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Possibilities of electricity generation in the Republic of Croatia by means of geothermal energy

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ABSTRACT

In the Republic of Croatia there are some medium temperature geothermal sources by means of which it is possible to produce electricity. However, only recently concrete initiatives for the construction of geothermal power plants have been started. Consequently, the paper provides proposals of the possible cycles for the Republic of Croatia. On the example of the most prospective geothermal source in the Republic of Croatia detailed analysis for the proposed energy conversion cycles is performed: for Organic Rankine Cycle (ORC) and Kalina cycle. On the basis of analysis results both the most suitable cycle for selected and for other geothermal sources in the Republic of Croatia are proposed. It is ORC which in case of the most prospective geothermal source in the Republic of Croatia has better both the thermal efficiency (the First Law efficiency) and the exergetic efficiency (the Second Law efficiency): 14.1% vs. 10.6% and 52% vs. 44%. The ORC gives net power of 5270 kW with mass flow rate 80.13 kg/s, while the Kalina cycle gives net power of 3949 kW with mass flow rate 35.717 kg/s.

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1. Introduction

Geothermal energy is a form of renewable energy contained in the solid Earth and its internal fluids. For the first time electricity was generated from geothermal steam at Larderello, Tuscany, Italy when Prince Piero Ginori Conti powered a 3/4-horsepower reciprocating engine to drive a small generator. By 1914, the first commercial 250 kW geothermal power plant was in continuous operation there [1].

During the last four decades, the utilisation of geothermal energy has increased significantly both for electricity generation and for direct use. Already today, geothermal energy is an important source of electricity in many countries. Today, electricity is produced from geothermal energy in 24 countries, worldwide, with a capacity of 8.9 GW [2].

Despite the fact that economic potential of geothermal energy utilization for power generation is usually significantly less than corresponding solar or wind potential, geothermal plants are regularly included in future energy systems development scenarios [3–5].

Geothermal power plants in operation at present are essentially of three types for high and medium temperature geothermal sources: dry steam, flash and binary [1].

The availability of geothermal energy in the Republic of Croatia from deep wells has been known already for about 40 years. This long period saw single attempts at starting the economic projects based on geothermal energy, but they used to be abandoned already in the preliminary phase, with the exception of building and spas heating. There are several reasons for such a condition, among others the most important one being: the policy of satisfying energy demands without renewable energy sources, except from the large hydro power plants, insufficiently developed awareness of the need for environmental protection, and lack of entrepreneurial initiative.

As early as 1998, the Energy Institute “Hrvoje Požar” prepared a Program of Geothermal Energy Usage in the Republic of Croatia, which shows that in the Republic of Croatia there are some medium temperature geothermal sources by means of which it is possible to produce electricity [6]. However, only recently concrete initiatives for the construction of geothermal power plants have been started.

The paper will provide the following:

- on the basis of experiences in the world, proposal of geothermal sources in Croatia suitable for electric power generation;
- proposal of the possible cycles for electricity generation;
- on the example of the most prospective geothermal source in Croatia detailed analysis for the proposed conversion cycles, and the selection of the most suitable plant;
- proposal of the energy conversion cycle for other geothermal sources in Croatia.

Comparison of the possible energy conversion cycles will be performed based on the results of their energy–exergy analysis. For

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Nomenclature

$\bar{c}$	average specific heat (J/kg K)
$\dot{E}$	exergy flow rate (J/kg)
e	specific exergy (J/kg)
$\dot{H}$	enthalpy flow rate (W)
h	specific enthalpy (J/kg)
$\dot{m}$	mass flow rate (kg/s)
p	pressure (Pa)
$\dot{Q}$	heat flow rate (W)
s	specific entropy (J/kg K)
T	temperature (K)
$\dot{W}$	work flow rate-power (W)
x	contents of ammonia–water mixture (−)

Greek symbols

ε	exergetic efficiency (−)
η	efficiency (−)

Subscripts

cf	cooling fluid
gf	geothermal fluid
in	input
is	isentropic state
KC-liq	liquid phase of the working fluid in Kalina cycle
KC-mix	ammonia–water mixture in Kalina cycle
KC-vap	vapour phase of the working fluid in Kalina cycle
net	net
ORC-wf	working fluid in ORC
out	output
p	pump
t	turbine
th	thermal

thermodynamic modeling and energy–exergy analysis the fundamentals from literature [1,7–17] are used.

2. Geothermal potential of the Republic of Croatia

The Republic of Croatia has many centuries of tradition of geothermal energy usage from natural springs for medical purposes and bathing. Geothermal energy is the basis of the economic success of numerous spas in Croatia.

There are a total of 28 geothermal fields, out of which 18 are in usage. For the needs of space heating a total of 36.7 MW of heating power has been installed with annual usage of heating energy of 189.6 TJ/year. For bathing 77.3 MW of heating power is used, i.e. 492.1 TJ/year. Until now, geothermal energy was not used for the production of electricity [6].

Along with the research activities regarding oil and gas, Croatia has also developed the technique and technology for obtaining geothermal energy from deep geothermal layers. At the same time, abandoned oil wells could be considered for geothermal energy utilization [18].

