayey marl with thin layers of light gray fine-grained moderately cemented micaceous sandstone.
	Gorice marl	1350-1376	Gray hard marl.
	Paka sandstones	1376-1447	Light gray fine-grained micaceous sandstones with medium cementation, underlain by marl (gray medium-hard marl).
	Lendavčica marl	1447-1469	Gray medium-hard marl.
	Upper Ratka sandstones	1469-1485	Light gray fine to medium-grained loosely to moderately cemented micaceous sandstone, gray medium-hard marl.
	Dolina marl	1485-1539	Gray medium-hard marl with layers of light gray fine-grained moderately cemented micaceous sandstone.
	Lower Ratka sandstones	1539-1605	Gray medium-hard marl with layers of light gray fine-grained loosely to moderately cemented micaceous sandstone.
	Pince marl	1605-1674	Gray medium-hard marl.
	Siget sandstones	1674-1686	Fine-grained loosely to moderately cemented micaceous sandstone.
Lenti marl	1686-1766	Gray medium-hard marl with occasional sandy patches.	



Mura-Sobot formation	Petišovci sandstones	1766-1818	Gray fine-grained micaceous sandstone alternating with gray medium-hard to hard marl.
	Međimurje member	1818-1822,4	Light gray to greenish-gray rock with quartz and clusters of pyrite (silicified effusive andesite?).

Table 9 Geological description of the stratigraphic units on well Mih-3B

4.1.8. Lithology description for well Mihovljan-4

The Mihovljan-4 borehole penetrated the deposits of the Mura Formation, the Lendava Formation and the Mura-Sobot Formation. Based on the observation of sieve samples, calcimetry, coring testing, gas manifestations, mud and mechanical drilling speed, lithostratigraphic formations were determined (Table 9), while the geological description of each formation is given in Table 11.

Formation	Interval (m)
Mura Formation	0-1260
Lendava Formation	1260-1624
Mura-Sobot Formation	1624-1665

Table 10 Stratigraphic units with corresponding intervals at well Mih-4

Formation	Interval, m	Description
Mura formation	0-1260	Gray, marly slightly sandy clays with layers of gray fine-grained loosely cemented sandstone, with medium to coarse-grained sands and gray sandy clay in the upper part, coarse-grained gravel, layers of moderately carbonized coal.
Lendava formation	Paklenica member	1260-1334 Light gray and gray-brown sandy and clayey marl with layers of gray fine-grained moderately cemented quartz sandstone. Throughout the interval, there are also thin layers of moderately to well carbonized coal. In the upper part, there are gray marly clays with some sand.
	Gorice marl	1334-1347 Light gray to gray-brown sandy and clayey marl with thin layers of fine-grained loosely cemented quartz sandstone and moderately carbonized coal.
	Paka sandstones	1347-1385 In the upper part, there is light gray, fine-grained, gritty sandstone, while the lower part consists mainly of gray-brown siltstone.
	Lower Lendavčica marl	1385-1453 Light gray and gray-brown siltstone, fine-grained micaceous sandstones.
	Lower Ratka sandstones	1453-1523 Gray, fine-grained micaceous sandstones with layers of dark gray sandy siltstone interleaved.



	Pince marl	1523-1570	Sandy siltstone with thin layers of gray, fine-grained micaceous sandstone.
	Siget sandstones	1570-1588	Gray, micaceous, and fine-grained sandstones, and slightly sandy dark gray siltstones.
	Lenti marl	1588-1624	Siltstone with very thin and sparse layers of gray, fine-grained micaceous sandstone.
Mura-Sobot formation	Međimurje member	1624-1665	Silicified chloritized effusive rock (andesite?), olive green in color, associated mineralogically with plagioclase, quartz, calcite, chlorite, and pyrite.

Table 11 Geological description of the stratigraphic units on well Mih-4

4.1.9. Lithology description for well Mihovljan-4 α

The Mihovljan-4 α borehole penetrated the deposits of the Mura Formation, the Lendava Formation and the Mura-Sobot Formation. Based on the observation of sieve samples, calcimetry, coring testing, gas manifestations, mud and mechanical drilling speed, lithostratigraphic formations were determined (Table 12), while the geological description of each formation is given in Table 13.

Formation	Interval (m)
Mura Formation	0-1355
Lendava Formation	1355-1768
Mura-Sobot Formation	1768-1774

Table 12 Stratigraphic units with corresponding intervals at well Mih-4 α

Formation	Interval, m	Description	
Mura formation	0-1355	Gray, clayey slightly sandy clays with layers of gray, loosely cemented fine-grained sandstone, in the upper part are represented by medium to coarse-grained sands and gray sandy clay, coarse gravel, layers of moderately carbonized coal.	
	Paklenica member	1355-1442	Gray to gray-brown clayey siltstone and gray, fine-grained micaceous loosely cemented sandstone.
	Gorice marl	1442-1456	Gray to gray-brown clayey siltstone with thin layers of gray, fine-grained micaceous loosely cemented sandstone.
Lendava formation	Paka sandstones	1456-1504	Gray, fine-grained loosely cemented sandstones with layers of brown sandy siltstone.
	Dolina-Lendavčica marl	1504-1581	Brown sandy siltstone with thin layers of gray, fine-grained loosely cemented sandstone.
	Lower Ratka sandstones	1581-1654	Gray, fine-grained micaceous sandstones with layers of gray to gray-brown sandy siltstone.
	Pince marl	1654-1697	Gray to gray-brown siltstones that are occasionally sandy.



	Siget sandstones	1697-1738	Gray, fine-grained micaceous sandstones with interbedded gray to dark gray moderately hard siltstones and micaceous siltstone-sandstone.
	Lenti marl	1738-1768	Gray to dark gray moderately hard siltstone.
Mura-Sobot formation	Međimurje member	1768-1774	Silicified chloritized effusive rock (andesite?).

Table 13 Geological description of the stratigraphic units on well Mih-4a

4.1.10. Lithology description for well Mihovljan-4B

The Mihovljan-4B borehole penetrated the deposits of the Mura Formation, the Lendava Formation and the Mura-Sobot Formation. Based on the observation of sieve samples, calcimetry, coring testing, gas manifestations, mud and mechanical drilling speed, lithostratigraphic formations were determined (Table 14), while the geological description of each formation is given in Table 15.

Formation	Interval (m)
Mura Formation	0-1500
Lendava Formation	1500-1938
Mura-Sobot Formation	1938-2022

Table 14 Stratigraphic units with corresponding intervals at well Mih-4B

Formation	Interval, m	Description	
Mura formation	0-1500	Gray, clayey slightly sandy clays with layers of gray, loosely cemented fine-grained sandstone are represented in the upper section by medium to coarse-grained sands and gray sandy clay, coarse gravel, and layers of moderately carbonized coal	
	Paklenica member	1500-1615	Gray to gray-brown clayey siltstone and gray, fine-grained micaceous loosely cemented sandstone.
	Gorice marl	1615-1676	Gray to gray-brown clayey siltstone with thinner layers of gray, fine-grained micaceous loosely cemented sandstone.
	Paka sandstones	1676-1680	Gray, loosely cemented fine-grained sandstones with layers of brown sandy siltstone.
Lendava formation	Lendavčica marl	1680-1724	Gray to gray-brown clayey siltstone with very thin layers of gray, fine-grained micaceous loosely cemented sandstone.
	Upper Ratka sandstones	1724-1731	Gray, loosely cemented fine-grained micaceous sandstone, gray to gray-brown sandy siltstone.
	Dolina marl	1731-1788	Brown sandy siltstone with thin layers of gray, fine-grained loosely cemented sandstone.
	Lower Ratka sandstones	1788-1840	Gray, fine-grained micaceous sandstones with layers of gray to gray-brown sandy siltstone.
	Pince marl	1840-1898	Gray to gray-brown siltstones that are occasionally sandy.



	Siget sandstones	1898-1921	Gray, fine-grained micaceous sandstones interbedded with gray to dark gray moderately hard siltstones and micaceous silty sandy siltstones.
	Lenti marl	1921-1938	Gray to dark gray moderately hard siltstone.
Mura-Sobot formation	Međimurje member	1938-2022	Silicified chloritized effusive rock (andesite?).

Table 15 Geological description of the stratigraphic units on well Mih-4B

4.1.11. Lithology description for well Mihovljan-5

The Mihovljan-5 borehole penetrated the deposits of the Mura Formation, the Lendava Formation and the Mura-Sobot Formation. Based on the observation of sieve samples, calcimetry, coring testing, gas manifestations, mud and mechanical drilling speed, lithostratigraphic formations were determined (Table 16), while the geological description of each formation is given in Table 17.

Formation	Interval (m)
Mura Formation	0-1170
Lendava Formation	1170-1634
Mura-Sobot Formation	1634-1898

Table 16 Stratigraphic units with corresponding intervals at well Mih-5

Formation	Interval, m	Description	
Mura formation	0-1170	In the upper part of the formation, there are coarse-grained sands and medium-grained variegated gravel, while the predominant part of the formation is clayey with layers of coal. The lower part of the formation consists of grayish-blue soft clay with layers of sandstone.	
	Paklenica member	1170-1273	Grayish-blue soft clay with layers of light gray, fine-grained, loosely cemented sandstone.
	Gorice marl	1273-1289	Soft clay and loosely cemented fine-grained sandstone.
	Paka sandstones	1289-1346	Grayish-blue soft clays, fine-grained and loosely cemented sandstones, towards the base transition into soft and marl-like clays.
Lendava formation	Dolina-Lendavčica marl	1346-1475	Soft and grayish-blue marl, with layers of light gray, loosely cemented sandstone in the lower part of the member
	Lower Ratka sandstones	1475-1510	Light gray, loosely cemented sandstones, soft, gray to blue siltstone.
	Pince marl	1510-1546	Marl, sandstone appears only in the interval from 1535 to 1540 m.
	Siget sandstones	1546-1580	The upper and lower parts are sandstones, while the central part is marly.



	Lenti marl	1580-1634	Gray moderately hard marl with thin layers of loosely cemented gray sandstone.
	Petišovci sandstones	1634-1675	Fine to medium-grained light gray well-cemented micaceous sandstone with layers of marl.
Mura-Sobot formation	Benica marl	1675-1692	Marl with layers of fine to medium-grained light gray well-cemented micaceous sandstone.
	Međimurje member	1692-1898	Effusive rocks of gray-greenish-white color in which quartz and pyrite are macroscopically observed.

Table 17 Geological description of the stratigraphic units on well Mih-5

4.1.12. Lithology description for well Mihovljan-6

The Mihovljan-6 borehole penetrated Quaternary, upper Pontic, lower Pontic, upper Pannonian and lower Pannonian deposits. Based on the observation of sieve samples, calcimetry, coring testing, gas manifestations, mud and mechanical drilling speed, lithostratigraphic formations were determined (Table 18), while the geological description of individual formations is given in Table 19.

Stratigraphic unit	Interval
Quaternary	0 - 20 m
Upper Pontian	20 - 1161 m
Lower Pontian	1161 - 1449 m
Upper Pannonian	1449 - 1658 m
Lower Pannonian	1658 - 1754 m

Table 18 Stratigraphic units with corresponding intervals at well Mih-6

Stratigraphic unit	Interval, m	Description
Quaternary	0 - 20	Multicolored gravel of heterogeneous composition and various grain sizes, sand, clayey sands, gray-green clays.
Upper Pontian	20 - 1161	Gray and light gray sandy clays with layers of lightly carbonized coal, fine-grained clayey sand, gray siltstone-like clays, and gray clayey siltstone.
Lower Pontian	1161 - 1449	Gray clayey siltstone, gray soft siltstone, gray sand, and gray fine-grained micaceous loosely cemented quartz sandstone.
Upper Pannonian	1449 - 1658	Gray moderately hard marl and gray fine-grained micaceous quartz sandstone, loosely to moderately cemented.
Lower Pannonian	1658 - 1754	Gray to brown-gray moderately hard to hard marl and brown-gray fine-grained micaceous quartz sandstones, loosely to moderately cemented.



Table 19 Geological description of the stratigraphic units on well Mih-6

4.1.13. Lithology description for well Mihovljan-7

The Mihovljan-7 borehole penetrated Quaternary, upper Pontic, lower Pontic, upper Pannonian and lower Pannonian deposits. Based on the observation of sieve samples, calcimetry, coring testing, gas manifestations, mud and mechanical drilling speed, lithostratigraphic formations were determined (Table 20), while the geological description of individual formations is given in Table 21.

Stratigraphic unit	Interval
Quaternary	0 - 20 m
Upper Pontian	20 - 1124,5 m
Lower Pontian	1124,5 - 1426 m
Upper Pannonian	1426 - 1657 m
Lower Pannonian	1657 - 1745 m

Table 20 Stratigraphic units with corresponding intervals at well Mih-7

Stratigraphic unit	Interval, m	Description
Quaternary	0 - 20	Multicolored gravel of heterogeneous composition and various grain sizes, sand, clayey sands, gray-green clays.
Upper Pontian	20 - 1124,5	Gray sandy clay, multicolored gravel, gray fine-grained sand, gray marl-like clays, and gray fine-grained loosely cemented sandstone.
Lower Pontian	1124,5 - 1426	Gray clayey marl, gray moderately hard marl, and gray fine-grained micaceous quartz sandstone, loosely to moderately cemented.
Upper Pannonian	1426 - 1657	Gray moderately hard marl and gray fine-grained micaceous quartz sandstone, moderately cemented.
Lower Pannonian	1658 - 1754	Gray to brown-gray moderately hard to hard marl and brown-gray fine-grained micaceous quartz sandstones, loosely to moderately cemented.

Table 21 Geological description of the stratigraphic units of well Mih-7

4.1.14. Lithology description for well Mihovljan-8

The Mihovljan-8 borehole penetrated Quaternary, upper Pontic, lower Pontic, upper Pannonian and lower Pannonian deposits. Based on the observation of sieve samples, calcimetry, coring testing, gas manifestations, mud and mechanical drilling speed, lithostratigraphic formations were determined (Table 22), while the geological description of individual formations is given in Table 23.

Stratigraphic unit	Interval
Quaternary	0 - 20 m
Upper Pontian	20 - 1164 m



Lower Pontian	1164 - 1452 m
Upper Pannonian	1452 - 1668 m
Lower Pannonian	1668 - 1761 m

Table 22 Stratigraphic units with corresponding intervals at well Mih-8

Stratigraphic unit	Interval, m	Description
Quaternary	0 - 20	Multicolored gravel of heterogeneous composition and various grain sizes, sand, clayey sands, gray-green clays.
Upper Pontian	20 - 1164	Gray sandy clay, multicolored gravel, gray fine-grained sand, gray marl-like clays, and gray fine-grained loosely cemented sandstone.
Lower Pontian	1164 - 1452	Gray clayey marl, gray moderately hard marl, and gray fine-grained micaceous quartz sandstone, loosely to moderately cemented.
Upper Pannonian	1452 - 1668	Gray moderately hard marl and gray fine-grained micaceous quartz sandstone, moderately cemented.
Lower Pannonian	1668 - 1761	Gray to brown-gray moderately hard to hard marls and brown fine-grained micaceous quartz sandstones, loosely to moderately cemented.

Table 23 Geological description of the stratigraphic units of well Mih-8

5. Geothermal Features of the Potential Location with Quantification of Possible Brine Production from the Current Well Assets and any New Drilling

5.1. Size of the Reservoir

- Reservoir Area & Effective Thickness

At the Mihovljan site, the reservoir area is defined as the drainage area of the water saturated Paka, Upper Ratka, Lower Ratka and Siget sandstones layers (Figure 5-1). The rocks in which the oil is accumulated consist of light gray and gray, moderately to firmly cemented quartz Petišovci sandstones. Ranges of permeabilities vary significantly, but effective permeability for entire field is set at 20 mD. It is presumed that water saturated shallower layers of sandstones have similar values. The oil-water contact is located at a depth of -1655 m. Two production-injection well pairs are defined. The first pair consist of Mihovljan-3 β as production and Mihovljan-6 as injection well (drainage area A), with distance of 360 m. The second pair consist of Mihovljan-1 as production and Mihovljan-7 as injection well (drainage area B), with distance of



385 m. Based on the distance between respective production and injection wells, the drainage area using Ramey-Nabor's method [XX] is determined at:

Drainage area of the reservoir A = 139,450 m²

Drainage area of the reservoir B = 159,490 m²

The water saturated layer is determined in Paka, Upper Ratka, Lower Ratka and Siget sandstones layers. According to available data, the average effective thickness of the reservoir is 35 meters. It is important to emphasize that it is unknown which part of these layers is saturated with water and their permeability. Therefore, further testing of the sandstone layers is required to determine the production characteristics of the potential reservoir.

