Analysis of geothermal energy exploitation on Karlovac geothermal field

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REVIEW

Geothermal reservoir Rečica was discovered with two wells: Ka-2 and Ka-3. Based on the results of investigations from abovementioned wells, the reservoir temperature of 140 Celsius degrees was determined. Ka-3 would be production well and Ka-2 injection well. Depth interval from 1 900 to 3 523 meters is designed for hot water production in Ka-3 well and depth interval from 3 200 to 4 145 meters is designed for injection of chilled water in Ka-2 well. Gradual utilization of reservoir heat energy can be planned by, applying Clausius-Rankin process. In view of total efficiency factor, energy output of geothermal source should be expressed as maximum useful work or exergy where reversible processes lead working fluid into mechanical and thermal environment conditions equilibrium. Chilled geothermal water would be returned through injection well to the same reservoir what assures heating reproducibility and pressure maintenance in the reservoir. Economic analysis estimated total investment costs needed for development of geothermal power plant, and economic indicators of profitability of geothermal project. The production of electricity from Rečica reservoir would be economically viable with cascade principle of heat energy utilization and a high annual degree of utilization.

Key words: Geothermal power production, geothermal energy, binary Rankine cycle

1. INTRODUCTION

Geothermal water wells in Croatia are not properly utilized for heating of residential sector, in agricultural and industry production, nor in production of electricity. National energy program, as a part of Development and Organization of Croatian Energy Sector program implemented by Hrvoje Požar Energy Institute, proposed more detailed analyses of all the reservoirs discovered by INA during exploration of oil and gas reservoirs. INA has recently made a big improvement in valorization of its geothermal potential and new results in the field of geothermal water production are to be expected. The use of geothermal water, which is renewable and ecologically acceptable energy source, would be significantly improved if the legal regulations are enforced that would encourage exploration and production from geothermal reservoirs.

One of the conditions of becoming a member state of the European Union is also the utilization of renewable energy sources and ecological requirements in choosing the energy products. Former INA Department for Water Management has signed a Letter of Intent with the City of Karlovac which announces the interest for using thermal water in Rečica. Geothermal reservoir was discovered 25 years ago while the water temperature at a depth of approximately 1 500 m is around 140 °C. The production of electricity could be possible from this reservoir, while the water, after being used with temperature of around 40 °C, would be injected back into the reservoir. The Letter of Intent is allowing INA exploration team to continue working on source exploitation project. The Government of the Republic of Croatia has recommended INA to use thermal water for energy production. Along with electricity production, water might be also used for heating of greenhouses and residential sector.

2. GEOLOGICAL - PHYSICAL CHARACTERISTICS OF KARLOVAC GEOTHERMAL LOCALITY

Geological structure of Croatian underground places geothermal localities mostly in the area of the Pannonian Basin. Among these localities, the characteristics of which are water temperature in the reservoir exceeding 100 °C, are also wells drilled in Karlovac area that were drilled with the aim of discovering hydrocarbons.

Geothermal locality situated approximately 8 km northeast of Karlovac (Figure 1) was discovered in 1983 by Ka-2 well. Later, during 1988, Ka-3 well was drilled which confirmed the geothermal potential of this locality. The distance between Ka-2 and Ka-3 wells is approximately 3 km. Both wells are owned by INA. The area around the wells is mainly lowland, 110 m height above sea level, and the wells are located within relatively big forest. Approximately 3 km west of Ka-2 well there is a big fish farm Draganići, potential consumer of produced thermal energy.

Ka-2 deep exploration well was drilled in the period from December 15, 1982 until July 7, 1983. The well has reached final depth of 4 145 m and cut through a series of sediments with expressed sealing characteristics, like argillaceous marl, marl, siltstone and shale as well as rocks with good sealing characteristics. Five well intervals were tested by DST method; however commercial hydrocarbon reserves were not determined. During the abandonment phase of the well in 2001, two intervals were tested for water production and receiving tests were performed.