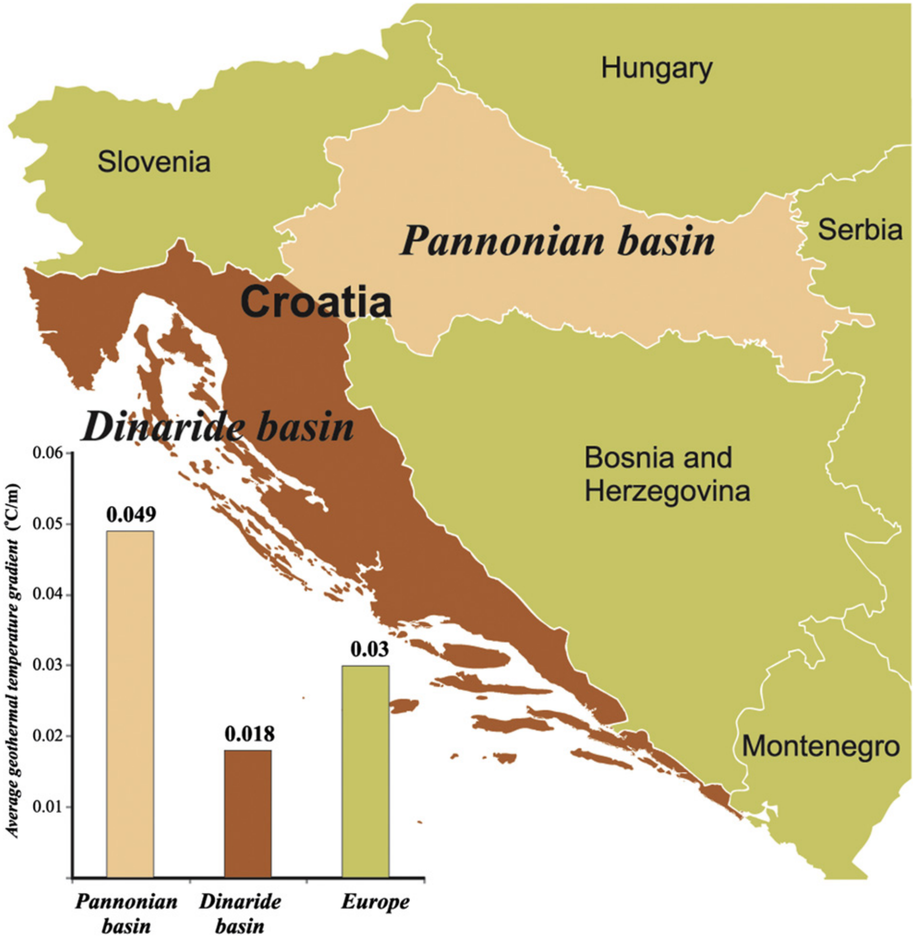


Fig. 1. The average geothermal temperature gradient in Croatia [3].

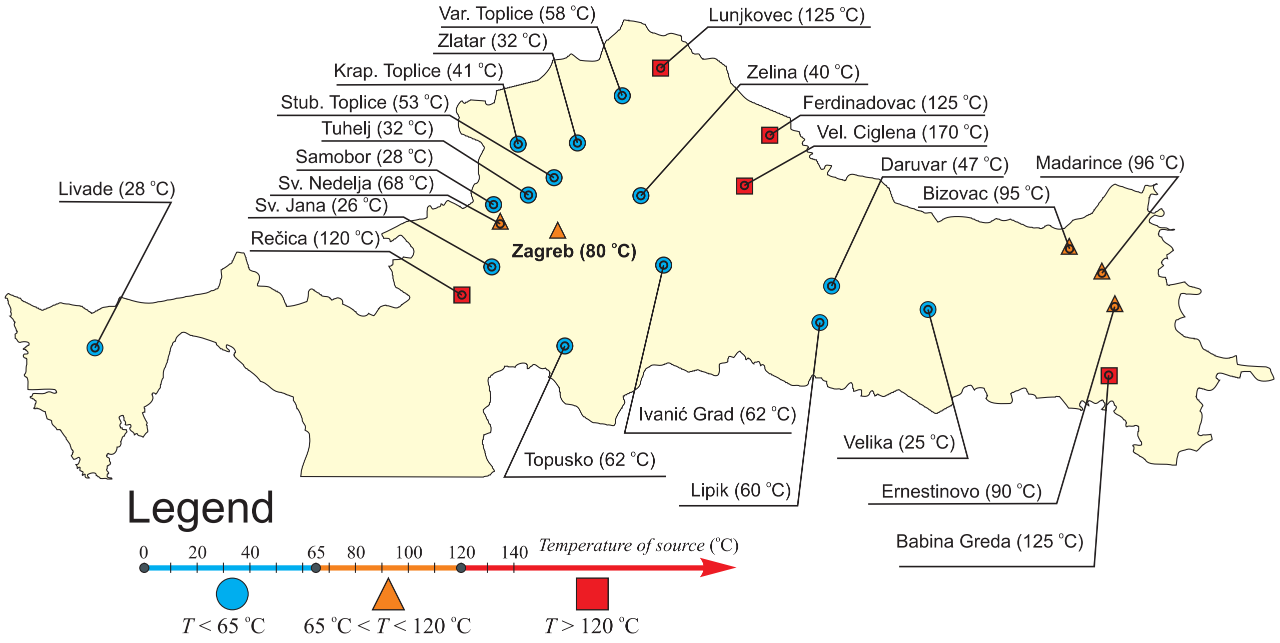


Fig. 2. Geothermal potentials in Croatia [3].

The two sedimentary basins cover almost the entire territory of the Republic of Croatia: the “Pannonian” basin and the “Dinarides” basin, Fig. 1. Large differences between these two basins are in geothermal potentials which have been obtained by investigation works with the aim of discovering oil and gas.

In the “Dinarides” basin the average geothermal temperature gradient and heat flux are 0.018 °C/m and 29 mW/m^2 [6].

Unlike the “Dinarides” basin, which has no significant geothermal potentials, the average geothermal temperature gradient and heat flux in the “Pannonian” basin are much greater: 0.049 °C/m and 76 mW/m^2 [6]. Since the geothermal gradient in the “Pannonian” basin is considerably greater than the European average value, in this region, besides the already discovered geothermal fields, the discovery of new geothermal fields is to be expected.

Geothermal potentials in Croatia can be divided into three groups, Fig. 2: the medium temperature sources with 100–200 °C; low temperature sources with 65–100 °C and geothermal sources with water temperature below 65 °C [6].

The entire heating power of geothermal energy potential of Croatia from the already worked-out wells is estimated at 203.47 MW (up to 50 °C) i.e. 319.21 MW (up to 25 °C), and with complete work out fields 839.14 MW (up to 50 °C) i.e. 1169.97 MW (up to 25 °C) [6].