-Assumed average effective thickness of the reservoir = 35 m

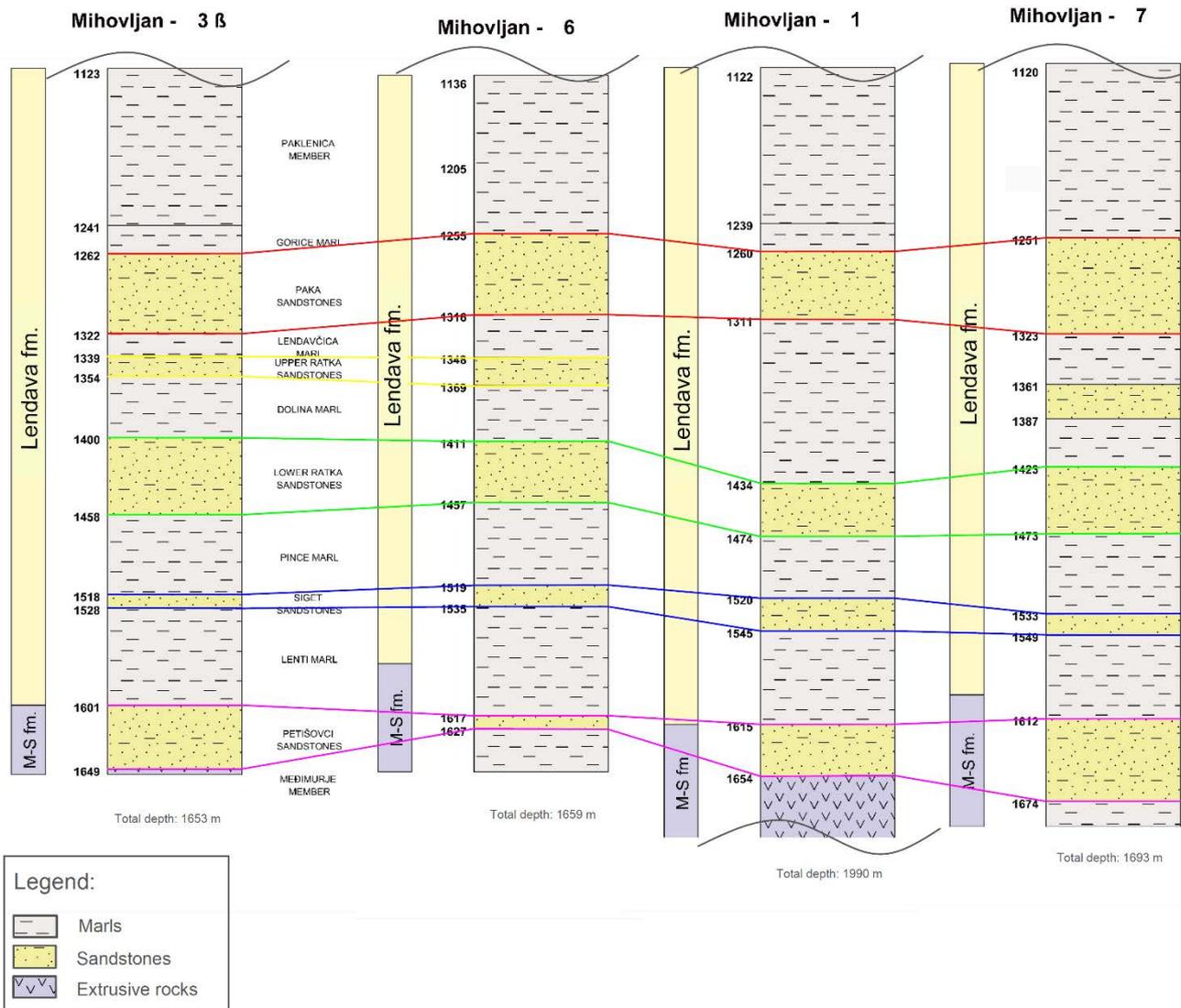


Figure 5-1 Lithological columns of selected wells for production and injection wells in Mihovljan field

- Reservoir Volume

The volume of the entire rock complex of the analyzed parts of the water saturated sandstone deposits would be calculated as the product of the considered drainage area of respective doublets and effective thickness of the reservoir. Thus, the volume of the reservoir rock mass is:

$$V_A = 4\,880\,736 \text{ m}^3, \text{ or } 4,88 \text{ km}^3$$

$$V_B = 5\,582\,153 \text{ m}^3, \text{ or } 5,58 \text{ km}^3$$

5.1.1. Initial Reservoir Pressure and Reservoir Temperature

During the testing of wells that penetrated the Lower Pannonian reservoir in Petišovci sandstones, the following extrapolated pressures and temperatures were obtained (Table 24):



Well name	P_{ext} (bar)	Temperature (°C) (Depth, m)
Međimurje-4	183,50	75,0 (1805,0)
Mihovljan-1	161,30	80,0 (1625,0)
Mihovljan-2	171,02	70,6 (1678,2)
Mihovljan-3β	160,00	98,3 (1775,5)
Mihovljan-6	160,66	92,8 (1686,0)
Mihovljan-7	163,91	96,0 (1661,4)

Table 24 Extrapolated pressures and temperatures

Based on the available data, the initial pressure and temperature, reduced to the reservoir center, are 150 bar and 85 °C. The depth of the reservoir center is 1545 meters.

5.1.2. Characteristics of the Reservoir Fluid

- Amount of dissolved gas in water

This passage addresses a key uncertainty in the development of the project, as it necessitates a different approach to completing wells and utilizing geothermal water. During several Drill Stem Tests (DST) and production tests, occurrences of gas were recorded. Additionally, during DST measurements, instances of gas-infused water inflow into the drill pipes were observed. The total quantity of gas dissolved in the water remains unknown, as production tests and the determination of Gas to Water Ratio (GWR) have not been conducted. Based on drilling data and gas log analysis results, the presence of a natural gas and CO₂ mixture in varying ratios is most common. From the available information, it can be assumed that gas production alongside geothermal water production is a possibility. The assumed dissolved gas content is GWR=5 m³/m³ (predominantly methane and some CO₂).

Due to the ecological necessity of utilizing geothermal energy, natural gas must be separated at the separator and flared, with the resulting CO₂ from combustion being reinjected into the reservoir. Alternatively, if production volumes allow, natural gas can be used in a gas turbine for electricity generation, followed by CO₂ reinjection into the reservoir. Long-term considerations include the injection of produced gas back into the reservoir to maintain reservoir pressures, which facilitates higher extraction rates over time.

- Water formation volume factor

According to McCain (1991), the formation volume factor for water under initial reservoir conditions at a depth of 1545 m ($p_i = 150$ bar, $T = 85$ °C) is:

$$B_{wi} = 1,0305 \text{ m}^3/\text{m}^3$$

At the conditions at the wellhead of the production well ($p_w = 1$ bar, $T = 82$ °C), the formation volume factor for water is:

$$B_{ww} = 1,0316 \text{ m}^3/\text{m}^3$$



- Water density

The density of water under standard conditions is:

$$\rho_{ws.c} = 1018 \text{ kg/m}^3$$

The volumetric mass of water under pT conditions is:

a) Reservoir conditions at 1545 m ($p_i = 150 \text{ bar}$, $T = 85 \text{ }^\circ\text{C}$)

$$\rho_{wr} = 987,8 \text{ kg/m}^3$$

b) At the wellhead conditions ($p_w = 1 \text{ bar}$, $T = 82 \text{ }^\circ\text{C}$)

$$\rho_{wr} = 986,1 \text{ kg/m}^3$$

- Water viscosity

The viscosity of the reservoir fluid is calculated according to McCain (1991):

$\mu_w = 0,40 \text{ mPa}\cdot\text{s}$; it applies to reservoir conditions and production conditions.

- Compressibility of water

The compressibility of reservoir fluid according to Osif (1988):

$$c_w = 4.4 \times 10^{-5} \text{ bar}^{-1}$$

- Volumetric heat capacity of water

The specific heat capacity of water under reservoir conditions is:

$$c_{wr} = 4200 \text{ J/(kg K)}$$

At the wellhead conditions:

$$c_{ww} = 4197 \text{ J/(kg K)}.$$

Volumetric specific heat capacity of water under reservoir conditions:

$$(c_p)_{wr} = 4,149 \times 10^6 \text{ J/(m}^3 \text{ K)}$$

At the wellhead conditions:

$$(c_p)_{ww} = 4,139 \times 10^6 \text{ J/(m}^3 \text{ K)}.$$

5.1.3. Physical Properties of Rocks



- Rock Density

Rock density of the matrix according to Jelić (1987):

$$\rho_m = 2487,9 \text{ kg/m}^3$$

Average value of rock density from the top of the reservoir to the bottom:

$$\rho_s = 2272,8 \text{ kg/m}^3$$

- Volumetric heat capacity of matrix

For calculating the specific heat of the rock's matrix, the following equation is used (Jelić, 1987):

$$c_m = 0,557 e^{-1,460 \cdot H} + 0,908 \quad (5-1)$$

At the center of the reservoir (1545 m), it follows that:

$$c_m = 980,3 \text{ J/(kg K)}$$

The average value for rocks above the reservoir from 0 to 1545 m:

$$c_s = 872,5 \text{ J/(kg K)}$$

Volumetric specific heat of the matrix in the reservoir:

$$(c\rho)_m = 2,430 \times 10^6 \text{ J/(m}^3 \text{ K)}$$

- Thermal conductivity

The thermal conductivity is calculated according to the formula (Jelić, 1987):

$$\lambda = 0,142 \times \rho^{2,86} + 0,623 \quad (5-2)$$

where ρ is expressed in g/cm^3 .

For rocks that heat the injected water in the reservoir at 1545 m, the thermal conductivity is:

$$\lambda = 2,53 \text{ W/(m K)}$$

For rocks through which heat is lost from the water in the well (0-1464 m):

$$\lambda = 2,11 \text{ W/(m K)}$$

- Volumetric heat capacity of a reservoir

The volumetric heat capacity is calculated, with porosity estimated at 20%, according to the formula:

$$(c\rho)_r = \theta (c\rho)_{wr} + (1 - \theta) (c_m \rho_m) \quad (5-3)$$

$$(c\rho)_r = 2,774 \times 10^6 \text{ J/(m}^3 \text{ K)}$$



- Quality of total reserves

The quality of the heat accumulated in the water is obtained as the product of the volumetric specific heat of the water at the wellhead $(cp)_{ww}$ and the difference between the temperature at the wellhead and the average annual temperature.:

$$(cp)_{ww} \times (T_{ww} - T_a) = 4,139 \times 10^6 \times (82 - 11) = 293,9 \times 10^6 \text{ J/m}^3,$$

- Reserve quality

The reserve quality is the portion of the total heat quantity accumulated in the water that is delivered to the user in the heating station. The balance quality is calculated based on the following formula:

$$(cp)_{ww} \times (T_{ww} - T_w) = 4,139 \times 10^6 \times (82 - 30) = 215,2 \times 10^6 \text{ J/m}^3,$$

which amounts to 73,2% of the total quality. The value of the lower temperature limit is estimated based on the outlet temperature at the heat exchanger plant, considering that the thermal energy consumption needs are to be determined.



6. Extraction and Definition of the Geothermal Potential of the Area with Defining the Technical-Technological Aspects of Energy Use of Geothermal Brine for Electricity Production with ORC Technology and/or Direct Use in District Heating

6.1. Production engineering of the geothermal brine

Overall, 15 well channels were drilled within the Mihovljan field (Figure 6-1) out of which 10 are already liquidated and 1 is still producing, while 3 are production inactive and 1 is used for injection (Table 25). Out of the 4 completed wells at the surface, the Mih-1 well is a vertical one, while Mih-3beta (re-entry), Mih-6 and Mih-7 are inclined wells. The active wells are proposed for the repurposing into two production-injection well pairs (doublets) for geothermal brine utilization. The first production-injection pair would be Mih-1 as production well and Mih-7 as injection well, while the second pair would be Mih-3beta as production well and Mih-6 as injection well (Figure 6-2). In all of 4 wells Mura formation, Lendava formation and Mursko-Sobotska formation deposits were drilled. The sediments of interest are water saturated sandstones of Lendava formation (Paka sandstone, Upper Ratka sandstone, Lower Ratka sandstone) of Upper Pannonian and Lower Pontian age, as seen in Figures 6-3, 6-4 and 6-5.

No.	Well	Year	Well Length MD (TVD) (m)	Reservoirs	Opened Reservoirs	Well Status	Proposed geothermal revitalization
1	Mih-1	1974.	1990,6	-	II	oil producing (inactive)	Doublet 1 Production
2	Mih-2	1975.	2967,0	I	-	abandoned	-
3	Mih-3	1975.	1862,4	-	-	abandoned	-
4	Mih-3α	1975.	1780,4 (1662,1)	-	-	abandoned	-
5	Mih-3β	1975.	1822,4 (1653,3)	II	II	oil producing (inactive)	Doublet 2 Production
6	Mih-4	1975.	1665,0	-	-	abandoned	-
7	Mih-4α	1975.	1774,0 (1628,8)	-	-	abandoned	-
8	Mih-4β	1976.	2022,0 (1668,2)	-	-	abandoned	-
9	Mih-5	1985.	1898,0	-	-	abandoned	-



10	Mih-6	1985.	1734,0 (1667,5)	-	II	oil producing	Doublet Injection	2
11	Mih-7	1985.	1743,0 (1693,3)	-	II	oil producing (inactive)	Doublet Injection	1
12	Mih-8	1975.	1761,0 (1669,0)	-	-	abandoned	-	
13	Mač-1	1975.	3050,0	-	-	abandoned	-	
14	Mač-1R	2015.	1642,0	-	-	injection for WOR/GWR	-	
15	Md-4	1968.	3010,0	-	-	abandoned	-	

Table 25 List of all drilled wells and channels in the Mihovljan area



Figure 6-1 Location of all wells in the vicinity of the City of Čakovec and nearby settlements area

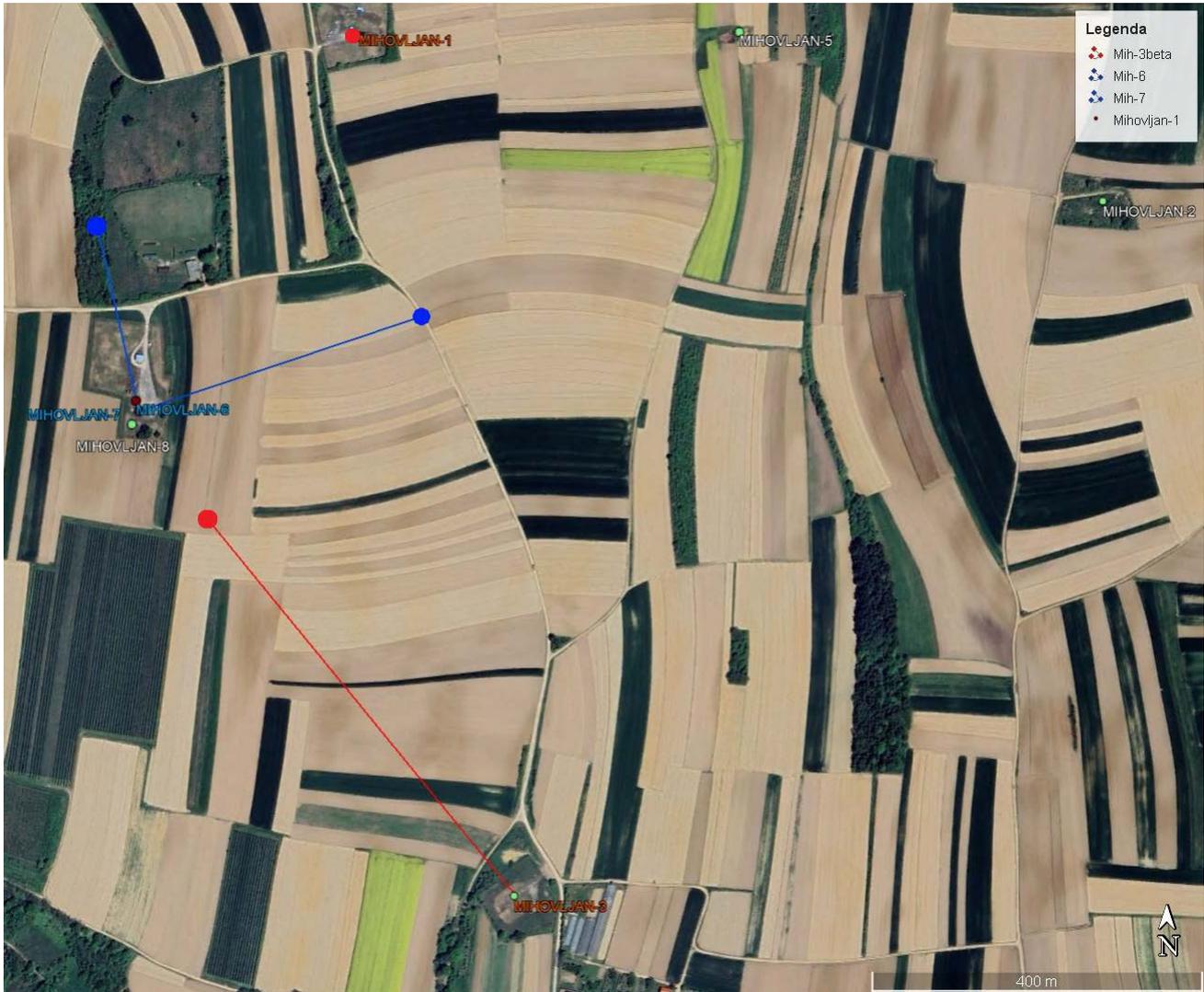


Figure 6-2 Micro location of two doublets; Mih-3 beta and Mih-1 as suggested to be production wells and Mih-6 and Mih-7 as suggested to be injection wells.