Ka-3 exploration well was drilled in the period from January 6, 1988 until May 29, 1988. Well has reached the sequence of deposits foreseen by the project. The

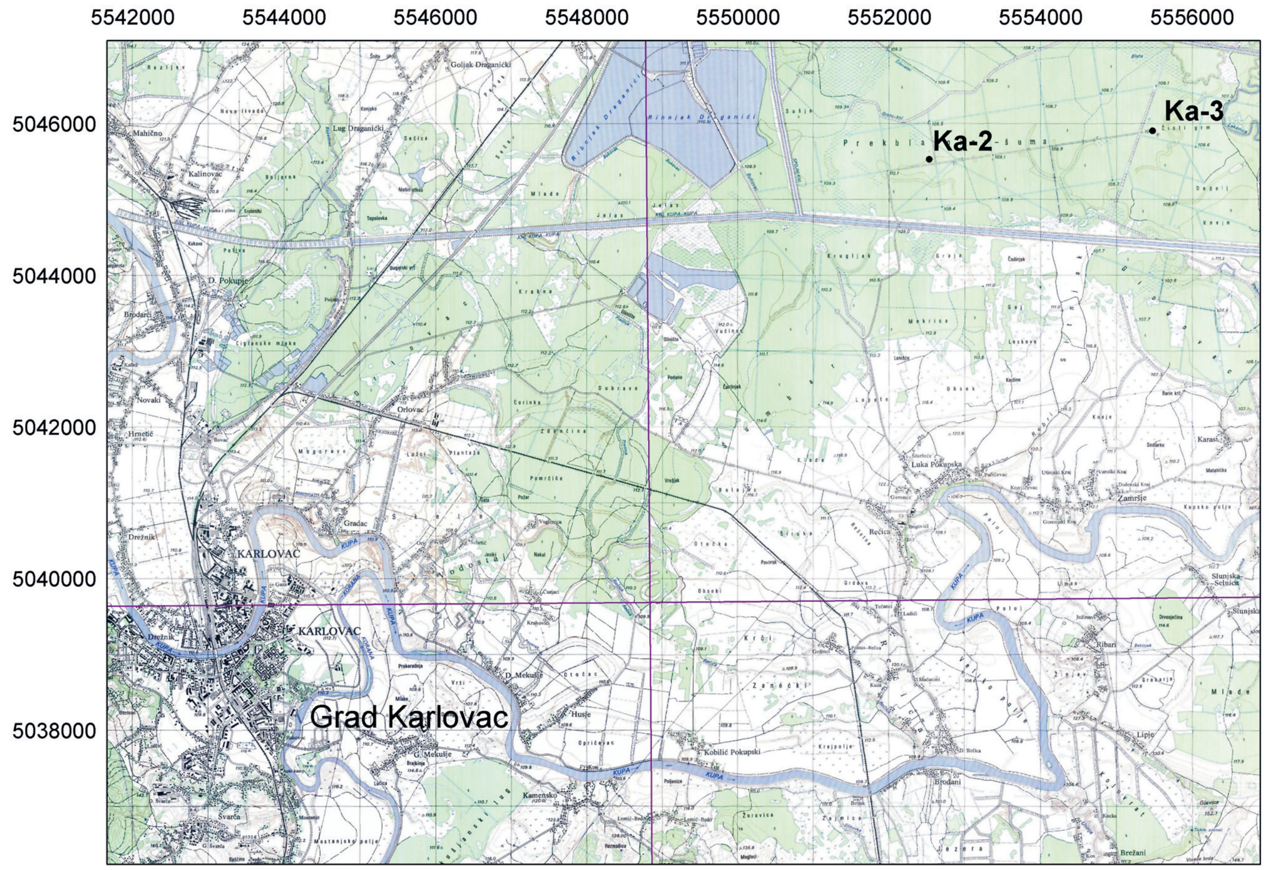

Fig. 1. Map of Ka-2 and Ka-3 wells location (INA Naftaplin 2006)
Sl. 1. Karta lokacije bušotina Ka-2 i Ka-3 (INA Naftaplin 2006)

drilling was completed in Mesozoic complex at the depth of 3 523 m. Based on geological monitoring, testing and well log analyses; there was no hydrocarbon saturation as planned. Well was tested for inflow, and testing water was acquired by eruption (20 – 50 m^3/h). It had salinity of 0.99 gNaCl/l and temperature on well head was from 87 °C to 94 °C. Commercial hydrocarbon reserves were not recognized and the well was plug back cemented and abandoned. Further testing of this well was performed within its abandonment program in 2001.

From geological point of view, there are two different sediment complexes of different geothermal potential. Clastic sediments complex is made of sandstone, marl and silk. Water salinity in these deposits is from 17.5 to 21 $gNaCl/dm^3$, which indicates saline water. Although water temperature in this complex reaches the values of 138 °C, geothermal potential of the complex is not high due to low quantities.