3. Types of geothermal power plants

High temperature geothermal resources such as dry steam and hot water and medium temperature geothermal resources such as medium temperature water can be gainfully utilized to generate

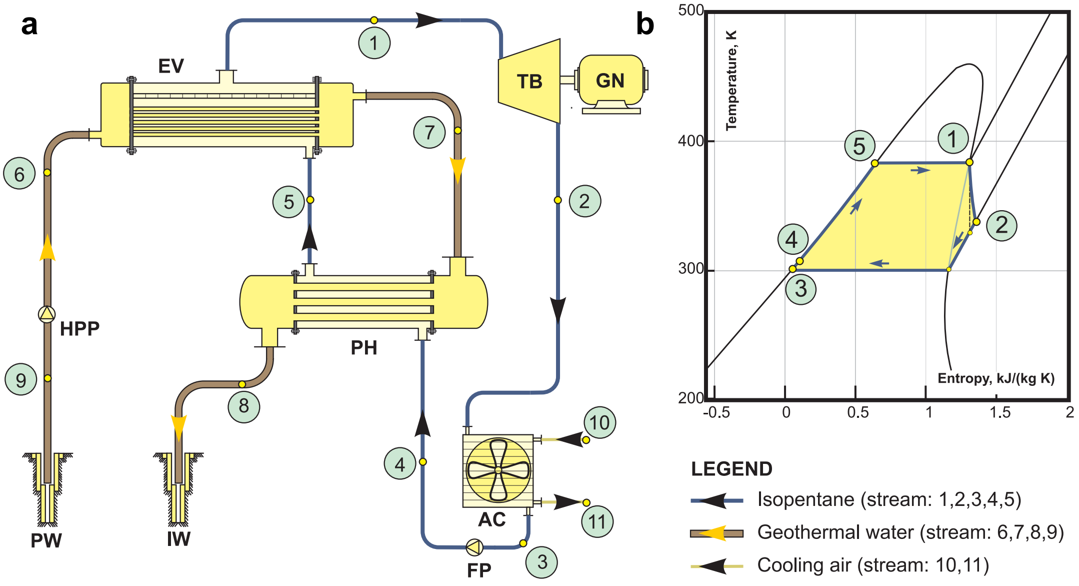


Fig. 3. Binary cycle with the ORC: (a) scheme of a plant (HPP-high pressure pump, FP – feed pump, PH – preheater, EV – evaporator, AC – air condenser, TB – turbine, GN – generator, PW – production well, IW – injection well) and (b) temperature–entropy diagram.

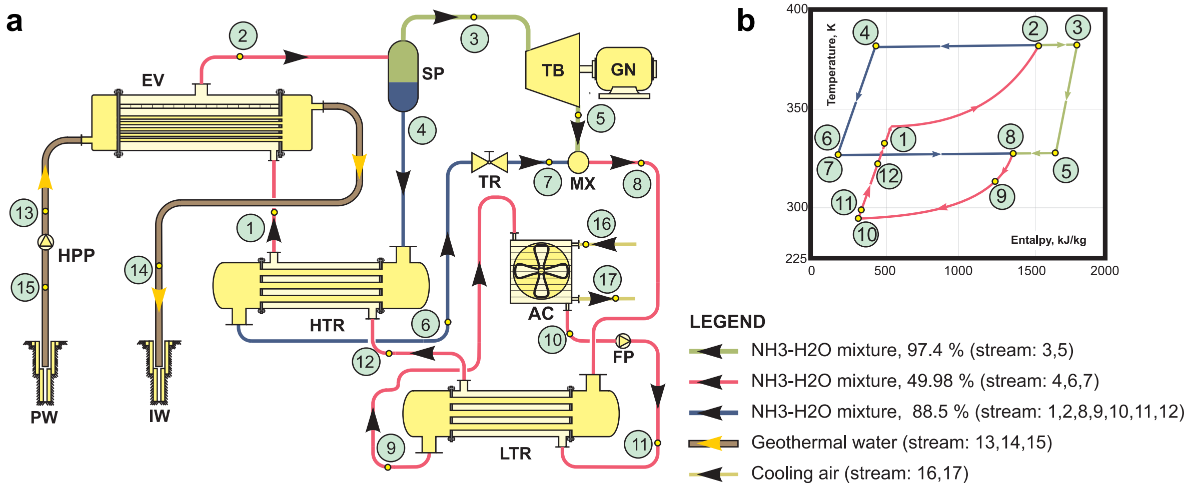


Fig. 4. Binary cycle with the Kalina cycle: (a) scheme of a plant (HPP – high pressure pump, FP – feed pump, LTR – low temperature preheater, HTR – high temperature preheater, EV – evaporator, SP – separator, MX – mixer, TR – throttle valve, AC – air condenser, TB – turbine, GN – generator, PW – production well, IW – injection well) and (b) temperature–enthalpy diagram of the binary cycle with the Kalina cycle.

electricity using three types of geothermal power plants: dry steam, flash and binary power plants.

Dry steam geothermal power plants use very hot steam (>235 °C) and little water from the geothermal resources.

Flash steam power plants (single and double) use hot water (>180 °C) while binary cycle use medium temperature water (100–180 °C) from geothermal resources.

Binary plants convert medium temperature resources into electricity more efficiently than other technologies. In binary plants a heat exchanger transfers heat from the produced hot geofluid in a primary loop to a low boiling-point working fluid in a secondary loop, such as propane, isobutene, pentane, isopentane, etc. This thermodynamic cycle is known as Organic Rankine Cycle (ORC) because initially organic compounds were used as the working fluid (Fig. 3). The working fluid in the secondary loop is evaporated in the vaporizer by the geothermal heat provided in the primary loop. The vapour expands as it passes through the organic vapour turbine which is coupled to the generator. The exhaust vapour is condensed in a water-cooled condenser or air cooler and is recycled to the vaporizer by the feed pump. The cooled geofluid can be discharged or reinjected into the reservoir without flashing, which minimizes scaling problems.