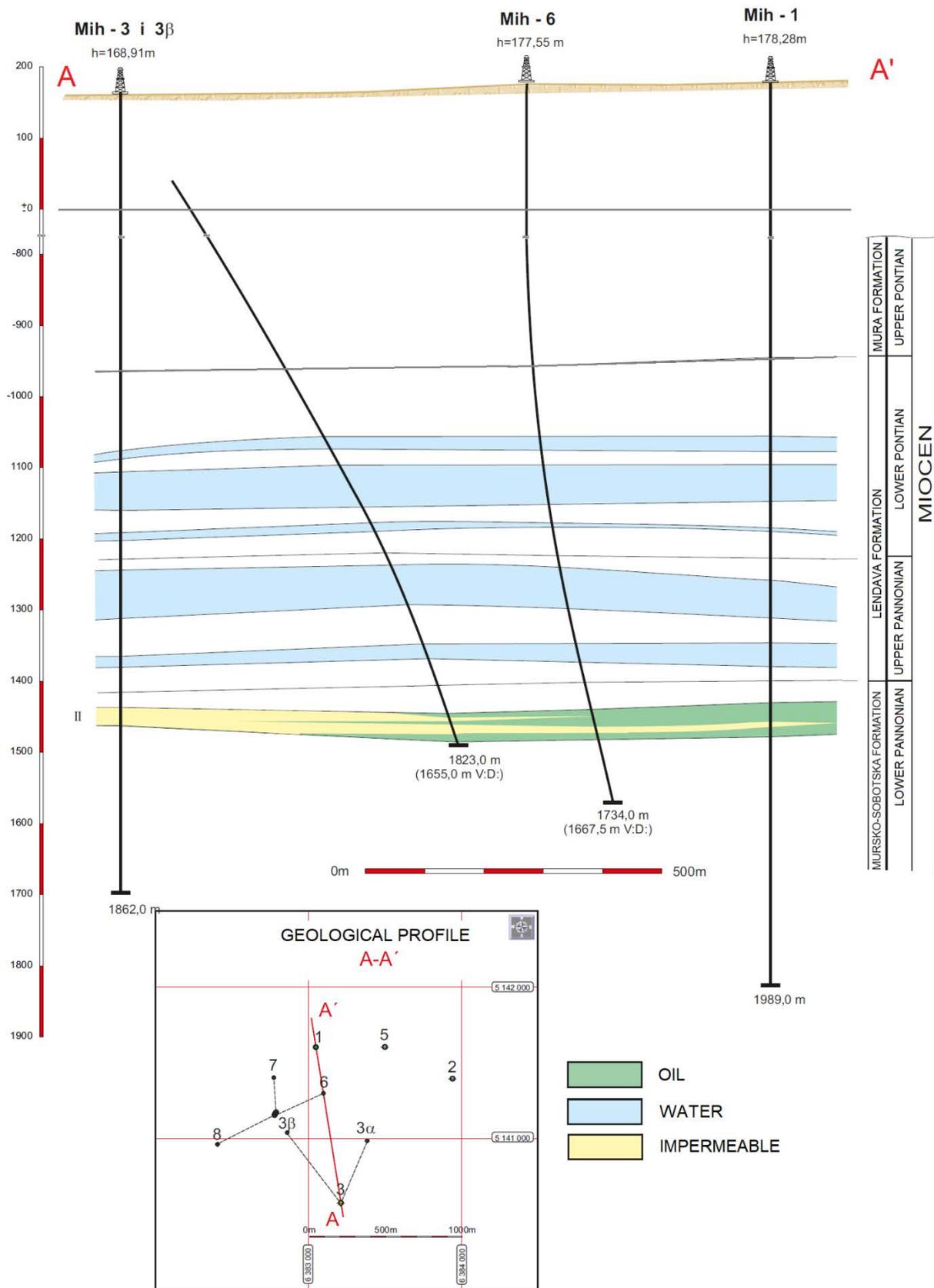


Figure 6-3 Geological profile section A-A' of the oil field Mihovljan and upper water saturated layers for geothermal development

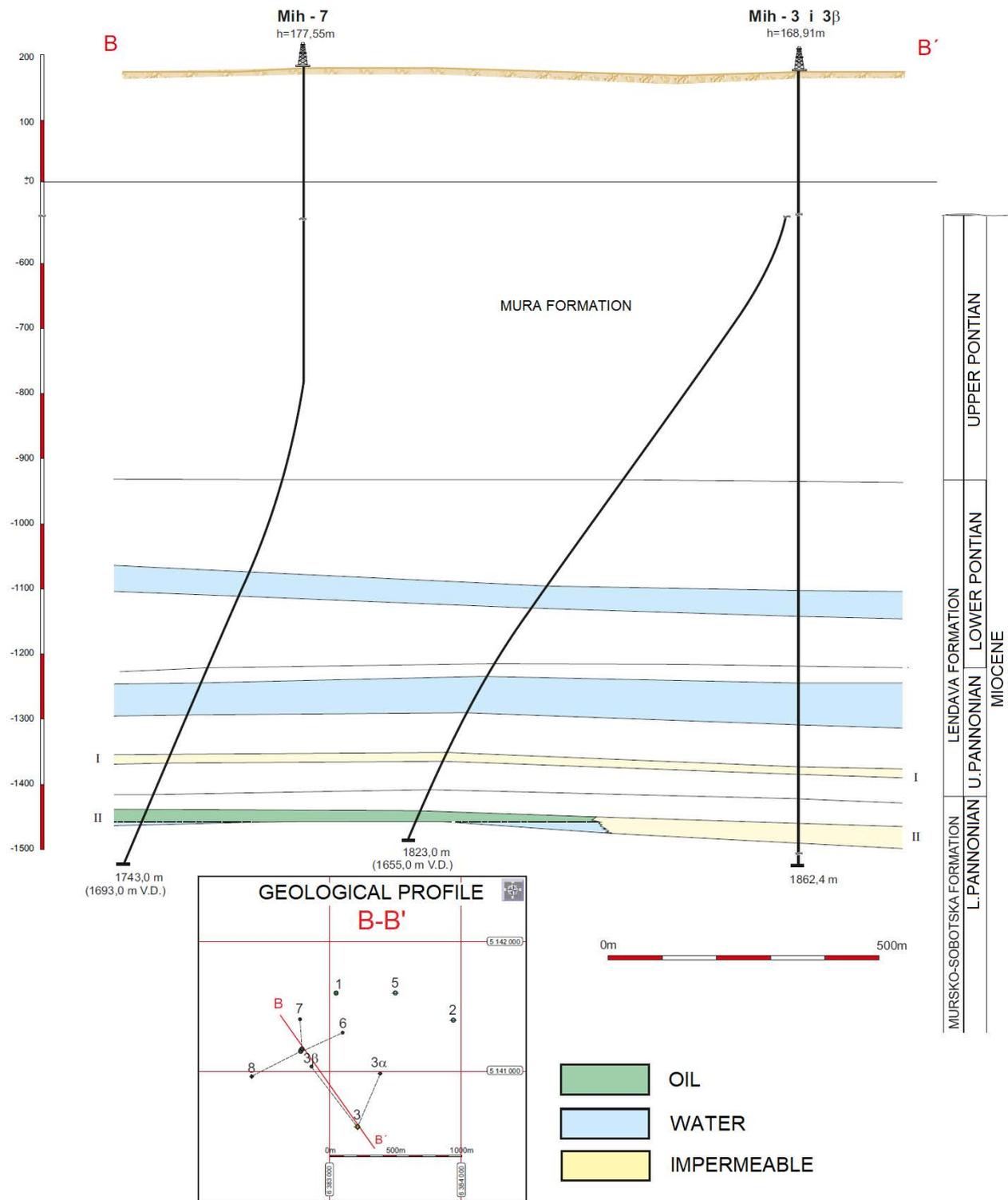


Figure 6-4 Geological profile section B-B' of the oil field Mihovljan and upper water saturated layers for geothermal development

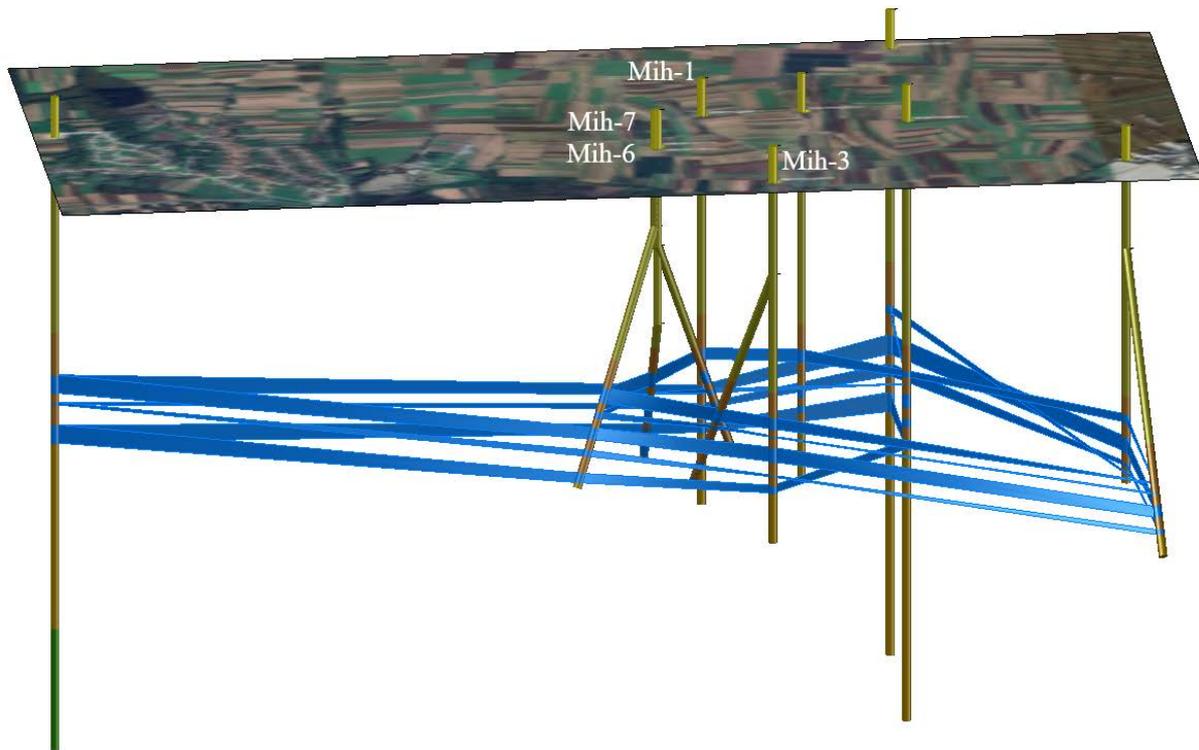


Figure 6-5 Simplified overview of thin water saturated sandstone layers at the Mihovljan area.

By analysing the data from the well fund of the oil field related to testing production capacities, it is evident that hydrodynamic tests were performed on the wells to determine reservoir characteristics. The results of drill stem testing (DST) and hydrodynamic measurements are satisfactorily precise, and good permeability of relatively thin layers of Petišovci sandstones has been established. Ranges of permeabilities vary significantly, but effective permeability for entire field is set at 20 mD. It is presumed that research focused water saturated shallower layers of sandstones have similar values (Paka, Upper Ratka, Lower Ratka sandstones layers). Sandstone layer pressures at all wells are of hydrostatic value, approximately to 1 bar/10m. The basic techno-economic criterion for designing production-injection geothermal well pairs is sizing the flow rate as a function of dynamic pressure in the reservoir and at the production wellhead, i.e. the pressure at the injection wellhead and the dynamic pressure at the bottom of the injection well with the combined power consumption of the ESP and injection pump. Namely, the relationship between the production rate and the bottomhole pressure is conditioned by the physical parameters of the geothermal reservoir (porosity, permeability, layer damage or skin), and reservoir conditions (thickness of the water-saturated production layer and method of opening the interval), as well as the basic design of working conditions through inflow/outflow analysis of reservoir parameters and installed well equipment (layer productivity indicator curve - IPR and fluid lift curve - VLP). This relationship is also influenced by the pipe flow area and surface roughness, but in petroleum engineering, it usually involves a standard 9 5/8" 2nd technical casing column with an outer diameter of 244.5 mm and an inner diameter of 219 mm in this case, with some bottom sections of 5 1/2" production casing.

If the production layers are of low permeability or smaller thicknesses, it is necessary to achieve a large pressure depression at the bottom of the well to produce significant quantities of geothermal fluid. Every exploration of geothermal energy and production characteristics of a potential reservoir carries significant geological risk and reducing the risk and accurately defining geothermal water reserves can be proven by hydrodynamic measurements, i.e., long-term production tests and pressure build-up tests on the exploratory well to define the boundaries of the reservoir and the distribution of permeable parts of the reservoir. Hydrodynamic connectivity of the reservoir is also proven by interference tests on two wells. To provide



guidelines for the decision on further investment in exploratory activities at the microlocation in this initial phase of geothermal potential exploration, a calculation of production characteristics was performed by analysing pressure gradients in the well as a function of fluid type, dissolved gas content, assumed reservoir properties, and technical parameters of the assumed well. Detailed values collected from the analysis of the well fund, geological reports, as well as petrophysical data from upper water saturated thin sandstone layers, were entered. The entire analysis was performed at the node level at the defined bottom reservoir depth of 1545 m (depth of deepest sandstone layer). The interpretation of dynamic pressure results at the bottom of the well at a certain production (with analysis of pressure and temperature drop from the bottom of the well to the wellhead) took the minimum wellhead pressure into account of 1 bar, determining the possibility of corresponding eruptive flow, or usage of ESP if that is not possible. For the purposes of the analysis, it was necessary to select realistic market-available production and injection pumps to analyze with real data. The manufacturers were arbitrarily chosen, given the wide range of production and injection pumps for use in geothermal and petroleum engineering. Also, the sustainable use of geothermal energy at a microlocation requires that the production-injection well pairs be planned so that there is sufficient spacing within the reservoir to prevent the breakthrough of cooled water before an economically set time. It is common for isothermal production to be guaranteed for at least 30 years, after which the breakthrough of the cold fluid front leads to a continuous drop in the production wellhead temperature.

For the microlocation Mihovljan, and two doublets consists of Mih-1 and Mih-3beta as production wells, and Mih-6 and Mih-7 as injection wells, dynamic pressure calculations were performed at a depth of 1545 m, representing the bottom of the deepest sandstone layer of the Lendava formation. The initial pressure in the analysis is hydrostatic and amounts to 150 bar with a temperature of 85 °C at the centre of the reservoir. The analysed cumulative permeable thickness of the all effective production sandstone layers is 35 m (perforations as opening method) with a 5 1/2" column from 1545 m TVD to the 1200 m TVD, and 9 5/8" casing from 1200 m TVD to the wellhead (presumably part of 5 1/2" would be cut in uncemented part during workover). The assumed dissolved gas content is GLR=5 m³/m³ (predominantly methane and some CO₂), and the two-phase correlation MONA modified (1986) was used for vertical correction of the flow. The reservoir IPR curve was calculated based on the assumption of a fully developed transient flow type after 100 days. Effective porosity is adjusted to 20% according to the analysis of reservoir data, and the skin of the near-wellbore zone is 0 (layer treatment after completion). The reservoir radius is assumed to be 1500 m, with a total system compressibility of 7.25×10^{-4} bar.