Carbonates sediments complex is situated below clastic sediments, it is saturated with water of less than 1 g $NaCl/dm^3$ salinity, and thus it is clearly drinking water. Geothermal potential of the complex is big as there are significantly cracked deposits of wide spreading and thickness. The highest measured water temperature is 140 °C. Carbonates complex at Karlovac locality is situated on end northern margin of big Mesozoic carbonate platform which existed from Permian until the end of Cretaceous. This complex is significantly different in Ka-2 and Ka-3 wells, which indicates that during geological history they were developed in very different environments.

Ka-2 well is situated in the deepest part of Karlovac valley where the thickness of Tertiary clastic sediments is 3 000 m. Carbonates complex spreads upward toward Ka-3 well, thus Tertiary deposits on this well are approximately 1 567 m thick. The well has reached final depth of 4 145 m. Carbonate and clastic sediments complex appears in deeper part of the well while clastic deposits of Neogene age are situated in shallower part. Ka-3 well has reached the depth of 3 523 m. Clastic sediments complex of Tertiary age was drilled, whereas below was a thick complex of carbonate sediments where the drilling was stopped. Clastic sediments complex was drilled up to the depth of 1 567 m. It is composed of marly clay, sandstone and coal intercalations, while at greater depths marl and sandstone are present.

Reservoir temperature in Ka-3 well was estimated according to geothermal gradient calculated from DST data (INA Naftaplin 2006). At the depth of HDST = 2 511 m