ORC systems have been installed in significant numbers within the past 30 years because binary plants convert medium enthalpy geothermal resources more efficiently into electricity than other technologies, which widens the spectrum of locations suitable for geothermal power production significantly. It makes decentralized geothermal production feasible and economically attractive in many remote or less developed regions of the world, where financial incentives promote low CO_2 emission energy production technologies.

Recently, the efficiency of binary power plants has been further improved by the Kalina cycle technology (Fig. 4). Here, a mixture of

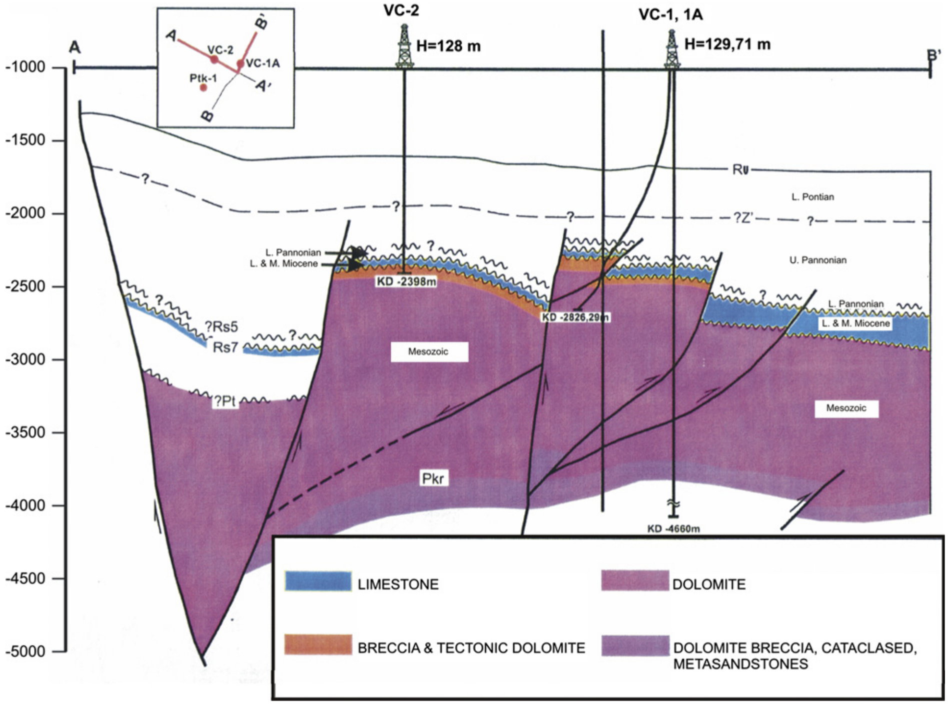


Fig. 5. Geological and geophysical structure of geothermal field Velika Ciglena [25].

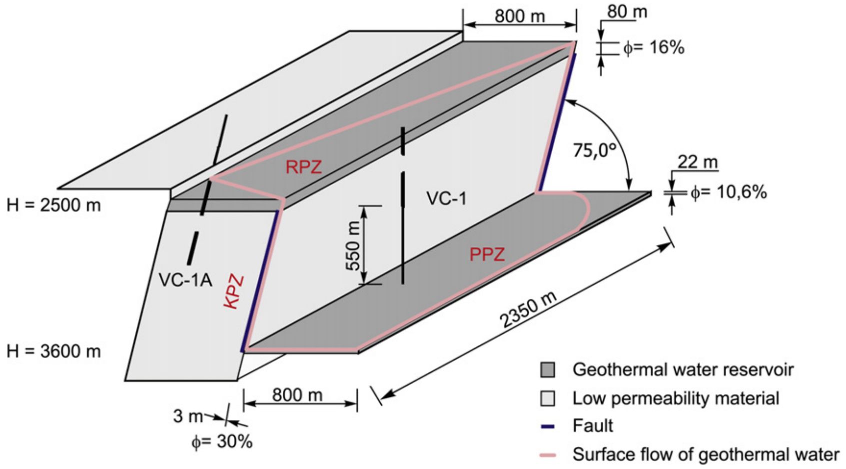


Fig. 6. Hydro-geological structure of geothermal field Velika Ciglena [25,28].

water and ammonia (NH_3) is evaporated over a finite temperature range, producing a two-component vapour in contrast to the ORC which is based on pure fluids evaporating at specific boiling temperatures. The main thermodynamic advantage of the Kalina cycle over the ORC is due to the fact that the water-ammonia mixture, unlike pure fluids, boils at variable temperatures. Therefore the working fluid temperature remains closer to the temperature of the hot geofluid in the primary circuit which improves the exergy efficiency.

In particular, in the Kalina cycle the working fluid is circulated in different parts of the cycle at different compositions: low ammonia concentration is used during condensation, while evaporation occurs at higher ammonia concentrations for optimum cycle performance. This provides an improved efficiency of the Kalina cycle over the conventional ORC, according to literature [19] of impressive 30–50%.

Geothermal energy could be utilised also in conventional fossil fired power plants in so called hybrid configuration, for example for condensate preheating [20].

A detailed description of all energy conversion systems for the utilization of geothermal energy for electricity generation is presented in [1,21–24].

4. Characteristics of geothermal field Velika Ciglena

As already stated, the Croatian part of the Pannonian Basin generally has an increased geothermal flow, especially in the area of the Bjelovar depression, in which the geothermal field Velika Ciglena is located. The geothermal field Velika Ciglena is a hydrothermal resource in carbonate rocks of tertiary base. It was discovered in the Mesozoic dolomites by the construction of the deep test well Velika Ciglena-1 (VC-1) during 1989 and 1990, Fig. 5 [25]. Works, which preceded the drilling of the VC-1 well were focused on oil and gas investigation on this site, but the main result at this location was the detection of the geothermal field. Geothermal field was additionally bored with yet three wells within the considered area. After that, the basis for the continuation of geothermal research in the wider area of this part of Bjelovar depression was made. In 1990 the well VC-1A was built as a production geothermal well, Fig. 5. The remaining wells, which have bored the geothermal reservoir are Velika Ciglena-2 (VC-2) and Patkovac-1 (Ptk-1), Fig. 5.