The sensitivity analysis of the reservoir capacity was performed for a permeability range of 10/20/30 mD, according to the obtained measurement data of sandstone layers from the oil field. Although higher permeabilities were obtained in some wells during certain tests, it is considered that the best-case approach at this stage of initial reservoir development is not justified due to the high geological risk. The predicted permeabilities can reasonably be considered realistic for upper thin sandstone layers saturated with water. As seen in the calculation results in Figure 6-6, nodal analysis of two-phase fluid flow in the well, with an almost atmospheric wellhead pressure, predicts there is no possibility of establishing eruptive production. The temperature drop during fluid flow from the bottom to the wellhead was calculated using the unified model by Alves et al. (1992) and amounts to 82°C at the wellhead for the ESP mechanical production of 5 l/s. Sensitivity analysis of dynamic pressures at the bottom was performed for effective variations in interval permeability for the same wellhead pressure.

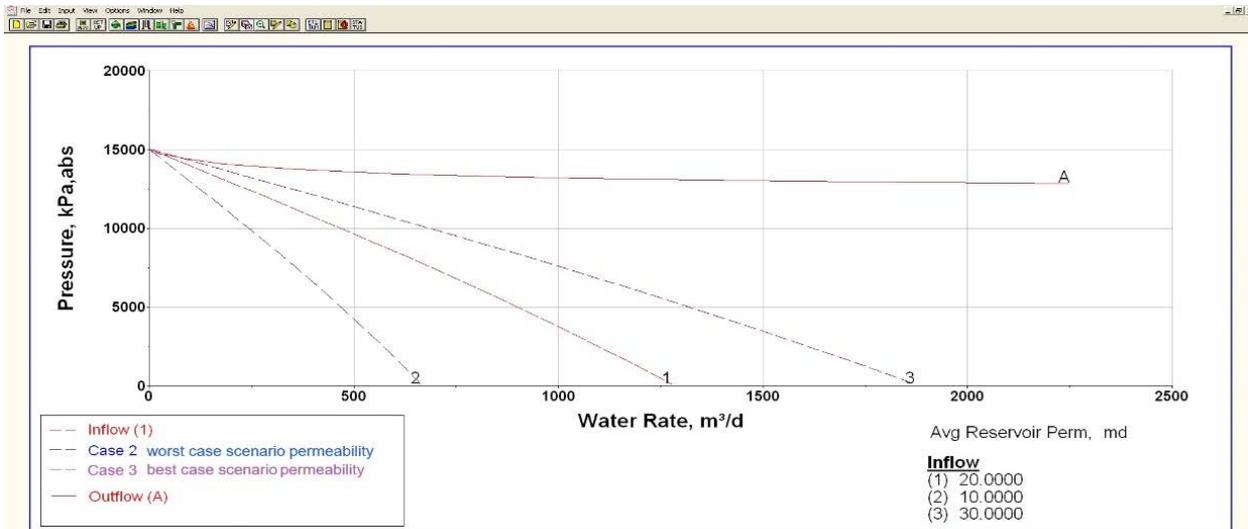


Figure 6-6 Production capabilities of the well (inflow/outflow - IPR inflow performance curve and VLP fluid lift curve) with sensitivity analysis on effective permeability

In Figure 6-6, it is evident that a flow of 465 m³/d (5.4 l/s) can be established for this reservoir and production model with a realistic effective permeability of 20 mD, considering the pressure depression for the mentioned production of $\Delta 50$ bar and dynamic pressure at the bottom of the well of 100 bar, with a theoretically minimal dynamic wellhead pressure of 1 bar. For the production model with sensitivity analysis on worst case scenario effective permeability of 10 mD, it is evident that a flow of 243 m³/d can be established for this reservoir model and same bottom and wellhead pressures. For the production model with sensitivity analysis on best case scenario for effective permeability of 30 mD, it is evident that a flow of 688 m³/d can be established for this reservoir model, and same bottom and wellhead pressures. By using stronger electric submersible pumps (ESP), it is possible to increase the production of geothermal water but working with higher depression of pressure can cause a fracturing of sandstone and inflow of particles into the well damaging the submersible pump.

The amount of brine that can be obtained using ESP depends on several parameters: the diameter of the submersible pump, the depth of the pump placement according to the dynamic water level in the well, the induced flow, and the gas phase content in the liquid at a certain well depth. The dynamic water level in the well during pump intake is a function of the layer's production capacities (dynamic pressure vs. flow), as seen from the IPR curves shown in Fig 6-6. The gas content in the liquid is also one of the important criteria for the depth of the submersible pump placement, i.e., the retention capacity. The surface ratio should generally not be below 0.85, meaning 85% of the cross-sectional area should be occupied by the liquid, using the pump's separator section to separate the gas phase. With the achievement of the mentioned flow and an overall pump efficiency of 80%, the total pump power must be 34 kWe for each of the production wells. This electricity consumption is also called the internal system load and is an important item in the project's economics. The total annual energy consumption of the pump is calculated depending on the operating profile and the consumer's needs, considering that the inverter pump power and flow are adjusted to the actual current demand for thermal energy in the thermal plant at a given moment.

When injecting water back into the reservoir, a model with degassed geothermal water at a temperature of 30°C (after transferring thermal energy at the thermal plant) was used. The design, which includes nodal analysis, is done on the injection well for the same parameters obtained on the production well (physical characteristics of the reservoir), but the dynamic pressure at the wellhead is increased until data matching (inflow/outflow curve matching - IPR inflow performance curve and VLP fluid lift curve) is achieved. Through nodal analysis, the wellhead pressure was adjusted until a flow rate of 465 m³/d was obtained on the production well for the ESP operation option. This case is possible for an injection pump pressure at the



wellhead of 78 bar. The dynamic pressure at the bottom of the injection well for 465 m³/d is 228 bar (Figure 6-7). The electricity consumption for injecting brine into the reservoir with a 78 bar pump would be 52 kWe for operating conditions at peak production of 465 m³/d for each of the injection wells. As same with the ESP on the production well, this electricity consumption of the injection pump is classified as an internal system load and is an important item in the project's economics. Cumulative consumption of the both ESP pump and injection pump per well pair would be 86 kWe.

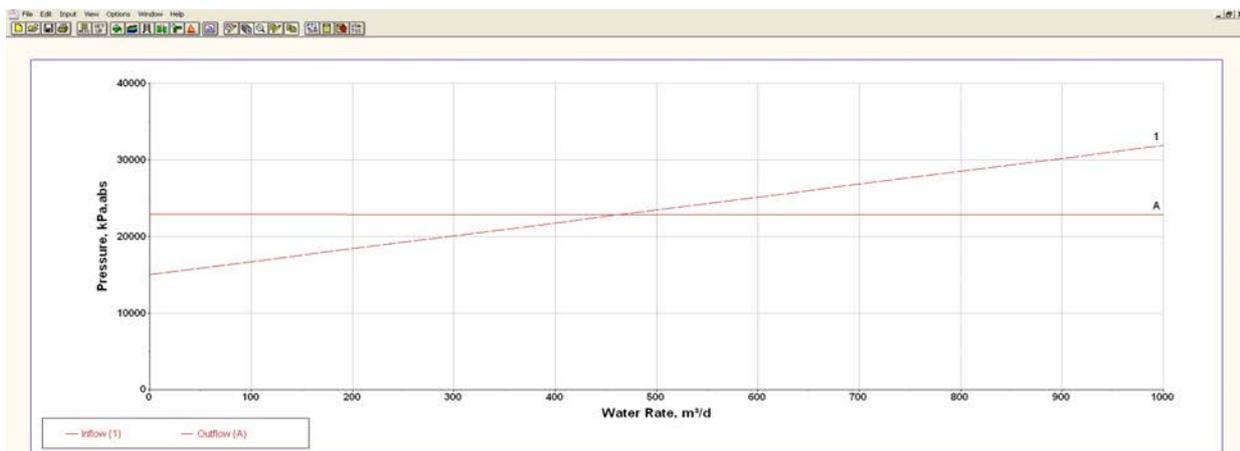


Figure 6-7 Injection well capabilities (inflow/outflow - IPR inflow performance curve and VLP fluid lift curve) for a realistic effective layer permeability of 20 mD in program WellPerform

With two geothermal doublets at the Mihovljan site (as seen from Figure 6-2) setup as Mih-1 and Mih-3beta as production wells, and Mih-6 and Mih-7 as injection wells, cumulative production of 930 m³/d can be obtained for realistic scenario of effective permeability of thin sandstone layers of 20 mD. The wellhead temperature is 82 °C, which means geothermal heat could be used for heating purposes of near-by city buildings or in greenhouses since there is an abundant agricultural land present at the microlocation. With an injection of temperature of 35°C back into the reservoir, total available heat power from two geothermal doublets would be 2124 kWth. Since there is a need to use electric submersible pump at Mih-1 and Mih-3beta, and injection pumps at Mih-6 and Mih-7, total internal electric power needed for geothermal system to operate would be 172 kWe.

If these two values are compared similar to heat pumps efficiency standards, this would give seasonal performance factor of 12,3 for the proposed geothermal system, or to say simply, to achieve 12,3 kW of useful geothermal energy for heating, one must secure input of 1 kW of electric energy to drive production and injection pumps.

6.2. Determination of isothermal production and wellhead temperature

The movement of the fluid through the casing from the reservoir to the wellhead causes the transfer of heat from the fluid to the rock formation, due to the difference in the temperature of the fluid and the geothermal temperature. Also, if the fluid contains larger amounts of dissolved gases, there may be an additional effect of subcooling the liquid by the expansion of the gas in the well itself, based on the reduction of pressure towards the surface. This effect is often called the Joule-Thomson subcooling effect. In petroleum engineering, the generally accepted theory of wellbore temperature drop calculations is the



Ramey model of thermal energy loss to rocks by fluid production. Also, if it is produced through a casing, the simplified Trebin model is often applicable in the oil industry. In 1962, H.J. Ramey calculated the temperature distribution in the well through which the hot fluid is injected, as well as the heat transfer of the fluid in the well to the surrounding rock. He made the calculations under the assumption that the fluid maintains the initial temperature, and the analyses are the results of heat loss during the infinite flow of the fluid. For geothermal wells, it is necessary to calculate the time-limited flow of the fluid, and the heat loss is obtained as a function of the properties of the fluid and the velocity of the fluid flow. The flow of only one phase is observed. Given that the overall heat transfer coefficient, U , is obtained by summing the individual heat transfer coefficients, there are three main guidelines for calculating the overall coefficient. The thermal resistance of the pipe or column of protective pipes (casing) is often neglected, given that the thermal conductivity of steel is higher than the thermal conductivity of other materials found in the well and the thermal conductivity of the rock formation itself.

The thermal resistance of liquid or steam can often be ignored, given that the coefficients of thermal heat transfer through a thin layer are high, and they provide little resistance to heat transfer. The formula for determining the temperature of the fluid in the tubing is valid under the assumptions that:

- physical and thermal properties of rock and drilling fluid do not change with temperature change
- heat transfer to the rock formation takes place radially
- heat transfer in the well takes place faster than heat transfer in the rock formation, and it can express as a steady state:

$$A = \frac{2\pi\lambda}{qc_{pf}f(\tau)} \quad (6-1)$$

$$f(\tau) = \ln\left(1 + \sqrt{\frac{\lambda\pi\tau c_{pf}}{(c_p\rho)_m r^2}}\right) \quad (6-2)$$

$$T_1 = (T_0 - G_t H) + \frac{G_t}{A}(1 - e^{-AH}) \quad (6-3)$$

22

Where λ is thermal conductivity of the formation [W/mK], q geothermal fluid production [kg/s], c_{pf} specific heat of the fluid [J/kgK], $f(\tau)$ dimensionless function of time, A dimensionless variable, G_t geothermal gradient [K/m], H depth [m], fluid temperature at the bottom of the well [K], T_1 temperature at the wellhead [K].

6.2.1. Location Mihovljan

Considering that the bottom of the geothermal sandstone reservoir is located at the depth of 1545, it is to be expected that there will be a certain difference in the temperature of the bottom and at the wellhead, even with longer periods of time of fluid production, due to loss of thermal energy in shallower, but colder, rock horizons. The adopted temperature values at the centre of the reservoir in the calculations serve as a starting factor for the analysis of heat energy loss from the geothermal fluid to the surrounding rocks. The



calculation of the temperature drop of the fluid in the pipes was performed in accordance with the known correlations of thermogeological parameters for the rock formations of the Drava Basin.

As can be seen from the earlier analysis and testing at Mihovljan wells, the static temperature at the centre of the reservoir of 85 °C was taken for calculations. A pumping rate, i.e. production, of 5,4 l/s for one production well for the case of permeability of 20 mD was assumed. Since both production wells target the same depths, the calculation is valid for both production wells. The Figure 6-8 shows the temperature during production for more than a year, while Figure 6-9 shows the temperature in semi-log scale.

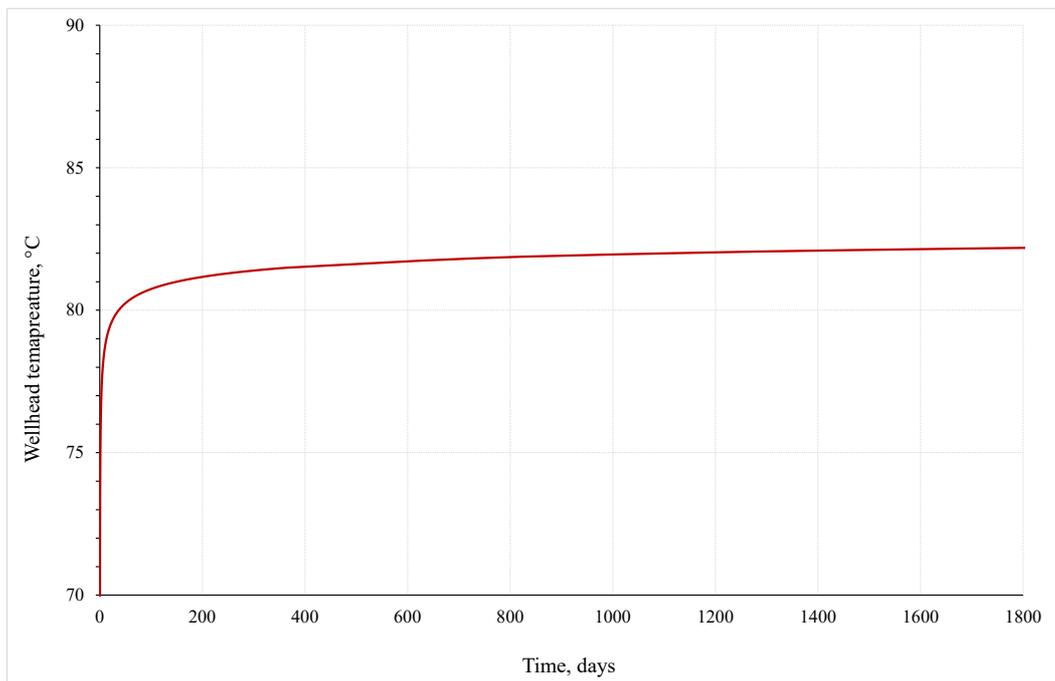


Figure 6-8 Temperature evolution during production from the production well at the Mihovljan location at a flow rate of 5,4 l/s

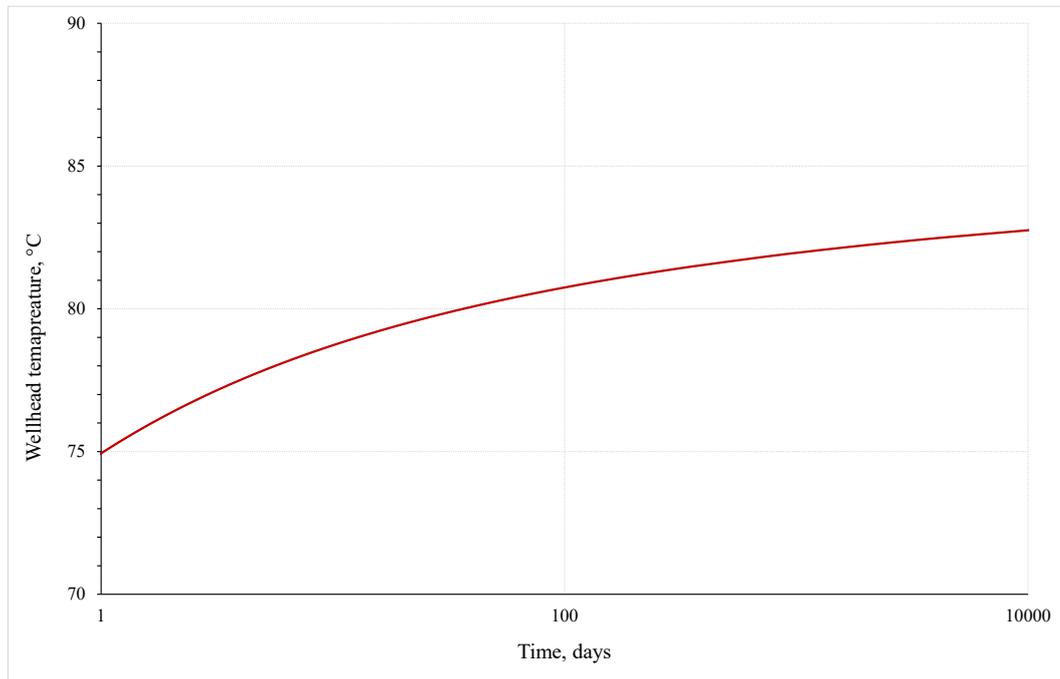


Figure 6-9 Temperature evolution during production from the production well at the Mihovljan location in a semi-log scale at a flow rate of 5,4 l/s

6.3. Sustainability and renewability

For each geothermal reservoir with a technologically selected method of production and injection, there is a marginal production below which it is possible to exploit constant energy for a longer period. If this limit value is exceeded with energy consumption from the reservoir, the production life of the reservoir will be significantly shortened. Production almost equal to or less than this limit can be called sustainable production. The production of thermal energy and its recovery within the reservoir behaves mostly asymptotically. In the initial stage, the curve reflects an accelerated decrease in energy or an intense increase during heat restitution by processes within the reservoir itself, and then the decrease or increase in function slows down. The initial state of energy in the reservoir in the theoretical sense would be reached only after an infinite time, but in practice it happens much earlier, according to the time of exploitation and as a result of the action of natural forces such as pressure and temperature gradients.