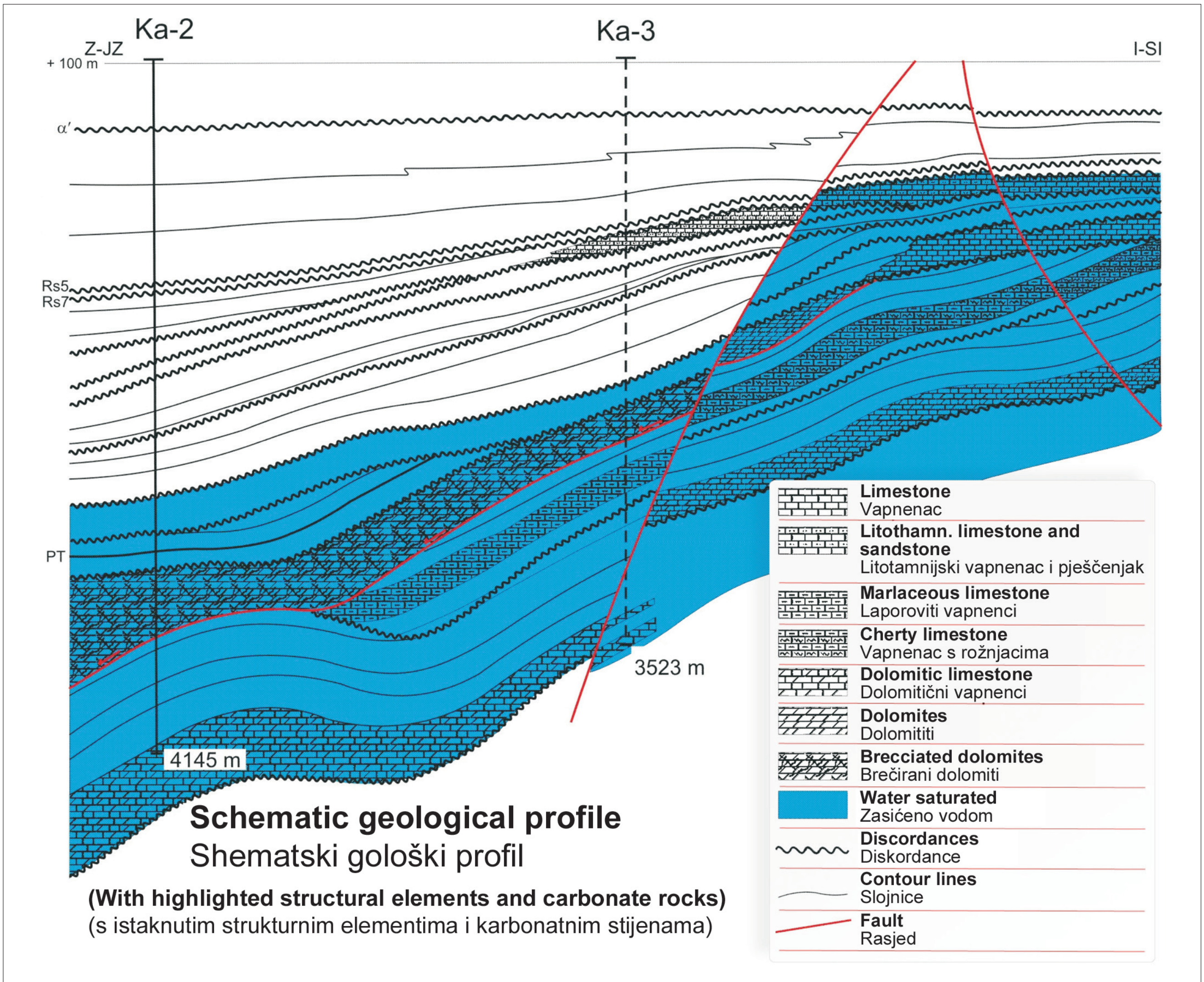

Fig. 2. Geological cross section through geothermal reservoirs on Karlovac locality (INA Naftaplin 2006)
Sl. 2. Geološki profil geotermalnih ležišta na lokalitetu Karlovac (INA Naftaplin 2006)

temperature is t_{max} = 120 °C. Geothermal gradient G_t = 4.32 °C/100 m, was also acquired from the data, average annual environmental temperature of well head of 11.6 °C was also taken in consideration during calculation which lead to the conclusion that this was drinking water. According to this gradient, the estimation is that at the depth of H = 2 821 m, the average temperature is t_{sr} = 133 °C. Reservoir temperature in Ka-2 well is t_{max} =

Table 1. Average values of permeable intervals reservoir parameters for Ka-2 well (INA Naftaplin 2006)

Reservoir	Permeable interval, (m)	Formation fluid	Porosity, (%)	Effective thickness, (m)
Dolomite	3 385 – 3 440	Water	5	55
Dolomite	3 535 – 3 705	Water	5	170
Dolomite	3 715 – 3 780	Water	5 6	65
Dolomite	3 800 – 3 825	Water	5 6	25
Dolomite	3 835 – 4 145	Water	5 6	310

Table 2. Average values of permeable intervals reservoir parameters for Ka-3 well (INA Naftaplin 2006)

Reservoir	Permeable interval, (m)	Formation fluid	Vuggy porosity, (%)	Effective thickness, (m)
Dolomite	1 930 – 1 950	Water	8	20
Dolomite	2 089 – 2 102	Water	8	13
Dolomite	2 117 – 2 130	Water	5 7	13
Dolomite	2 379 – 2 436	Water	5 7	57
Dolomite	2 520 – 2 580	Water	5 7	60
Dolomite	2 760 – 2 845	Water	5 7	85
Dolomite	2 870 – 2 885	Water	5 7	15
Dolomite	3 002 – 3 027	Water	5 7	25
Dolomite	3 310 – 3 440	Water	5 6	130

139 °C. It is estimated according to geothermal gradient calculated from DST at the depth HDST = 3 344.4 m. Geothermal gradient G_t = 3.81 °C/100 m was derived from these data. According to this gradient, it is estimated that at the depth H = 3 806 m, the temperature is 157 °C.

Vuggy porosity values were estimated by well logging analysis.

According to the previously presented production testing of uncased parts of Ka-2 and Ka-3 well bores, this might be the case of abundant water reservoir, as the reservoir consists of massive carbonate crushed rocks that also appear in 3 km distant Ka-3 well. As well logging methods are suitable only for calculating inter-granular vuggy porosity, the estimation is that real vuggy porosity values are higher than the ones presented in Tables 1. and 2. Besides, effective thickness sum of stated formations in Table 2 is 418 m, which justifies good production volumes, while in the case of Ka-2 well, good injecting capacity can be expected (INA Naftaplin 2006).

3. TECHNICAL–TECHNOLOGICAL POSSIBILITIES OF RESERVOIR EXPLOITATION

For the purpose of hydrocarbon reservoirs discovery on the wider Karlovac area, three wells were drilled and all three were dry to hydrocarbons. Two of the three wells are suitable for exploitation of geothermal reservoir. Ka-3 well is planned to be production well and Ka-2 injection well. As this is a geothermal water reservoir, which is a renewable energy source, the return of chilled water back into the reservoir is planned. This way the condition of keeping the reservoir pressure shall be met and also ecological requirements shall be satisfied.