A characteristic of this hydrothermal resource is high water temperature, which was already indicated at the first drilling of the reservoir (the measured temperature is over 175 °C) and high permeability of the field. The geothermal gradient on geothermal field Velika Ciglena is estimated at 0.063–0.065 °C/m. Geothermal water contains 24 g/l dissolved minerals, 27 m^3/m^3 CO_2 and 59 ppm H_2S [25].

For the purposes of defining the geothermal aquifer Velika Ciglena the interpretations of geological, geophysical and hydrogeological data were connected. Main attention has been paid to the thick carbonate-sedimentary sequence in the tertiary base, i.e. on its accumulation and structural-tectonic features. It has fulfilled its objective and confirmed the presence of carbonate geothermal aquifer in the tertiary base and provided the current level of knowing the production possibilities.

According to the classification in [26,27], this reservoir is a combination of massive and conditionally stratified type, connected into a whole. The conditionally stratified parts of the reservoir means cap permeable zone (PPZ) and fault permeable zone (RPZ), whereas the basement permeable zone (KPZ) has massive character, Fig. 6 [25,28]. These three high permeable zones describe the geothermal source and they are interconnected in a Z-model [26,27].

The shallowest is the cap permeable zone (KPZ) at 2585 m (bored on all three investigated wells), then the fault permeable zone (RPZ) at 3210 m and the basement permeable zone (PPZ) at 3597 m, which constitute a common reservoir, Fig. 6.

The mentioned zones related to the faults have a stratified character only conditionally, because the phenomena along the fault planes remind of layers. Along these relatively steep surfaces the longitudinal ("horizontal") permeability has been developed and transverse to them – in the vertical direction, they are limited by less permeable parts of the carbonate complex.

The characteristics of geothermal field Velika Ciglena (e.g. temperature gradient, mean reservoir porosity, mean absolute permeability, the size of the reservoir – the total area and total volume of the rocks complex, the water volume in the reservoir, static pressure and temperature of reservoir, chemical composition of geothermal fluid, physical properties of rocks, volumetric specific heat, permeability and other hydrodynamic properties of the reservoir, etc.) have been determined in [25,29] on the basis of previously investigated and elaborated works on the geothermal field Velika Ciglena, of basic geological and physical characteristics of the reservoir, geometric characteristics of reservoir with the description of the geological structure, hydrodynamic properties of the reservoir and technological and technical possibilities of field exploitation.

The characteristics of production and injection wells were estimated on the basis of wells testing data (productivity, injectivity, pressure and temperature) given in [25,28]. The analysis of the carried out tests, performed by the Prosper program (Single