The time during which the temperature of the obtained geothermal brine will be constant depends on the rate of exploitation of the reservoir, that is, it is expressed as the ratio of production reserves in the reservoir and the yield of the well:

$$\tau_c = \frac{A h (c\rho)_L}{q_w (c\rho)_w} \quad [god] \tag{6-4}$$

Where τ_c indicates the time of isothermal production [year], A flow area of the reservoir [m²], h flow thickness of the reservoir (mean value) [m], $(c\rho)_L$ volume specific heat of the reservoir [J/m³°C], $(c\rho)_w$



volumetric specific heat of water $[J/m^3\text{°C}]$ and q_w annual amount of produced geothermal brine $[m^3/\text{god}]$. Since it is valid:

$$W_{pc} = q_w \tau_c \quad (6-5)$$

then the total amount of geothermal brine produced, W_{pc} $[m^3]$, at constant temperature, can be calculated as:

$$W_{pc} = \frac{A h (c \rho)_L}{(c \rho)_W} [m^3] \quad (6-6)$$

At the moment of its penetration into the production well, the subcooled geothermal fluid will not top the entire surface of the reservoir, so in this regard, the production well will have a double supply. Geothermal brine that is exhausted by the production well is replaced by injected water of a lower temperature. This injected water moves in the reservoir in the form of a wedge, so at the moment of its penetration into the production well, the affected flow surface is smaller than the total surface of the reservoir. The ratio between the affected and the total area when using geothermal energy is called the areal coefficient of coverage. At that moment, the bulk of the injected water takes on the initial reservoir temperature at the expense of heat transfer from the reservoir rock matrix. At the same time, the drop in the temperature of the geothermal brine in the production well will begin when the subcooled zone penetrates into it. The areal coefficient of coverage depends primarily on the layout of the production and injection wells and the viscosity ratio of the injected and produced geothermal brine. For the calculation of isothermal production, it is necessary to determine the flow surface, that is, the injection-drainage surface, which is determined in Variant 1 for one production and one injection well. The injection-drainage surface is calculated according to the method of Ramey and Nabor (1954), as:

$$A_d = a \cdot 2 \cdot D^2 \quad (6-7)$$

Where A_d represents the injection-drainage surface $[m^2]$, a represents the reservoir coverage coefficient, which varies in relation to the injection model, i.e. with regard to the number of injection and production wells, while D represents the distance between the production and injection wells $[m]$. In the case of the model of one injection well and one production well, the reservoir coverage coefficient is 0,538 (Figure 6-10) (Ramey and Nabor, 1954).

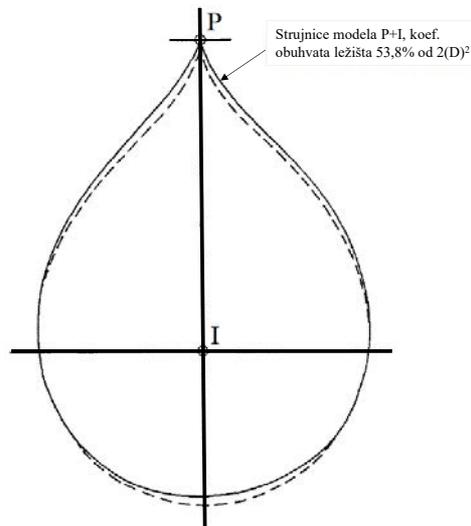


Figure 6-10 Determination of injection-drainage surface and presentation of model flow for one production and one injection well (adapted from Ramey and Nabor, 1954).

With regard to the calculated value of the time in which the cold front penetrates during a certain production, it is necessary to show the temperature drop of geothermal brine after isothermal production as a function of time. The passage of thermal energy through the reservoir is described by the differential equation:

$$\operatorname{div}(\lambda \operatorname{grad} T_L) - \operatorname{div}((c\rho)_w v T_L) = (c\rho)_L \frac{\partial T_L}{\partial \tau} \quad (6-8)$$

Where λ is thermal conductivity [W/m°C], T_L reservoir water temperature in time τ [°C], v water flow rate, τ reservoir exploitation time [s]. This is a multidimensional problem, which takes into account both convection and conduction, so there is no general analytical solution for it. For practical purposes, the differential equation can be simplified with certain assumptions that cause a smaller error than that caused by the unreliability of data on the hydrodynamic and thermodynamic properties of the reservoir and boundary (bed and top) rocks. Gringarten and Sauty (1975) assumed the following for solving expressions 6-9:

1. The reservoir is horizontal, homogeneous, isotropic and has a constant thickness and infinite surface, and the boundary (top and basement) rocks are impermeable.
2. Before the start of injection, the reservoir water and the matrix of the reservoir rocks, as well as the boundary rocks in contact with the reservoir, have an initial temperature that corresponds to the natural balance between heat flow and surface conditions. According to this model, the boundary rocks have an infinite thickness, and at initial conditions, the temperature in them is distributed according to the geothermal gradient. It is also assumed that the initial temperature at infinity (in the direction perpendicular to the Earth's surface) remains constant.
3. Water injection begins in time $\tau = 0$, with constant flow and constant temperature. It is assumed that the flow instantly becomes stationary, and that the incoming water particle and the rock skeleton suddenly assume thermal equilibrium.



4. In the reservoir itself, the conductivity in the horizontal direction is neglected, while it is infinite in the vertical direction. In this way, it is assumed that the temperature in the vertical section of the reservoir is the same everywhere.
5. In the boundary rocks, conduction in the horizontal direction is also neglected, but in the vertical direction it is not neglected (this is the basic condition of recovery). In this way, the transfer of thermal energy is achieved by horizontal convection in the reservoir and vertical conduction in the boundary rocks. Furthermore, the temperature at the contact between the boundary rocks and the reservoir is the same.
6. The thermal properties of the reservoir and boundary rocks are independent of temperature. In addition, it is assumed that the injected water has the same viscosity as that which was originally in the reservoir, so that the dividing line between them is sharp.

With these simplifications, the problem in the reservoir becomes one-dimensional (along the x-axis), and also in the boundary rocks (along the z-axis). In this way, the equation takes the following form:

$$(c\rho)_L \frac{\partial T_L}{\partial \tau} + v_x (c\rho)_W \frac{\partial T_L}{\partial x} = 2\lambda \frac{\partial T_s}{\partial z} \quad (6-9)$$

Where λ refers to conductivity of boundary rocks, and T_s represents the temperature of the boundary rocks [°C]. The first term of this equation represents the heat initially accumulated in the water and the matrix of the rock, the second term represents horizontal convection, and the third the conduction in the boundary rocks. Here, the third term has a positive sign (+), which means that it is heat loss from the reservoir. This equation was established by Lauwerier (1955) for the purposes of designing hot water displacement of viscous oil. The final form can be rearranged for the case of a geothermal reservoir. Conduction in boundary rocks is described by the following equation:

$$\frac{\partial^2 T_s}{\partial z^2} = \frac{(c\rho)_s}{\lambda} \frac{\partial T_s}{\partial \tau} \quad (6-10)$$

In addition to initial conditions:

$$T_L|_{\tau=0} = T_s|_{\tau=0} = T_0 \quad (6-11)$$

and boundary conditions:

$$T_s|_{z=h} = T_L, \quad T_L|_{x=0} = T_{inj}, \quad \lim_{z \rightarrow \infty} (T_s - T_0) = 0 \quad (6-12)$$

where T_0 reservoir temperature at time $\tau = 0$ [°C], T_{inj} temperature of water during injection [°C]. By solving the equations simultaneously, Lauwerier arrived at the final patterns. Gringarten and Sauty rearranged this form so that instead of linear velocity of water flow and layer length, water flow and area are used. The final Gringarten's expression for determining the temperature of the water in the reservoir after injection of the subcooled fluid reads:



$$T_L = T_{inj} + (T_0 - T_{inj}) \operatorname{erf} \left(\frac{A_L \sqrt{\lambda (c\rho)_s}}{q_w (c\rho)_w \sqrt{\tau - \frac{A h (c\rho)_L}{q_w (c\rho)_w}}} \right) \quad (6-13)$$

The equation can be solved by calculating the temperature change at the outlet of the reservoir, i.e. at the bottom of the production wells T_L as a function of time τ for a given area of the reservoir A . The temperature distribution for different surfaces from the inlet to the outlet of the reservoir can also be calculated for a given time. Instead of by the surface, and depending on the nature of the flow, we can calculate the temperature distribution by the radius of water progress for radial flow or by the length of the layer for plane-parallel flow, (since: $A = R^2 \cdot \pi$; i.e.: A = length x width).

It can be seen from the equation that the temperature change will occur only under the following conditions:

$$\tau \geq \frac{A h (c\rho)_L}{q_w (c\rho)_w} \quad (6-14)$$

6.3.1. Microlocation Mihovljan

The thermogeological parameters needed to calculate the time of isothermal production at the Mihovljan site are taken from the previous chapters. For the purposes of calculating isothermal production and determining the temperature response, production volumes for one production well are assumed at 465 m³/d, in order to gain insight into isothermal production of a wider range of production in view of the insufficiently known reservoir features. The stated amounts are assumed with regard to the production possibilities of the reservoir at different permeability conditions, from 10 mD to 30 mD with a step of 10 mD. Assumed well arrangement is in the form of two doublets, each with one production and one injection well. The isothermal production is calculated for each doublet separately. Results for the first well pair (Mih-3β + Mih-6) are seen in Figure 6-11 with the distance between the bottoms of the first well pair at 360 m. It can be seen that in the case of an assumed effective thickness of the reservoir rocks of 35 m, the time of isothermal production in the case of production of 465 m³/d (5.4 l/s) would be 19.2 years, in the case of production of 243 m³/d (2.8 l/s) 36.8 years and in the case of production of 688 m³/d (l/s) 13 years which would be followed by a temperature drop in the reservoir for the corresponding case of production, i.e. the thermal energy of the reservoir would no longer be able to heat the injected fluid to the initial values. Since the production of 456 m³/d was chosen to be realistic scenario, sensitivity analysis showed that in order to have isothermal production of 25 years, the effective thickness of water saturated sandstones should be 46 m.

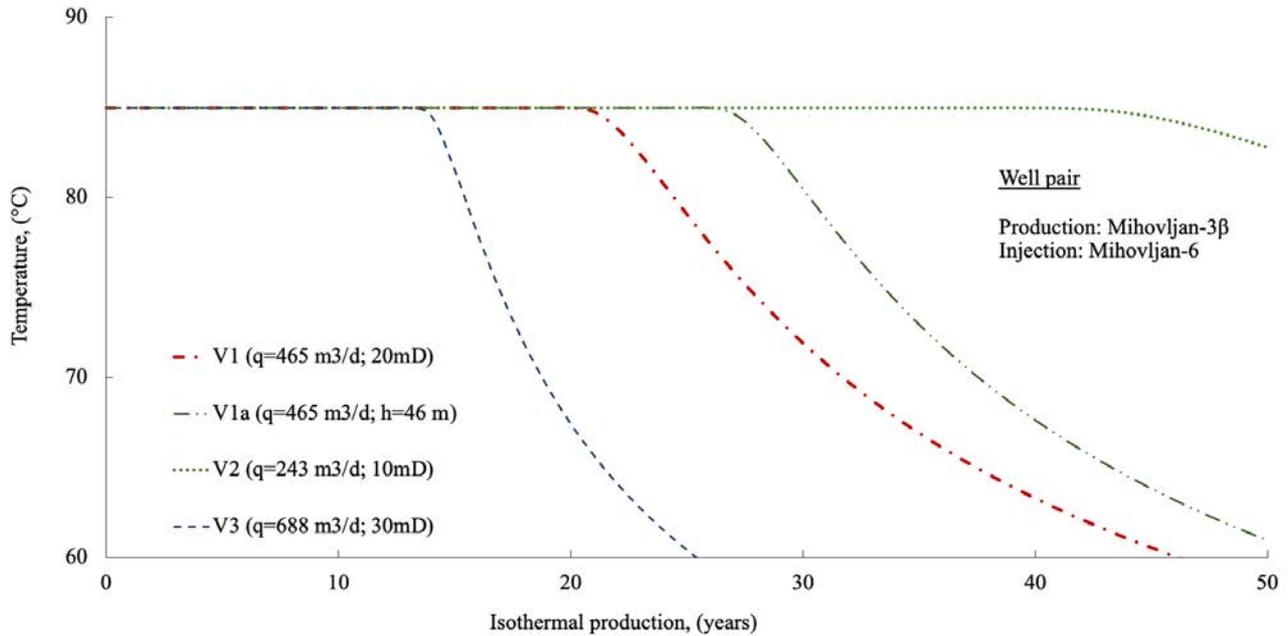


Figure 6-11 Isothermal production in the case of well doublet Mih-3B (production) and Mih-6 (injection) at the Mihovljan location under different production conditions

The results for the second well pair (Mih-1 + Mih-7), where the bottoms of the second well pair is 385 m, are seen in Figure 6-12. It can be seen that in the case of an assumed effective thickness of the reservoir rocks of 35 m, the time of isothermal production in the case of production of 465 m³/d (5.4 l/s) would be 21.9 years, in the case of production of 243 m³/d (2.8 l/s) 42.1 years and in the case of production of 688 m³/d (l/s) 14.9 years which would be followed by a temperature drop in the reservoir for the corresponding case of production, i.e. the thermal energy of the reservoir would no longer be able to heat the injected fluid to the initial values. Since the production of 456 m³/d was chosen to be realistic scenario, sensitivity analysis showed that in order to have isothermal production of 25 years, the effective thickness of water saturated sandstones should be 40 m.