As this is the case of very high temperature water, it is necessary to plan gradual water exploitation to make the degree of heat energy as high as possible thus making the project more economically efficient. Technological – technical possibilities restricted the implemented testing to determine maximal water quantities that the wells could produce or receive. Based on the measured data, Ka-3 well is able, under optimal conditions, to produce 50 l/s of geothermal water with the help of deep production pump. During the drilling of Ka-3 and Ka-2 well bores, the losses of working fluid occurred which indicated very good permeability of reservoir deposits. It is also assumed that Ka-2 well can receive all chilled water.

The knowledge of petrophysical and hydrodynamic reservoir characteristics is crucial for reliable and long-term exploitation of geothermal reservoir. This means the knowledge of reservoir size, reservoir capacity to renew reservoir pressure, knowledge on capacity of communication between wells through the reservoir, reservoir permeability value etc. (INA Naftaplin 2006). To acquire the mentioned data for each specific case, the following is necessary:

- make Ka-2 and Ka-3 wells suitable for geothermal water production; i.e. perform capital work-over of formation and equipment;
- perform detailed hydrodynamic measurements with well pressure increase measuring in Ka-3 and/or well pressure drop measuring in Ka-2 well and interference testing between the wells;
- after Ka-2 and Ka-3 wells are connected by pipeline, perform long-term production –injection well testing with simultaneous pressure and temperature measuring in both wells, to achieve the right conditions for functioning of the wells.

Only after the mentioned operations are completed, we can start with work on necessary documentation; like water reserves study with economical evaluation of geothermal reserves, environmental impact study, pre-investment study on the possibilities of geothermal water exploitation, main mining project of geothermal field.

Standard geothermal plant for transforming geothermal energy into electricity should consist of the following:

1. production and injection wells,
2. separating units for separating gas from water,
3. gathering system,
4. geothermal plant for geothermal energy transformation,
5. injection system for geothermal water injection ,
6. relief system for emergency situations, and
7. metering, control and regulation equipment for the efficiency of production line.

Beside the geothermal facility stated in item 4, the remaining part is a conventional system for oil and gas production.

As this is the case of mid-temperature reservoir in liquid state, the electricity production can be achieved by Clausius-Rankin process with secondary work fluid (binary cycle). Overheated steam of secondary work cycle starts the generator turbine, after which it condenses and circular pump in closed circle returns it to heat exchanger. Binary plant is ecologically acceptable as geothermal water from the first circle in closed cycle is injected into reservoir without any contact with the environment. Thermo-dynamical action degree of binary plant operations, according to the first main thermo-dynamics rule depend on temperature and geothermal fluid quantity and can be presented as a ratio of output power and total of energy brought to binary process. Real outlet power of the plant is acquired when the total energy is decreased by internal consumption of binary unit and injection system.

Geothermal fluid with temperature of 135 °C and 50 L/s (4 320 m^3/d) flow enters the first heat exchanger where this temperature drops to 80 °C. In accordance with the first one, the outlet temperature of the second heat exchanger is 40 °C arbitrary. Within this circulation circle, the heat of geothermal water is utilized directly (in a direct manner) for heating processes in hotels and greenhouses. In the eventual third circle, heat energy could be used for balneology purposes, with temperature drop to 10.8 °C, which corresponds to average annual temperature at the locality.