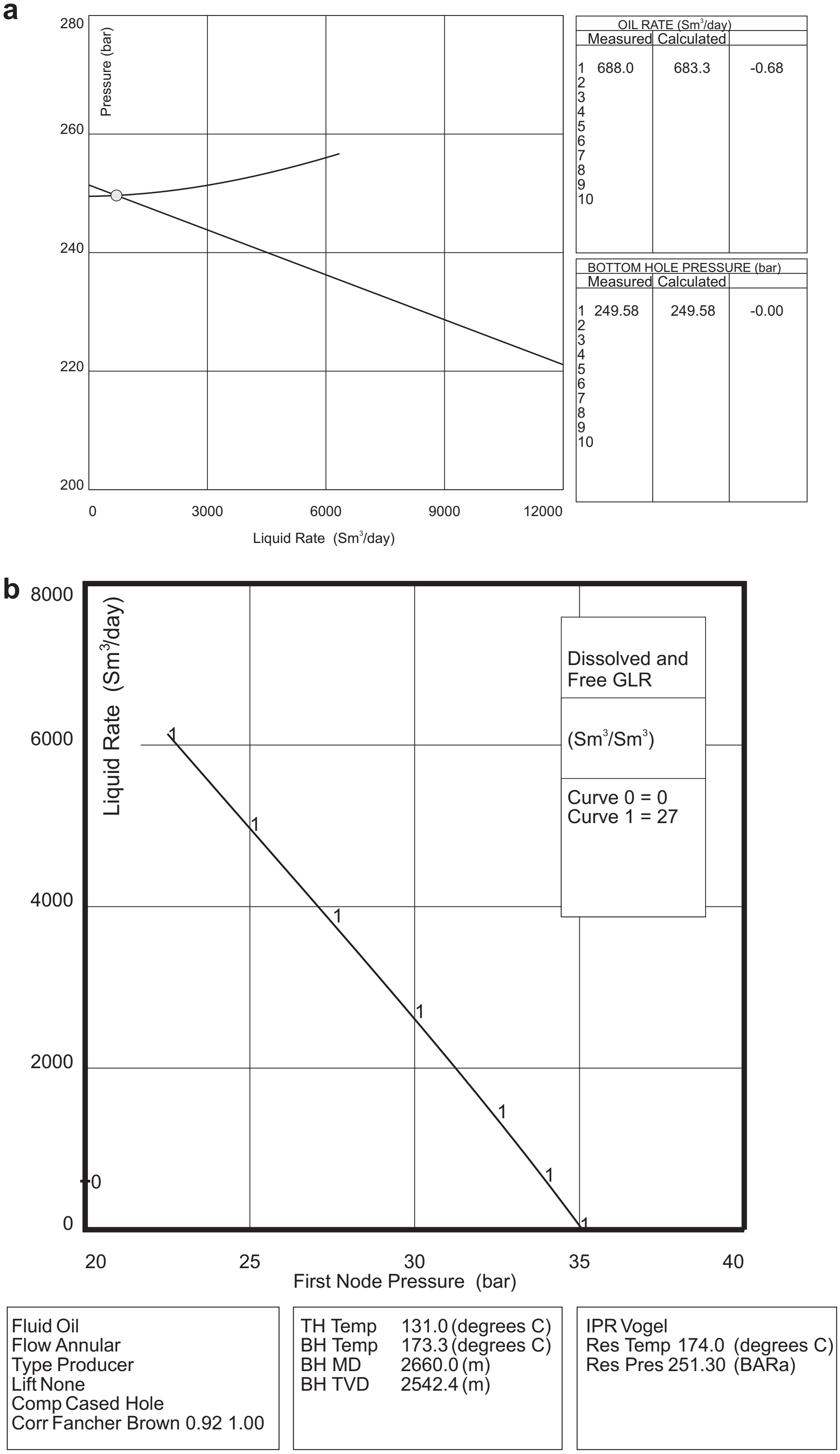
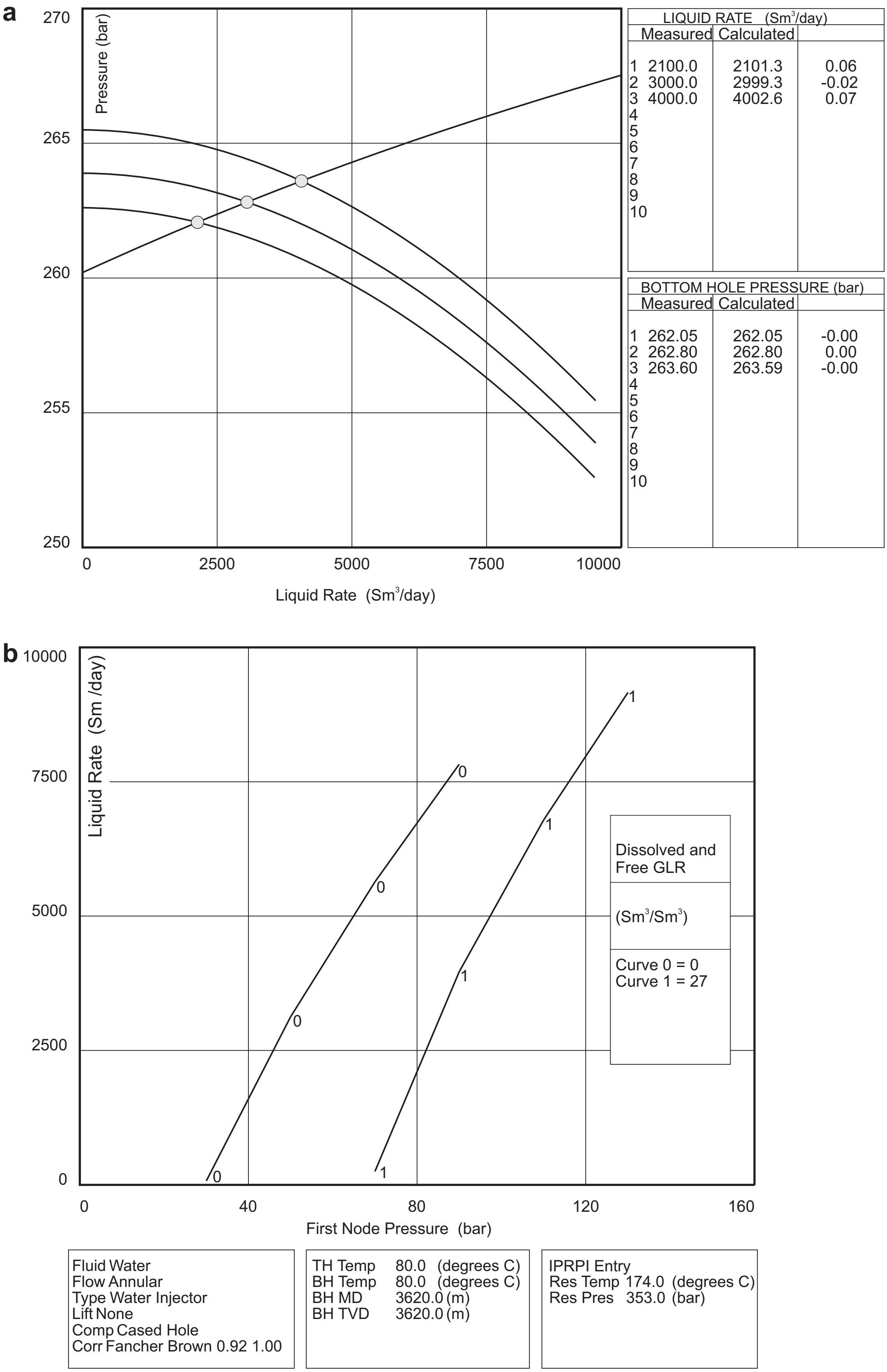


Fig. 7. Testing of production well VC-1A: (a) matching of results of productivity testing and (b) simulation of productivity possibilities [25,28].

Well Systems Analysis) in [25,28] yielded data about production possibilities of the production well VC-1A and injection possibilities of the injection well VC-1. The overall conclusion after the simulation of the production lifecycle and conducted tests is as follows: excellent compatibility of simulated and actual test results is obtained and with great certainty maximum production of the production well and conditions of injection of water and gas in the injection well may be assumed.



LIQUID RATE (Sm³/day)

	Measured	Calculated	
1	2100.0	2101.3	0.06
2	3000.0	2999.3	-0.02
3	4000.0	4002.6	0.07
4			
5			
6			
7			
8			
9			
10			

BOTTOM HOLE PRESSURE (bar)

	Measured	Calculated	
1	262.05	262.05	-0.00
2	262.80	262.80	0.00
3	263.60	263.59	-0.00
4			
5			
6			
7			
8			
9			
10			

Fluid Water
Flow Annular
Type Water Injector
Lift None
Comp Cased Hole
Corr Fancher Brown 0.92 1.00

TH Temp 80.0 (degrees C)
BH Temp 80.0 (degrees C)
BH MD 3620.0 (m)
BH TVD 3620.0 (m)

IPRPI Entry
Res Temp 174.0 (degrees C)
Res Pres 353.0 (bar)

Fig. 8. Testing of injection well VC-1: (a) matching of results of injectivity testing and (b) simulation of injection possibilities [25,28].