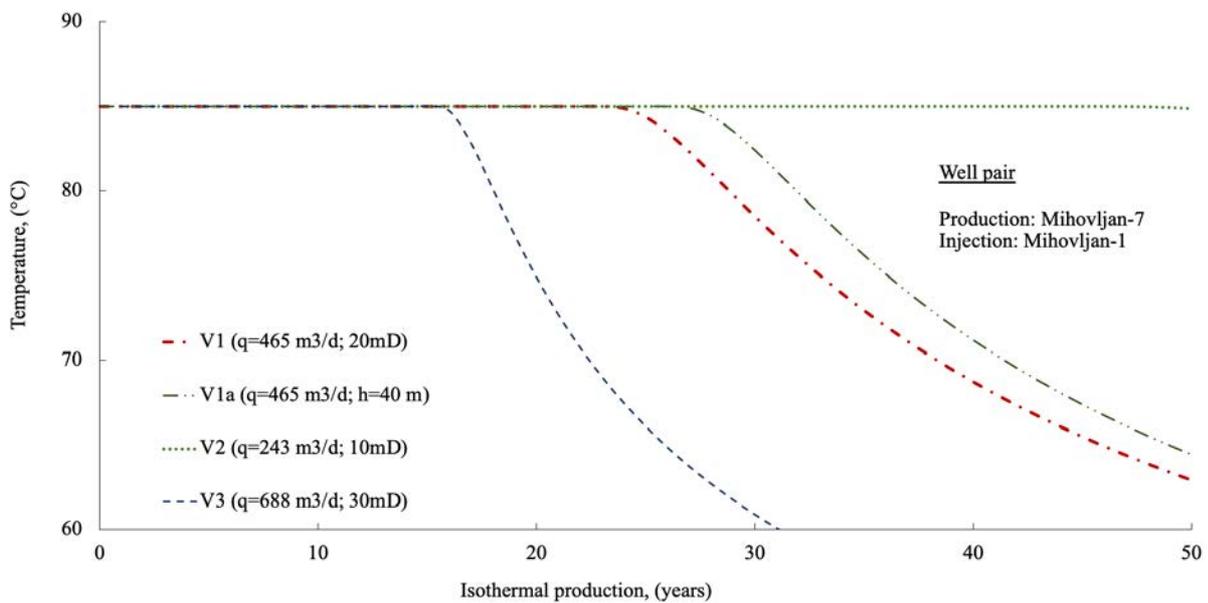


Figure 6-12 Isothermal production in the case of well doublet Mih-1 (production) and Mih-7 (injection) at the Mihovljan location under different production conditions



6.4. Energy potential of the geothermal reservoir

In accordance with the geological structure and temperature gradient values, the Republic of Croatia exclusively possesses geopressured-hydrothermal deposits with fluid as a single-phase liquid containing dissolved minerals and associated gases. Geopressured geothermal deposits contain fluids in a liquid state at relatively high pressures and relatively low temperatures. Dissolved gases must be separated due to optimal application and environmental requirements while simultaneously maximizing production parameters and energy conversion at the surface. The thermodynamic availability of geothermal fluid determines the maximum useful work, which is equal to the change in the fluid's energy availability under conditions at the wellhead and ambient pressure and temperature. Since it largely depends on temperature, availability expresses the thermal potential of the geothermal fluid. Direct use of geothermal energy refers to the immediate use of thermal energy for energy purposes, as opposed to indirect use, where it is converted into, for example, electrical energy. Geothermal energy is directly used in, for example, balneology, space heating, including district heating or centralized thermal systems, agriculture (e.g., greenhouse heating), aquaculture (e.g., heating fish farming pools), industrial processes (e.g., drying fruits and vegetables, drying timber, etc.), and in a cascade system using heat pumps (secondary thermal circuit). Direct use of geothermal energy involves exploiting medium to low-temperature geothermal deposits, with produced geothermal fluid typically in a temperature range from 150 °C to approximately 60 °C. There are numerous examples worldwide and in Croatia of direct geothermal energy use, such as greenhouse production of fruits and vegetables (e.g., Rajska d.o.o. - tomato cultivation in Sv. Nedjelja, Ruris d.o.o. - tomato cultivation in Bošnjaci, Greenhouse in the Snow - tropical fruit cultivation in greenhouses in the USA), balneology (e.g., Varaždinske Toplice, Bizovačke Toplice, Stubičke Toplice) and recreational spas (Hévíz thermal lake in Hungary, Blue Lagoon in Iceland - open-air spas), industrial processes (e.g., Sindirgi Geothermal Vegetable and Fruit Drying Plant - fruit drying in Turkey, The Gunion (garlic and onion) dehydration plant - onion drying in the USA, drying chopped wood mass in Tuscany, Italy, etc.), and for heating (centralized thermal system (CTS) Topusko, CTS Munich in Germany, CTS Bordeaux in France, etc.). Considering the microlocation of the examined Grubišno Polje - Donja Rašenica deposit, potential uses include the development of a CTS in the town of Grubišno Polje, greenhouse production in agriculture, industrial processes (e.g., drying), and similar applications. A positive example of direct geothermal energy use is the system in Topusko, where geothermal energy is used for pools, balneotherapy, and building heating through Croatia's first geothermal CTS. Typically, a system for utilizing thermal energy from geothermal deposits would consist of:

1. Production and injection wells
2. A collection system
3. Separation units for separating dissolved gas from water (depending on the gas composition and content)
4. Facilities for energy utilization (power plant with heat exchangers)
5. An injection system for reinjecting geothermal water
6. A system for pressure relief in emergency situations
7. Measuring, control, and regulatory equipment for the efficiency of the production chain.

The following presents the summarized results of the energy potential of the Mihovljan site energy facility. The input parameters are:

- Temperature of the produced fluid = 82 °C (366.35 K)
- Temperature from the heat exchanger = 30 °C (308.15 K)



- Geothermal fluid flow rate = 465 m³/day (5.4 l/s) per well doublet
- Geothermal fluid flow rate total = 930 m³/day (10.8 l/s) per well doublet

- 2+2 well pair Mih-3B & Mih-1 (production) + Mih-6 & Mih-7 (injection)

○ Total thermal power of the geothermal fluid from the Mihovljan wells (82 to 35 °C): $Q_{geo} = 2,124 \text{ MW}_t$

○ Internal consumption of the facility (production and injection well pumps): $P_{int} = (P_{ESP} + P_{inj}) = (52+34)_{Mih-3B+Mih-6} \text{ kW}_e + (52+34)_{Mih-7+Mih-1} \text{ kW}_e = 172 \text{ kW}_e$

○ Seasonal Performance Factor, SPF (obtained thermal power / consumed electrical power for pumps operation): $SPF = 12,3$



7. Techno-economic Analysis of the Feasibility of Investing in a Geothermal Field at the Potential Location with the Aim of Producing Electrical and Thermal Energy

7.1. Introduction to Techno-economic Analysis

The techno-economic analysis of investments in the construction of mining facilities for the exploitation of geothermal energy takes into account the final price of thermal energy in order to obtain potential revenues from the sale of energy according to the Act on Renewable Energy Sources and High-Efficiency Cogeneration (OG 138/2021, 83/2023).

For the purpose of analyzing the revenue side of the project, it is necessary to consider the prices of thermal energy as well as the prices of a competing energy source such as natural gas. The price of natural gas on September 26th, 2025 was 33.341 EUR/MWh at TTF for Winter 2025. When analyzing the prices of thermal energy, several prices were considered. One is the price of HEP's thermal energy for industrial consumers, which is around 47.9 EUR/MWh. The price used in the calculation is the price of thermal energy from existing distributors of thermal energy from central heating systems with a discount of around 27% in order to attract new customers to the thermal energy market and ensure the competitiveness of geothermal energy.

The Croatian natural gas market is primarily linked to the Central European Gas Hub - CEGH. Geopolitical factors have drastically affected the energy market in Europe in the previous period, and the current situation can be described as a recovery from an energy crisis that may deepen again.

Maintaining lower gas and oil prices, and consequently electricity prices, in the coming period will directly depend on political developments, namely the continuation of the war between the Russian Federation and Ukraine, as well as economic sanctions in response to them by the European Union, as well as on geopolitical developments in other parts of the world, primarily in the Middle East. Although lower prices compared to the extremely high prices of electricity, gas and oil, only show the additional economic and financial importance of investing in renewable energy sources and increasing the security of energy supply.

The economic analysis considered the technological options of the project, as follows:

- An option that assumes the revitalization of four existing wells into two production-injection pairs of wells for the production and use of thermal energy for near-by city buildings and/or agricultural purposes at the Mihovljan location outside protected areas, located at agricultural land P2 but near the settlement.

7.1.1. Plan of Engineering Works for the Revitalization of Existing and Construction of New Wells

To exploit the potential of the Mihovljan exploration area, it is proposed to convert the existing four wells (Mih-1, Mih-3beta, Mih-6 and Mih-7) to two production-injection pairs of wells. The costs of workover for well construction, completion and well testing are listed in Table 26.



The cost of revitalization and completion of wells Mih-1, Mih-3beta, Mih-6 and Mih-7 in the Mihovljan exploration area for geothermal needs is estimated, based on data on well depth, lithology, pressure and temperature conditions, dissolved gas content, well revitalization duration and well purpose, at around EUR 1.275-1.425 million per well, together with well testing. Geothermal wells require special well equipment due to higher flow rates and operating conditions. Due to high temperature and high pressure, higher quality and unit weight of the pipe are required, which makes the equipment more expensive compared to equipment for hydrocarbon production. Special cementing is also required, which is included in the price, as well as the wellhead with blowout preventer. The price also includes the cost of service, equipment and materials based on the current prices for well construction in 2025.

Well	Mih-1	Mih-3beta	Mih-6	Mih-7
Well status (before revitalization)	oil producing (inactive)	oil producing (inactive)	oil producing	oil producing (inactive)
Well status (after revitalization)	production	production	injection	injection
Borehole length (m MD)	2967	1822.4	1734	1743
Maximum temperature	80.0 (1625.0)	98.3 (1775.5)	92.8 (1686.0)	96.0 (1661.4)
Estimated revitalization and completion cost (EUR)	750 000	750 000	1 000 000	1 150 000
Well testing cost (EUR)	550 000	550 000	275 000	275 000
Estimated cost per meter (EUR/m)	438.15	713.35	735.29	817.56

Table 26 Project revitalization and repurposing costs

7.2. Defining Assumptions for Economic and Financial Analysis

Some assumptions of the economic and financial analysis are defined below:

The calculation was made without price indexation according to inflationary trends in the market. Since it is difficult to predict the movement of energy prices in the future in the revenue side, as well as in the expenditure side of the project, the above was not taken into account during the economic and financial calculation of the project.

The project was analyzed over a period of 1 year of the project's exploration phase, i.e. 1 year of construction and 25 years of production, i.e. a total of 27 years. Although the isothermal exploitation period of geothermal energy is estimated to be longer, 25 years is a period that is often taken into account when analyzing energy projects in accordance with the guidelines of the European Commission's Guide to Cost-Benefit Analysis (CBA) (EC, 2014).

The remaining value of the investment after the considered period and after depreciation was not considered as a non-depreciated part, but given the market value of wells and equipment, the stated amount after 25 years of production can be estimated differently, since the stated technological facilities will be used for the same purposes with continuous workover and regular maintenance, and therefore the economic life of the project is significantly longer than 25 years of exploitation. Decommissioning works on well decommissioning are not included in the budget, since it is possible to use the mentioned wells even



after the expiration of 25 years of exploitation. Decommissioning costs may occur before or after the expiration of the 25-year period in the event of an adverse event or cessation of isothermal production.

In the following, the technological solution was analyzed from an economic and financial point of view from the aspect of revitalizing two production and two injection wells at the Mihovljan area and their use for the purpose of producing thermal energy.

According to the Guide for creating CBA analyzes (EC, 2014), it is recommended to take into account a discount rate of 5%. As the project refers to the exploitation of geothermal energy from a deposit that has not been formally determined as exploitable, as well as the exploration works at this stage have yet to be carried out, this economic calculation was made with a discount rate of 10%. Since there are previous results of exploratory drilling on selected boreholes and boreholes in the surrounding area but given the fact that no geothermal aquifer was tested at the location, it is possible to use a different discount rate than the one stated. For this reason, as part of the economic analysis, an NPV profile was created for the technological variant at different discount rates of 1-20%. A rate of 5-7% is normally a common discount rate used in the segments of exploitation activities, while the use of a higher discount rate is associated with potential risks of geothermal potential assessment, but also changes in exploitation volumes, prices of capital costs and exploitation conditions. It is possible to take into account a higher discount rate in the initial phase of the potential assessment (12%) in order to eliminate the geological risks, while after testing the deposit, it is possible to take into account a lower discount rate of 5-7% in the investment study.

Economic benefits and costs (such as reduced CO₂ emissions, increased employment, share of renewable energy sources in the energy mix, etc.) are not monetized in this calculation, but could be calculated during the preparation of a detailed economic analysis as part of the investment study and may positively affect economic indicators, i.e. the profitability of the project for the community.

Exploitation fees are calculated in accordance with the provisions of the Regulation on fees for the exploration and exploitation of hydrocarbons (OG 25/2020 and 43/2023), Section IV - Fee for the exploitation of geothermal waters. For the proposed exploration area Mihovljan, it will be necessary to carry out the procedure for obtaining a permit for the exploitation of a geothermal aquifer. Tributary will be obliged to pay the exploitation fee for geothermal energy in accordance with the Act on the Exploration and Exploitation of Hydrocarbons (OG 52/18, 52/19 and 30/21) and the mentioned Regulation. The analysis took into account the obligation of the investor, who is obliged to pay a monetary fee for the produced quantities of geothermal water in the amount of 3% of the market value of the extracted quantities of geothermal water.

Different heat prices were considered for the revenue calculation. One is the price of HEP's heat energy for industrial consumers, which is 47.9 EUR/MWh. The price of heat energy in the calculation is taken as the price of heat energy from existing distributors of heat energy from central heating systems with a discount of 27%, i.e. a price of 35 EUR/MWh. The stated price will depend on the demand for central heating systems for households or industry or in the agricultural sector in the area under consideration, which will depend on direct negotiations with final consumers on site.

The technological option implies the use of geothermal energy and the revitalization of four active wells into two injection-production pairs is assumed. The limitations include resolving relations with the owners of the land and wells on which the revitalization of the wells is planned and that are the current concessions filed for the hydrocarbons. The price of land has not been considered, and it was assumed at the moment that the price of land is way too low than the price of decommissioning for the previous concessionaire. The technological option considers the relevant costs of necessary documentation and the implementation of all necessary procedures that precede obtaining permits for exploration and exploitation, and within the legal timeframe required for their acquisition. The time for project implementation may be many times longer, and the costs of individual contributions (municipal and water management) may be extremely high, which may negatively affect the results of the project, but the exact amount cannot be predicted at this time, so



they have been taken into account as unforeseen costs in the amount of 2% of investment costs in each year of investment.

The cost structure has been created, with the main costs relating to the revitalization, and completion testing of wells and the construction of connecting pipelines to heat exchangers, which were not taken into account because they will depend on the needs and investments of final heat energy consumers and these costs are shown in the capital investment overview table.

It is calculated that the exploitation field Mihovljan will operate depending on the capacity of the wells, which is currently estimated based on existing data on the thermodynamic and petrophysical characteristics of the reservoir. There is a high degree of uncertainty in the above estimate until individual layers are tested.

The economic and financial assessment of the profitability of reserves of the future Mihovljan geothermal water exploitation field was prepared based on legal regulations and obligations, as well as prices and exchange rates from September 2025.

7.3. Assessment of Investment

Estimates of the investment value in revitalization of existing wells are listed in the tables below. The value of the works is based on the costs of works on similar wells in the Pannonian Basin. The above estimates may vary depending on current market trends, which are rapidly changing due to the geopolitical situation in the world, significant fluctuations in the costs of energy, transport and raw materials, especially metals. In this case, price increases can be expected in all markets. It should also be noted that the relevant exchange rate between the US dollar and the euro is relevant when preparing a techno-economic analysis, since most well drilling and completion prices are referenced in dollars.

On the other hand, technological progress, especially in the production of energy from renewable energy sources, can affect the reduction of technological costs. The assessment did not take into account the reduced price due to the development of technology, nor the increase in market prices due to geopolitical developments in the global market (further increase in energy and raw material prices). For a more detailed cost estimate, inquiries from companies for the purchase and installation of plant and equipment at the analyzed location should be requested.

The creation of the necessary documentation was estimated at EUR 0.2 million for the specified technological option. The costs of the documentation that must be prepared before the start of geothermal water exploitation include the preparation of documents such as the Preliminary mining project, Environmental Impact Study/Elaborate, Reserve Report, Well Construction Project, Main Mining Project for the exploitation of geothermal water, and the Main construction design of mining facilities and pipelines, Location permit, Building permit, and Approval for use of wells and related facilities. Other costs are estimated at a minimum amount.