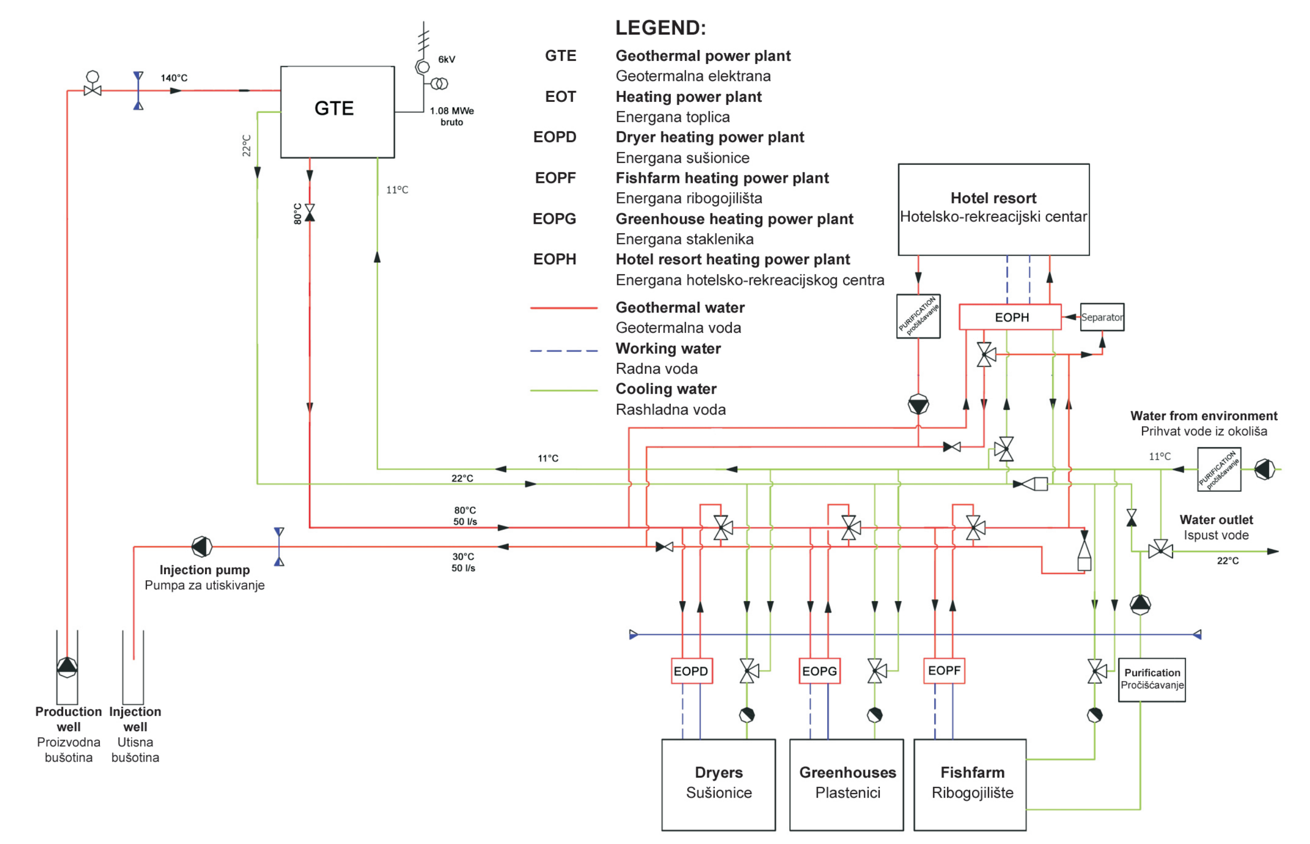

Fig. 3. Geothermal energy production scheme (modified from Kutnjak-Lunjkovec production scheme, Ekonomski fakultet)
Sl. 3. Shema proizvodnje geotermalne energije (modificirano prema proizvodnom ciklusu ležišta Kutnjak-Lunjkovec, Ekonomski fakultet)

4. ECONOMICAL-FINANCIAL ANALYSIS OF THE PROJECT

While technological solutions depend directly on characteristics of a certain source, economical analysis is often performed with numerous assumptions and balancing over the item of increased unforeseeable expenses. Geothermal energy production cost consists of two important components: amortization of initial capital investment and operative costs and maintenance cost during the production cycle. Initial capital investment costs include all the expenses related to project development which include the following: lease, licenses, exploration, reserves appraisal, project development and numerous expenses titled conditional expenses. Generally, capital expenses of geothermal projects depend on location and reservoir characteristics, while reservoir temperature, depth, water chemistry and permeability are factors with the greatest impact on development costs of geothermal projects. Operative and maintenance costs refer to all the costs needed for uninterrupted operation of electricity plant in standard operation mode, and they also directly depend on location and reservoir characteristics (mainly reservoir depth and water chemistry).