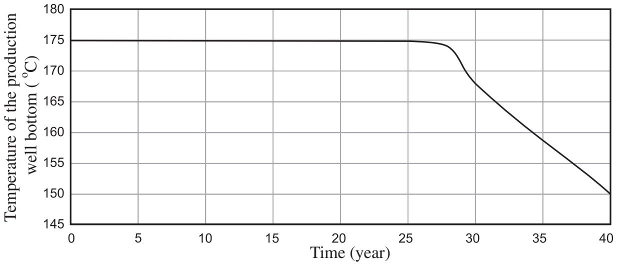


Fig. 9. Representation of the calculation dynamics of the temperature change of the gained geothermal water [25].

The simulated and actual testing results as well as forecast of production and injection are shown in Figs. 7a and b, and 8a and b [25,28]. The presented simulation results show that the maximum production of the production well is 7200 m^3/day or 83.3 l/s. This production is maximum production in which the pressure at the mouth is the minimum required 20 bar in order to avoid the silica scaling in the surface system.

According to the simulation results [25] in case of the fall of gas factors for geothermal water to zero there is practically no eruptive production. The gas factor for water according to calculations will start to fall in the sixth year of exploitation [25]. Therefore, in order to insure the eruptive work of the well for the whole time of exploitation both water and gas are to be returned into the reservoir.

The time in which the temperature of the gained water is constant depends on the intensity of reservoir exploitation. Constant temperature will be maintained until the cool front penetrates into the production well. The penetration time of the cold front determined in [25] is 8733.6 days or 23.9 years. The amount of geothermal water, which will be gained at constant temperature is 62.88×10^6 m^3.

The calculation dynamics of the temperature change of the gained water is shown in Fig. 9 [25]. For the production life, in the technical-economic evaluation of profitability, the time period of 20 years has been taken, and the figure shows that the temperature begins to drop in the 24th year. The risk of an earlier start of the fall of temperature is minimal, because it is very likely that the injected water will move over the larger flow surface as well as over the flow volume reservoir.

Total reserves may be classified into category B [6]. Since the current reserves of geothermal field Velika Ciglena are determined by the production capabilities of the production wells and amount to: total reserves 83.3 l/s and annual production 2,628,000 m^3 [25].

5. Case study: geothermal power plant Velika Ciglena

In the Republic of Croatia there are several medium temperature geothermal sources with temperature in the range of 100–200 °C (Fig. 2), by means of which it is possible to produce electricity: Velika Ciglena (175 °C), Lunjkovec (125 °C), Ferdinandovac (125 °C), Babina Greda (125 °C) and Rečica (120 °C). From the review of today's available technologies for the generation of electric power from geothermal energy, the binary plants come to the fore, either with the ORC or with the Kalina cycle. The comparison of these two cycles will be performed on the previously described the most prospective geothermal field in the Republic of Croatia, Velika Ciglena.

In the proposed binary plants with the ORC and with the Kalina cycle the geothermal fluid transfers heat to the working fluid by cooling from 175 °C to 69 °C. After that geothermal water will be used for direct usage, for heating of buildings, greenhouses, swimming pools, etc., if calculations show that this will not affect the production of electricity. Results of economic analyses usually favour combined heat and power generation [30]. The working fluid in the ORC is a low boiling-point isopentane, and in the Kalina cycle, a mixture of water and ammonia, whose composition changes during the cycle. The proposed binary plants (Figs. 3a and 4a) with regard to configurations and cycle working parameters (maximal pressure and temperature, mixture composition, etc.) are chosen in such a way that they are very close to the performed, type-designed plants of the leading world manufacturers.

Since at the location of the geothermal field Velika Ciglena the amounts of cooling water for the water-cooled condenser are not sufficient, in both cases, the air-cooled condensers are used, whose thermodynamic calculations have been performed with the average annual air temperature of 15 °C. In thermodynamic calculations special attention is paid to the values of pinch points which are not below 5 °C.

The presumed turbine isentropic efficiencies are 0.85 for the ORC (dry turbine) and 0.75 for the Kalina cycle (wet turbine). In both cases the presumed efficiencies for feed pumps are 0.8, the same as for high pressure pump for geothermal water. The calculation results for the ORC are given in Table 1 and for the Kalina cycle in Table 2. Single points from tables correspond to those in Figs. 3a and b, and 4a and b.

Thermodynamic calculations are performed on a computer by means of binary cycle model with ORC and Kalina cycle which is developed on the basis of Refs. [1,7–11] and presented in Appendix, where thermodynamic properties of working fluids are determined by REFPROP program [31]. The exergy analysis of ORC and Kalina cycle is performed by the use of REFPROP program special routine on models of the most important cycle units and both cycles developed on the basis of Refs. [1,12–17]. Models and corresponding exergy efficiencies are presented in Fig. A1 in Appendix.

From Tables 1 and 2 it is evident that the mass flow ratio of isopentane (80.13 kg/s) in the ORC is twice the mass flow ratio of the water-ammonia mixture (35.717 kg/s) at Kalina cycle, which has a positive reflection on the turbine design (rotational speed, blades height, etc.). Also, during the expansion process in the turbine at ORC the isopentane steam is superheated, while at Kalina cycle the vapour of water-ammonia mixture is wet. Therefore in the turbine at ORC the erosion of rotor blades is completely avoided,

Table 1
Calculation results for ORC.