Connection pipelines include the connection from production wells to heat exchangers at the consumer location or in the immediate vicinity and the return to injection wells. The price of the pipeline with installation that was included in the budget was estimated based on literature data on prices, and given the unreliability of the amounts, it would be advisable to request offers from suppliers with current market prices. In the technological option, it is necessary to invest EUR 6 279 120 in investment funds in documentation, completion (production and injection equipment) and testing of wells, construction of connecting pipelines and installation of piezometers for environmental monitoring. The price of the land was not considered. The structure of expenditures is shown in Table 27.



Rb	Items	2026	2027	Total
1	Land	0.00	0.00	0.00
2	Documentation	150 000.00	50 000.00	200 000.00
2.1	Exploration phase	150 000.00		150 000.00
2.2	Construction phase		50 000.00	50 000.00
3	Well revitalization and repurposing	5 300 000.00	0.00	5 300 000.00
3.1	Workover and completion	3 650 000.00		3 650 000.00
3.2	Well testing	1 650 000.00	0.00	1 650 000.00
4	Connection pipelines	0.00	600 000.00	600 000.00
5	Environmental protection and monitoring system	56 000.00	0.00	56 000.00
6	Unforeseen costs (2%)	110 120.00	13 000.00	123 120.00
	Total (1-7)	5 616 120.00	663 000.00	6 279 120.00

Table 27 Project investment structure

7.4. Defining Benefits and Financial Effects of the Project

7.4.1. Price and Revenue

The revenues from the sale of thermal energy have been established in accordance with the Law on Renewable Energy Sources (NN 138/2021, 83/2023). The price of 47.9 EUR/MWh was taken as the price of thermal energy for calculating the revenue according to the previous explanation, with a 27% reduction for the competitiveness of geothermal energy and increasing market share.

The income from geothermal energy is calculated according to the calculation of the optimal flow obtained based on existing data Table 28.

Revenue	Megawatt-hours (MWh)	Price EUR/MWh	Annual EUR
Thermal energy	4115.70	35.00	144 050

Table 28 Project revenue

Depreciation is calculated on the investments for the technological option and is calculated at a rate of 2.5% in the years of cost and is shown in Table 29. The remaining value of the project is taken into account at the end of the considered exploitation period in the economic assessment of the project.



Depreciation - utilization of borehole thermal energy storage							
Fixed assets	Project start date	Land	Documentation	Civil works and facilities			Total
				Wells	Pipelines	Equipment	
Depreciation rate		0.00%	2.50%	2.50%	2.50%	2.50%	
Utilization of geothermal energy	1.1.2026.	0	200 000	5 300 000	600 000	56 000	6 156 000
Depreciation	2026	0	5000	0	0	0	5 000
Depreciation	2027	0	5000	132 500	0	1400	138 900
Depreciation	2028	0	5000	132 500	15 000	1400	153 900
Depreciation	2029	0	5000	132 500	15 000	1400	153 900
Depreciation	2030	0	5000	132 500	15 000	1400	153 900
Depreciation	2031	0	5000	132 500	15 000	1400	153 900
Depreciation	2032	0	5000	132 500	15 000	1400	153 900
Depreciation	2033	0	5000	132 500	15 000	1400	153 900
Depreciation	2034	0	5000	132 500	15 000	1400	153 900
Depreciation	2035	0	5000	132 500	15 000	1400	153 900
Depreciation	2036	0	5000	132 500	15 000	1400	153 900
Depreciation	2037	0	5000	132 500	15 000	1400	153 900
Depreciation	2038	0	5000	132 500	15 000	1400	153 900
Depreciation	2039	0	5000	132 500	15 000	1400	153 900
Depreciation	2040	0	5000	132 500	15 000	1400	153 900
Depreciation	2041	0	5000	132 500	15 000	1400	153 900
Depreciation	2042	0	5000	132 500	15 000	1400	153 900
Depreciation	2043	0	5000	132 500	15 000	1400	153 900
Depreciation	2044	0	5000	132 500	15 000	1400	153 900
Depreciation	2045	0	5000	132 500	15 000	1400	153 900
Depreciation	2046	0	5000	132 500	15 000	1400	153 900
Depreciation	2047	0	5000	132 500	15 000	1400	153 900



Depreciation	2048	0	5000	132 500	15 000	1400	153 900
Depreciation	2049	0	5000	132 500	15 000	1400	153 900
Depreciation	2050	0	5000	132 500	15 000	1400	153 900
Depreciation	2051	0	5000	132 500	15 000	1400	153 900
Depreciation	2052	0	5000	132 500	15 000	1400	153 900
Remaining value		0	65 000	1 855 000	225 000	19 600	2 164 600

Table 29 Project depreciation



7.4.2. Operating Expenses (OPEX)

Planned revenues from the sale of thermal energy are charged with costs and obligations of internal energy consumption for production (required operation of pumps) and other operating costs estimated according to dynamics, the fund of production wells, the number of employees, norms and legal regulations.

The energy costs were estimated with regard to the required operation of the pumps and the pressures for pumping water into the reservoir, according to the design of the pumps, and were estimated by the efficiency factor SPF (Seasonal Performance Factor), which represents the ratio of consumed thermal energy and internal electrical energy to drive the pumps, and is 12 in the case of the proposed technological option.

Personnel costs are calculated on the basis of an annual gross salary of 25 000 EUR for one employee.

The fee for the exploitation of geothermal water has been calculated in accordance with the Government of the Republic of Croatia's Regulation on Fees for the Exploration and Exploitation of Hydrocarbons (Official Gazette 25/2020 and 43/2023). According to Article 10 of the Regulation, the fee consists of:

1. A fixed monetary fee for the surface area of the established exploitation field, as determined by registration in the register of exploitation fields maintained by the ministry responsible for energy, established under the provisions of the Act on the Exploration and Exploitation of Hydrocarbons. In accordance with Article 11 of the Regulation, the monetary fee amounts to EUR 132.72/km² for facilities that predominantly produce thermal energy from geothermal reservoirs with temperatures below 100 °C. The area of the considered exploration location Mihovljan is approximately 5 km², and it is expected that the exploitation field will be of a similar size; therefore, this surface area was considered when calculating the fixed fee, as the Mihovljan geothermal exploitation field has not yet been officially established. The total amount of the fixed fee is EUR 663.6 EUR per year, given that the facility will produce thermal energy from geothermal reservoirs with temperatures below 100 °C.

2. A variable monetary fee for the produced quantities of geothermal water is calculated according to Article 12 and this fee amounts to at least 3% of the market value of the produced geothermal water, and is calculated as follows:

$$N_{var} = \% \times (C_{el} \times K_{el}) + (C_{top} \times K_{top})$$

Where:

N_{var} - variable monetary fee under Article 10, Item 2 of the Regulation

% - fee percentage

C_{el} - price of electricity (EUR/kWhel)

K_{el} - quantity of electricity delivered to the grid (kWhel)

C_{top} - price of thermal energy (EUR/kWhel)

K_{top} - quantity of thermal energy delivered to the district heating system

The exploitation fee for geothermal water for the surface of the established exploitation field is paid for the duration of the exploitation field in the current year, in proportion to the amount of the annual fee, and becomes due no later than the end of the fourth quarter of the current year. The monetary fee represents revenue of the state budget of the Republic of Croatia, but is fully allocated to the local government unit in whose territory the exploitation field is located. If the exploitation field extends across several local government units, the fee is divided proportionally to the surface area of the exploitation field within each unit.



The monetary fee for the extracted quantities of geothermal water is revenue of the state budget. If there are contracts for the sale of electricity or thermal energy, the applicable price is the one achieved by the investor under the sales contract, i.e., the incentive price the investor may obtain through the sale of electricity and thermal energy. The calculation is therefore based on the actual amount of energy sold, rather than the total amount of energy produced, since a portion of the energy is required to operate the pumps. Allocated costs were calculated at a rate of 3% of revenues in each technological option of the project.

The calculation of the project's operating costs for the proposed technological option is presented below (Table 30).

Item	Calculation	Annual costs (EUR)
1. Direct costs		
Energy costs	37 840.00	37 840.00
Total		37 840.00
2. Workover costs (every five years)		
Workover	660 000.00	132 000.00
Total		132 000.00
3. Concession fee for exploitation		
Fixed part	132.72 EUR/km ² ; 5 km ²	663.60
Variable part	3% of the market value of delivered energy	4321.49
Total		4985.09
4. Gross salaries of personnel		
1 employee	25 000 EUR gross per year	25 000.00
Number of employees	1	25 000.00
Total		25 000.00
5. Indirect costs		
Allocated cost	3% of annual revenues	4321.49
Total		4321.49
Total		204 146.57

Table 30 OPEX calculation

7.4.3. Calculation of Economic Indicators for Variant 1

The discounted economic flow for the proposed technological option is shown in Table 31.



Year of project	Year	Total revenues (EUR)	Total revenues (EUR)	Expenditures (EUR)									Depreciation (EUR)	Residual value of investment (EUR)	Net revenues (EUR)	Cumulative net revenues (EUR)
		Mwht		Investments	Allocated costs	Energy costs	Workover	Personnel costs	Exploitation fee – fixed part	Exploitation fee – variable part	Corporate tax	Total expenditures				
1	2	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
0	2026		0	5 616 120	0	0		25 000	664	0	0	5 641 784	5000		-5 641 784	-5 641 784
1	2027		0	663 000	0	0		25 000	664	0	0	688 664	138 900		-688 664	-6 330 447
2	2028	4116	144 050		4321	37 840		25 000	664	4321	12 943	85 089	153 900		58 960	-6 271 487
3	2029	4116	144 050		4321	37 840		25 000	664	4321	12 943	85 089	153 900		58 960	-6 212 526
4	2030	4116	144 050		4321	37 840		25 000	664	4321	12 943	85 089	153 900		58 960	-6 153 566
5	2031	4116	144 050		4321	37 840	660 000	25 000	664	4321	0	732 147	153 900		-588 097	-6 741 663
6	2032	4116	144 050		4321	37 840		25 000	664	4321	12 943	85 089	153 900		58 960	-6 682 703
7	2033	4116	144 050		4321	37 840		25 000	664	4321	12 943	85 089	153 900		58 960	-6 623 742
8	2034	4116	144 050		4321	37 840		25 000	664	4321	12 943	85 089	153 900		58 960	-6 564 782
9	2035	4116	144 050		4321	37 840		25 000	664	4321	12 943	85 089	153 900		58 960	-6 505 821
10	2036	4116	144 050		4321	37 840	660 000	25 000	664	4321	0	732 147	153 900		-588 097	-7 093 919
11	2037	4116	144 050		4321	37 840		25 000	664	4321	12 943	85 089	153 900		58 960	-7 034 958
12	2038	4116	144 050		4321	37 840		25 000	664	4321	12 943	85 089	153 900		58 960	-6 975 998
13	2039	4116	144 050		4321	37 840		25 000	664	4321	12 943	85 089	153 900		58 960	-6 917 037
14	2040	4116	144 050		4321	37 840		25 000	664	4321	12 943	85 089	153 900		58 960	-6 858 077
15	2041	4116	144 050		4321	37 840	660 000	25 000	664	4321	0	732 147	153 900		-588 097	-7 446 174
16	2042	4116	144 050		4321	37 840		25 000	664	4321	12 943	85 089	153 900		58 960	-7 387 214
17	2043	4116	144 050		4321	37 840		25 000	664	4321	12 943	85 089	153 900		58 960	-7 328 253
18	2044	4116	144 050		4321	37 840		25 000	664	4321	12 943	85 089	153 900		58 960	-7 269 293
19	2045	4116	144 050		4321	37 840		25 000	664	4321	12 943	85 089	153 900		58 960	-7 210 332
20	2046	4116	144 050		4321	37 840	660 000	25 000	664	4321	0	732 147	153 900		-588 097	-7 798 429
21	2047	4116	144 050		4321	37 840		25 000	664	4321	12 943	85 089	153 900		58 960	-7 739 469
22	2048	4116	144 050		4321	37 840		25 000	664	4321	12 943	85 089	153 900		58 960	-7 680 509
23	2049	4116	144 050		4321	37 840		25 000	664	4321	12 943	85 089	153 900		58 960	-7 621 548
24	2050	4116	144 050		4321	37 840		25 000	664	4321	12 943	85 089	153 900		58 960	-7 562 588
25	2051	4116	144 050		4321	37 840	660 000	25 000	664	4321	0	732 147	153 900		-588 097	-8 150 685
26	2052	4116	144 050		4321	37 840		25 000	664	4321	12 943	85 089	153 900	2 164 600	2 223 560	-5 927 124
Total:		102 893	3 601 238	6 279 120	108 037	946 000	3 300 000	675 000	17 917	108 037	258 851	11 692 962	3 991 400	2 164 600	-5 927 124	

Table 31 The discounted economic flow for the proposed technological option



The planned production of geothermal energy from the Mihovljan field in the case of the proposed technological option is burdened by costs and obligations that directly or indirectly affect future revenues in the total amount of 111.1 EUR/MWh, which includes:

- Investment costs (documentation, exploration activities, wells, pipelines, revitalization works) amounting to 61.0 EUR/MWh.
- Direct costs amounting to 41.3 EUR/MWh annually, consisting of energy costs for internal consumption and operation and maintenance of wells and costs of materials and spare parts and other costs.
- Costs of compensation for geothermal energy exploitation of 1.2 EUR/MWh.
- Employee costs in the amount of 6.6 EUR/MWh.
- Allocated indirect costs in the amount of 1.1 EUR/MWh.

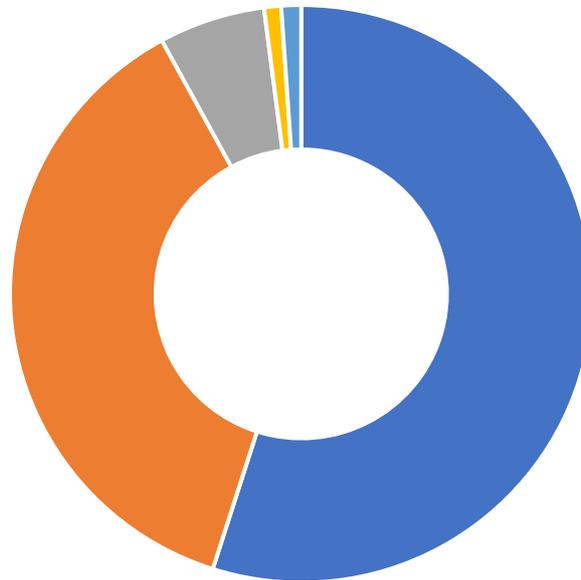
The structure of expenditures and obligations is presented in Table 32 and Figure 7-1.

Description	Total EUR	EUR/MWh _{th}	%
1. Investment costs (well revitalization and completion. pipelines. documentation)	6 279 120	61.0	54.9
2. Direct operating costs (energy consumption and workover. other costs)	4 246 000	41.3	37.1
3. Personnel costs	675 000	6.6	5.9
4. Allocated indirect costs	108 037	1.1	0.9
5. Fee for the exploitation of mineral resources	125 954	1.2	1.1
Total (1-5)	11 434 111	111.1	100

Table 32 Project cost structure for the proposed techno-economical option



Cost structure (%)



- Investment costs (well revitalization and completion, pipelines, documentation)
- Direct operating costs (energy consumption and workover, other costs)
- Personnel costs
- Allocated indirect costs
- Fee for the exploitation of mineral resources

Figure 7-1 Cost structure

The economic assessment of the efficiency of geothermal energy production was made based on the previously elaborated assumptions. According to the calculation of reserves and flow of geothermal water, according to the realized prices and economic conditions, the future exploitation field of geothermal water Mihovljan will achieve the following economic indicators, which are presented in Table 33.