As per Article 28. Paragraph 3. of the Energy Act, Government of the Republic of Croatia has passed the Tariff System (Official Gazette, 2007) for Electricity Production from Renewable Energy Sources and Cogeneration. Tariff system defines the rights of eligible electricity producers to stimulation price of electricity which market operator pays for the delivered electricity produced from the plants which use renewable energy sources and from cogeneration plants according to Article 26, Paragraph 5 of the Energy Act. Tariff system defines the tariff items as well as the amount of tariff items for electricity produced from the plants using renewable energy sources and from cogeneration plants, depending on the type of source, power and other elements of delivered electricity as well as terms and conditions for applying these elements. Stimulation price is the price paid to electricity producers who produce electricity from the plants using renewable energy sources and from cogeneration plants during the duration of electricity purchase agreement and is expressed in kn/kW h. For the plants connected to transmission and distribution network and which use geothermal sources for electricity production of installed electric power higher than 1 MW, the determined amount for tariff price is 1.26 kn/kW h. Purchase agreement for the electricity produces from the plants using renewable energy sources and from cogeneration plants is concluded for the defined duration of 12 years.

It is assumed that the total investment in geothermal water utilization on Rečica geothermal reservoir shall be from company's funds, thus loans and related interest rates are not foreseen. Total investments in wells and

Table 3. Revenues from the sale of reservoir electricity and heat energy

Inlet temperature into binary plant	°C	135
Outlet temperature from binary plant	°C	80
Water production	m^3/d	4 320
CO_2 production	m^3/d	0
Specific heat capacity of water	kJ/kg K	4.25
Specific heat capacity of CO_2	kJ/kg K	0.9
Utilization of Δt for electricity	°C	55
Utilization of Δt for heat energy	°C	40
Number of hours annually for electricity production	hour	8 500
Number of hours annually of heat energy utilization	hour	4 000
Electricity selling price	kn/kW h	1.26
Heat energy selling price	kn/MW h	120.00
Energy price for internal consumption	kn/kW h	1.00
Thermo-dynamic utilization of electricity production	%	0.078
Internal plant consumption	%	0.2
Recovered heat power 1st circle	MW	11.69
Electricity production plant power	MW	0.91
Internal plant consumption	MW	0.15
Net power of electricity production plant	MW	0.76
Heat power for heating	MW	8.50
Annual revenue from sold electricity	**kn**	**9 747 306**
Annual revenue from sold heat (+ subscription)	**kn**	**5 232 600**
TOTAL ANNUAL REVENUE	**kn**	**14 979 906**

Table 4. Total investment in plant and wells and expenses

Investment in wells for utilization of geothermal energy		kn
A)	Mining works on production well	1 500 000.00
	Retrieval of 5 1/2 " tubing 1000 m	
	Perforation and testing	
	Installation of sucker rod pump	
B)	Production equipment	3 380 000.00
	Sucker rod pump, cable, VSD	
	Exp. Head, gates	
	Spare sucker rod pump	
C)	Mining works on injection well	800 000.00
	Retrieval of equipment	
	Perforation and testing	
	Injection test	
D)	Injection equipment	520 000.00
	Exp. Head, gates	
	TOTAL kn	6 200 000.00

Investment in plant for utilization of geothermal energy	**kn**
Binary plant	7 100 000.00
Heat plant and heating pipes network to consumer - 5000 m	10 000 000.00
Instrumentation and remote surveillance system	6 000 000.00
Documentation and issuing of construction licenses	300 000.00
Connecting pipelines, pipe fittings, metering stations	709 800.00
Injection pump	500 000.00
Connecting trunk line - 3km	1 560 000.00
TOTAL kn	**26 169 800.00**
TOTAL INVESTMENT kn	**32 369 800.00**

plant for utilization of geothermal energy are presented in Table 4. Investments in wells are mining operations on production and injection wells and production and injection equipment. Investment in plant for production of electricity and heat energy consists of the cost of heat exchanger, heat pipeline to the customer in the length of 5 km, connecting pipeline and main pipeline, cost of injection pump and instrumentation system and the cost of necessary documentation and issuance of licenses. Table 4 shows the profit and loss account for the expected working duration of electricity plant of 20 years. Dynamic methods were used for evaluating the feasibility of investment in geothermal electricity plant development.

CONCLUSION

Installed electric and heat power were calculated for the production of geothermal water of 135 °C temperature and 50 l/s binary cycle with utilization Δt = 55 °C in the first circulation cycle and Δt = 40 °C in second circulation cycle. In the first circulation cycle, net installed electricity plant power is 0.76 MWe, while the installed heat power of the second circulation cycle is 8.50 MWt. Thermo-dynamic degree of binary cycle utilization is 7.8% while the internal plant loss is 15%.

For the operational duration of geothermal electric plant for the period of 20 years, the financial-marketing evaluation of the project estimated the invested feasibility by dynamic methods for project financing from company's funds. Analysis of investment feasibility indexes, with annual value amortization of 10 % of investment and for the period of 20 years, showed feasibility of the project. In case the development of geothermal electric plant is financed by company funds, net present value, with the discount rate of 8 % is 63 391 229 HRK, internal feasibility rate is 42.71 % while the time of return on investment is 4 years. This feasibility is possible only if the consumer is found for the total of produced heat energy (heating of facilities in Karlovac, fish farming area, industry).

Agreement on energy sale is an important insurance instrument enabling investors to reduce risk due to unstable energy prices. Agreement prevents the unsuccessfulness of the project when energy prices fall and also energy supply at acceptable price is guaranteed when fossil fuel prices get extremely high. Current high price of raw material partly explains the rise in cost, however different studies show that the lack of new development project during the last decade made the updating of construction cost more difficult, making the analyses de-

Table 5. Cash flow and return on investment

Year	Revenue	Expenses	Production cost	Internal consumption	Profit before tax	Net profit	Net profit cumulatively	Net cash flow	Net receipts
2011	14 979 906	37 635 509	2 371 405	1 275 000	8 096 521	6 477 217	6 477 217	-22 655 603	-22 655 603
2012	14 979 906	5 265 709	2 371 405	1 275 000	8 096 521	6 477 217	12 954 434	9 714 197	-12 941 407
2013	14 979 906	5 265 709	2 371 405	1 275 000	8 096 521	6 477 217	19 431 651	9 714 197	-3 227 210
2014	14 979 906	5 265 709	2 371 405	1 275 000	8 096 521	6 477 217	25 908 868	9 714 197	6 486 987
2015	14 979 906	5 265 709	2 371 405	1 275 000	8 096 521	6 477 217	32 386 085	9 714 197	16 201 183
2016	14 979 906	5 265 709	2 371 405	1 275 000	8 096 521	6 477 217	38 863 302	9 714 197	25 915 380
2017	14 979 906	5 265 709	2 371 405	1 275 000	8 096 521	6 477 217	45 340 519	9 714 197	35 629 577
2018	14 979 906	5 265 709	2 371 405	1 275 000	8 096 521	6 477 217	51 817 736	9 714 197	45 343 774
2019	14 979 906	5 265 709	2 371 405	1 275 000	8 096 521	6 477 217	58 294 953	9 714 197	55 057 970
2020	14 979 906	5 265 709	2 371 405	1 275 000	8 096 521	6 477 217	64 772 170	9 714 197	64 772 167
2021	14 979 906	5 265 709	2 371 405	1 275 000	11 333 501	9 066 801	73 838 971	9 066 801	73 838 968
2022	14 979 906	5 265 709	2 371 405	1 275 000	11 333 501	9 066 801	82 905 772	9 066 801	82 905 768
2023	14 979 906	5 265 709	2 371 405	1 275 000	11 333 501	9 066 801	91 972 573	9 066 801	91 972 569
2024	14 979 906	5 265 709	2 371 405	1 275 000	11 333 501	9 066 801	101 039 374	9 066 801	101 039 370
2025	14 979 906	5 265 709	2 371 405	1 275 000	11 333 501	9 066 801	110 106 175	9 066 801	110 106 170
2026	14 979 906	5 265 709	2 371 405	1 275 000	11 333 501	9 066 801	119 172 976	9 066 801	119 172 971
2027	14 979 906	5 265 709	2 371 405	1 275 000	11 333 501	9 066 801	128 239 777	9 066 801	128 239 772
2028	14 979 906	5 265 709	2 371 405	1 275 000	11 333 501	9 066 801	137 306 578	9 066 801	137 306 573
2029	14 979 906	5 265 709	2 371 405	1 275 000	11 333 501	9 066 801	146 373 379	9 066 801	146 373 373
2030	14 979 906	5 265 709	2 371 405	1 275 000	11 333 501	9 066 801	155 440 180	9 066 801	155 440 174

pendent on assumed optimal cost reductions. Today, high oil price and recent government initiative are helping geothermal projects to remain within economical frames of sustainability.

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