Description	Value
Total observed period (years of operation)	27
Years of positive operation (year)	20
Total revenues (EUR)	3.601.238
Total expenditure and investments (EUR)	11.692.962
Undiscounted net revenues (EUR)	-5.927.124
Revenues / expenditures ratio	0.31
Net present value (discount rate 10%. EUR)	-6 561 730
Internal rate of return (%)	-6.33%
Payback period (years)	-

Table 33 Results of the project economic evaluation

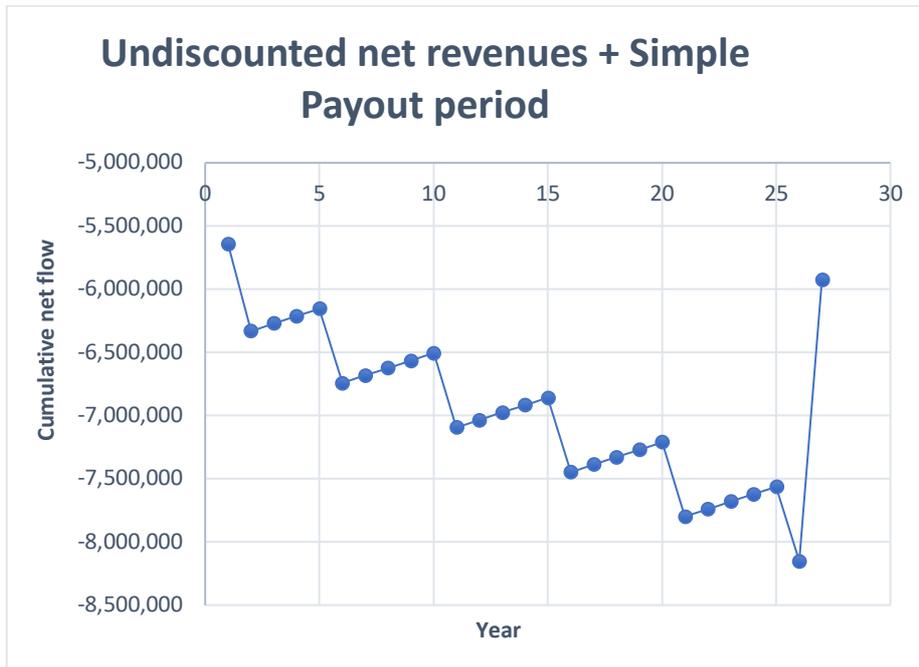


Table 34 Undiscounted net revenues and simple payout period

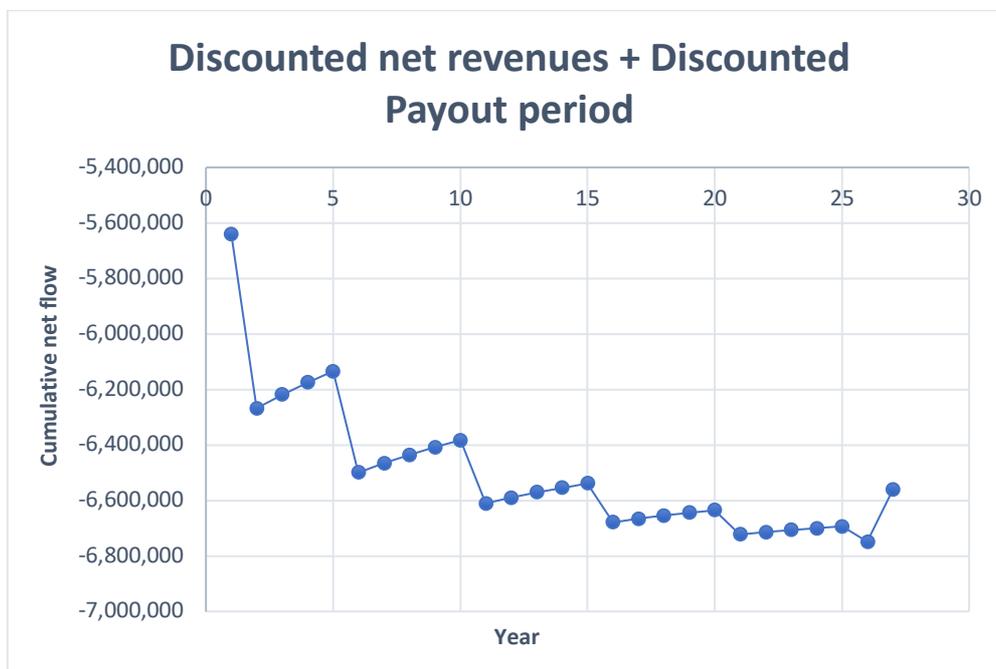


Table 35 Discounted net revenues and discounted payout period

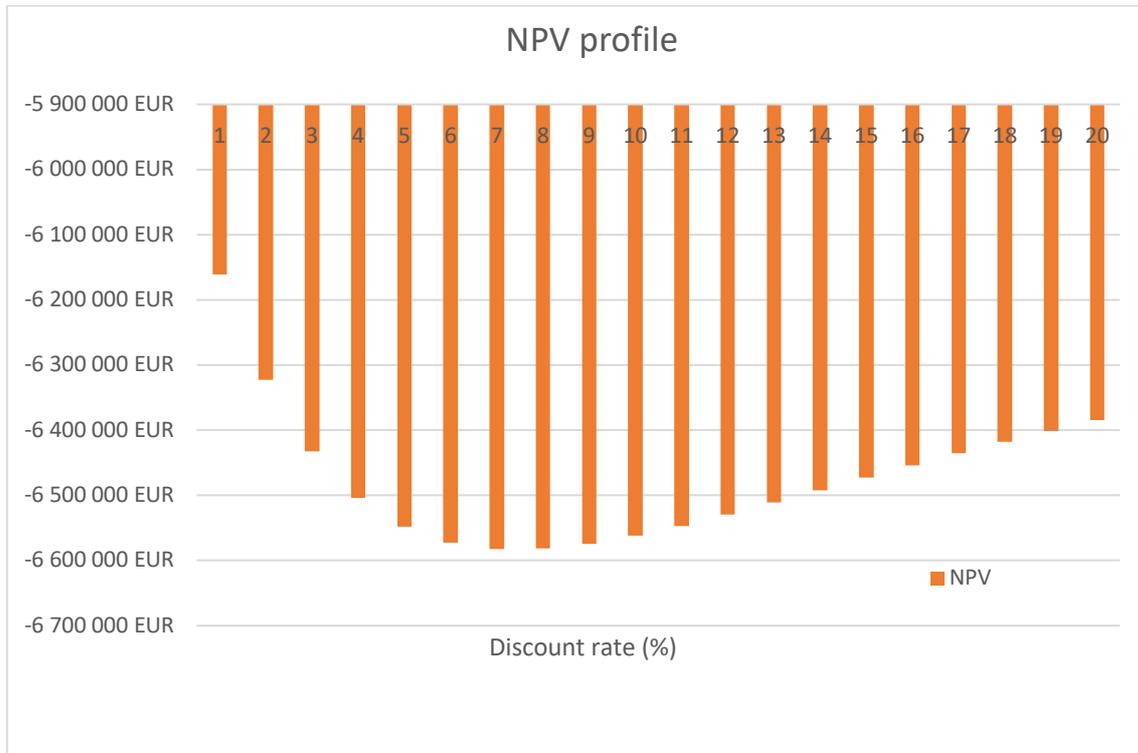


Table 36 NPV profile of the project

7.4.4. Conclusion of Economic Evaluation

According to the structure of revenues and expenses, an economic flow has been created for the observed exploitation period of 25 years, which is shorter than the life of isothermal production, as a basis for determining the profitability of utilizing thermal energy produced from the geothermal aquifer. According to the presented prices and operating conditions, in the envisaged production period, an economically unprofitable investment is expected for the proposed technological option. Sale of geothermal energy has not been analyzed for changes in energy prices in the future and the price of thermal energy. The above could possibly have a significant impact on the economic and financial indicators of the project as well as changes in capital and operating costs, so it was analyzed separately in the sensitivity analysis of the project. The net present value of the project was calculated with a discount rate of 10% (taking into account the nature and life of the exploitation), but the NPV profile for different discount rates of the project is also presented.

A summary of the economic assessment of the proposed technological option is presented below (Table 37).



Summary of the investment project for the utilization of geothermal potential at the Mihovljan location		
No.	Item	Description
1	Project title	Proof-of-concept study on reuse of abandoned wells for hydrothermal energy (HE) production
2	Variants	1
3	Installed capacity (MWt)	2.51
4	Completion of construction	
4.1	Start of exploration	1.1.2026
4.2	End of construction	31.12.2027
4.3	Start of energy sale	1.1.2028
4.4	End of energy sale	31.12.2052
5	Heat price (EUR/MWh)	35.00
6	Employees (full-time equivalent)	1
7	Revenues, expenditures and results (2050)	
7.1	Operating costs (EUR)	3 601 238
7.2	Operating costs (EUR)	5 154 991
7.3	Depreciation (EUR)	3 991 400
7.4	Corporate tax (EUR)	258 851
7.5	Net revenues (EUR)	-5 927 124
8	Financial decision-making criteria	
8.1	Discount rate	10.00%
8.2	Discounted to	31.12.2025
8.3	Payback period (years)	-
8.4	Year of payback	-
8.5	Discounted payback period (years)	-
8.6	Year of discounted payback	-
8.7	Net present value (EUR)	-6 561 730
8.8	Internal rate of return (IRR)	-6.33%

Table 37 Summary of the investment project parameters



7.5. Sensitivity Analysis

The sensitivity analysis of the net present value (NPV) of this investment was made taking into account the uncertainty of certain parameters important for calculating revenues and expenses over the entire period of exploitation of the geothermal potential at this location, using the same discount rate (10%) in all cases.

The sensitivity of the net present value of the entire investment to a change in the price of thermal energy, i.e. to an increase in sales revenue by 20%, was examined, since the aforementioned represents an unknown market price. Second variant was calculated with reduction in total investment costs (20%) with regard to the final technological exploitation and consumption of thermal energy by individual consumers at individual micro-locations with simultaneous reduction in total operating costs (20%), together with an increase in revenue from the sale of thermal energy (best case scenario) (Figure 7-2, Figure 7-3).

The analysis showed that by increasing the selling price of thermal energy, i.e. by increasing sales revenue, a slightly more favorable but still negative net present value (IRR>-5.60%) can be achieved, while in the best case scenario with a simultaneous increase in revenue and a reduction in investment and operating and costs, even better results are achieved, but still a negative net present value (IRR>-4.568%).

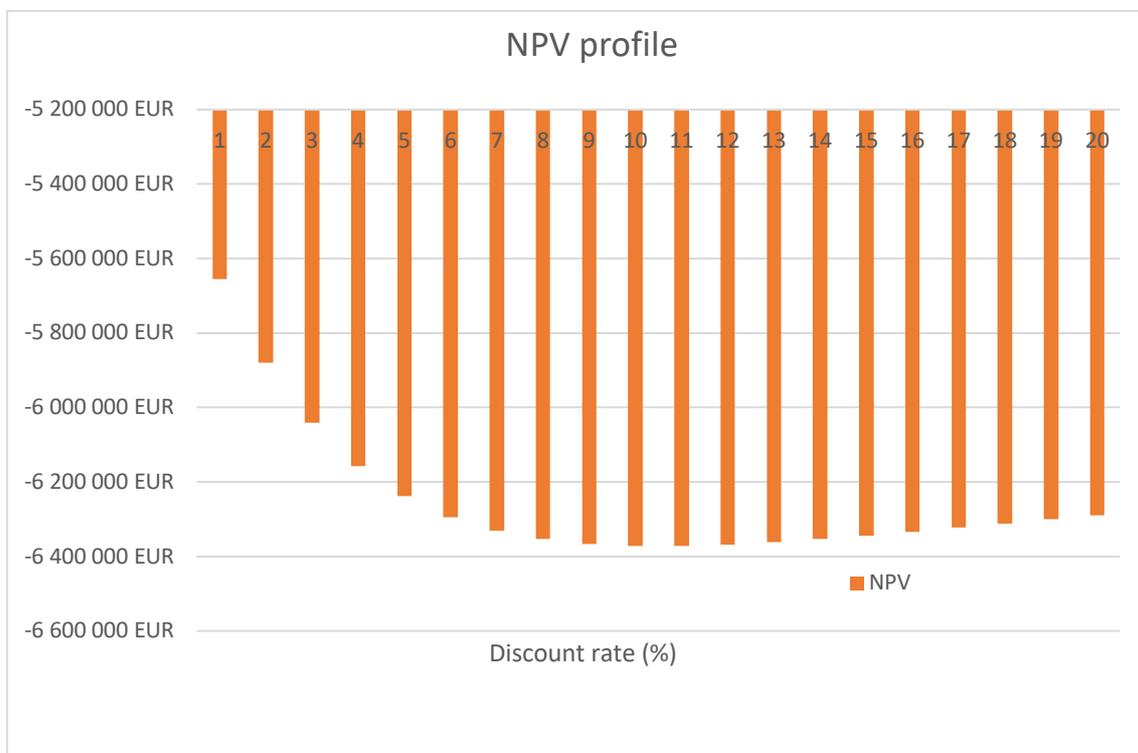


Figure 7-2 NPV for the increase of revenue by 20%

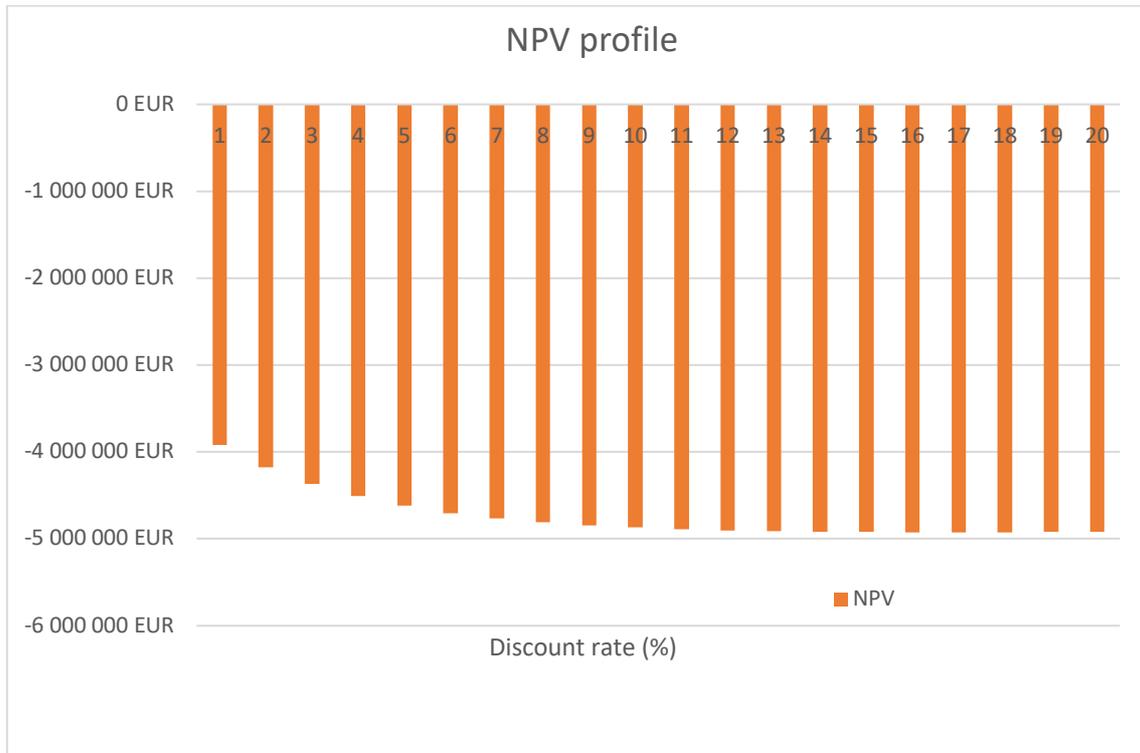


Figure 7-3 NPV for the simultaneous increase of revenue by 20% and decrease of CAPEX for 20% and OPEX for 20%



8. Conclusion

Developing pilot locations like Mihovljan pilot project after production of oil ceases will help to roll out an economically feasible and sustainable transformation of the carbon-intensive oil and gas sector in these regions. Furthermore, the project will help to reduce the non-technical barriers to the successful implementation of a new green energy strategy in the affected rural regions. Overall, a win-win situation will be created as employment opportunities will be secured in the old industrial sectors of the rural areas and the sector will be able to support the transition to a greener Europe. Analyzed microlocation designated as pilot site in Pannonian basin, the mature oil field Mihovljan, is at the end of the production cycle and this study demonstrated initial research results of repurposing possibilities for remaining well assets at the location which is in proximity of town Čakovec, but also wide agricultural land. Remaining four deep wells could be retrofitted into small geothermal project with two doublets by producing brine from upper thin sandstone layers which are not hydraulically connected to sandstone which was exploited for oil. Using well data, petrophysical and geological data and test data it is seen that smaller quantities of geothermal brine could be produced and injected from/into water saturated layers with submersible pump of around 10 l/s and 82 °C temperature at the wellhead. Total installed heat power of the geothermal flow could be around 2 MW from this small geothermal pilot project. Due to lower flow possible to obtain at production wells, economic analysis shows that project is positive after 25 years which is not suitable. Most costs are related to revitalization issues and reopening of shallower sandstone layers. Therefore, this feasibility study proved that currently without a support funding scheme, such small scale revitalization projects are not currently entirely feasible for investors, without co-funding from either local communities, or state funding.



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