Stream	Composition	$\dot{m}$(kg s^{-1})	T (K)	p (Mpa)	h (kJ kg^{-1})	s (kJ kg^{-1} K^{-1})	e (kJ kg^{-1})	$\dot{H}$ (kW)	$\dot{E}$ (kW)
1	Isopentane	80.13	383.55	0.90	471.59	1.29	86.46	37788.51	6927.96
2	Isopentane	80.13	335.24	0.11	404.20	1.33	8.40	32388.55	673.36
3	Isopentane	80.13	302.14	0.11	2.67	0.01	0.07	213.97	5.57
4	Isopentane	80.13	305.58	8.98	17.98	0.01	14.50	1440.34	1162.13
5	Isopentane	80.13	383.55	8.98	210.70	0.57	40.27	16883.39	3226.51
6	Geothermal water	83.00	448.20	7.00	744.48	2.08	127.96	61791.84	10620.68
7	Geothermal water	83.00	389.30	7.00	492.34	1.48	55.58	40864.22	4612.89
8	Geothermal water	83.00	342.20	7.00	294.80	0.94	19.27	24468.40	1599.33
9	Geothermal water	83.00	448.20	2.00	741.82	2.09	123.36	61571.06	10238.88
10	Cooling air		288.15	0.10	414.48				
11	Cooling air		297.15	0.10	423.53				

while in the turbine at Kalina cycle it will be significant. At Kalina cycle the maximum pressure of the cycle (in evaporator) is significantly higher (28 bar) than at ORC (8.9781 bar), but at the same time at Kalina cycle a minimum pressure of the cycle (in condenser) is also higher (8 bar) than at ORC (1.055 bar).

The geothermal field Velika Ciglena contains a substantial amount of dissolved carbon dioxide (CO_2): in reservoir conditions CO_2 is under supercritical conditions in the amount of 27 m^3/1 m^3 of water, and it is completely dissolved in hot water. Therefore, the geothermal fluid mixture consists of hot water and CO_2. The flow of geothermal fluid from the reservoir to the mouth of the well occurs with the pressure and temperature drop. The pressure drop leads to the extraction of CO_2 from the water so that at surface conditions at the well mouth there is a two-component and at the same time a two-phase mixture of geothermal fluid. The geothermal water that passed through the heat exchanger and the CO_2 dissolved in it has to be injected in the injection well for the following reasons:

- to mainttain the necessary conditions in the reservoir over a longer period of time that will enable optimal conditions of exploitation, and
- due to ecological reasons, to maintain the ecological balance and prevent greenhouse emissions of CO_2 into the atmosphere.

Therefore, using geothermal energy of the Velika Ciglena field requires construction of a plant for the back-injection of water and carbon dioxide (CO_2) obtained from the production well VC-1A. The plant should be dimensioned on the basis of estimated reserves which are defined by the flow possibility of the VC-1A well. One of the possible variants which is proposed in this paper is the installation of a special high pressure pump at the production well, which will raise the pressure of geothermal water over 70 bar and thus CO_2 will remain dissolved in water all the time. It is the simplest way but certainly not the most economical one. More economical but also more complex methods which will be analysed in the next phase are:

- pump for water injection and compressor for CO_2 injection – planned two independent flows of injected fluids;
- booster pump and compressor and pump for injection of water and CO_2 mixture;
- plant for liquefaction and injection of CO_2 and pump for water injection – planned possibility of two independent flows of injected fluids or a single mixed one.

6. Results and discussion

Thermodynamic calculation of the ORC gives gross power of 5400 kW with mass flow rate 80.13 kg/s, while thermodynamic calculation of the Kalina cycle gives gross power of 4085 kW with mass flow rate 35.717 kg/s. If the related powers for operation of feed pumps are subtracted from gross powers, which in case of the ORC is 130 kW and in case of the Kalina cycle 136 kW, net power is obtained, which in case of the ORC is 5270 kW and in case of the Kalina cycle 3949 kW. The thermal efficiency (the First Law efficiency) calculated on the basis of the obtained net power and transferred heat from geothermal fluid in case of the ORC is 14.1%, and in case of the Kalina cycle 10.6%. The heat rejection ratio in case of the ORC is 6.092 and in case of the Kalina cycle 8.434. The exergy efficiency (the Second Law efficiency) in case of the ORC is 52%, and in case of the Kalina cycle 44% (Fig. A1).

The obtained results are very interesting and at first act confusing, because in literature the Kalina cycle is cited as thermodynamically more favourable than the ORC, which reaches higher thermodynamic efficiency and gives more power [19].

The obtained results can be explained as follows:

- in this concrete case of medium temperature geothermal source with relatively high temperature of geothermal water the ORC is thermodynamically better than the Kalina cycle;
- evidently, the advantages of the Kalina cycle are manifested in cases of medium geothermal sources with relatively low temperature of geothermal water, when it can be thermodynamically better than the ORC;
- relatively high temperature of cooling air in condenser has more unfavourable influence in the Kalina cycle than in the ORC: condensation pressure in the Kalina cycle is 8 bar, compared to the ORC where it is 1 bar.

At present, however, there is just one geothermal Kalina cycle power plant in operation in Husavik, Iceland; several more are under construction [2].

While there are reports [32] about problems during the start-up and commissioning of the only plant with the Kalina cycle in the world, at the same time the ORC has a series of advantages [33].

Today the ORC is a mature technology with hundreds of megawatts of various kinds of cycles installed throughout the world [34].

Table 2
Calculation results for Kalina cycle.

Stream	Composition	$\dot{m}$(kg s^{-1})	T (K)	p (Mpa)	h (kJ kg^{-1})	s (kJ kg^{-1} K^{-1})	e (kJ kg^{-1})	$\dot{H}$ (kW)	$\dot{E}$ (kW)
1	NH_3–H_2O mixture, 88.5%	35.72	332.46	2.80	500.92	2.18	884.07	17891.36	31576.33
2	NH_3–H_2O mixture, 88.5%	35.72	381.93	2.80	1549.20	5.16	1043.30	55332.78	37263.55
3	NH_3–H_2O mixture, 97.4%	29.01	381.93	2.80	1806.30	5.88	1137.00	52407.99	32988.92
4	NH_3–H_2O mixture, 49.98%	6.70	381.93	2.80	436.41	2.07	542.29	2925.26	3634.97
5	NH_3–H_2O mixture, 97.4%	29.01	327.76	0.80	1665.50	6.02	952.91	48322.82	27647.73
6	NH_3–H_2O mixture, 49.98%	6.70	327.46	2.80	170.83	1.33	500.23	1145.07	3353.04
7	NH_3–H_2O mixture, 49.98%	6.70	327.44	0.80	169.27	1.33	497.80	1134.62	3336.75
8	NH_3-H_2O mixture, 88.5%	35.72	327.46	0.80	1383.40	5.14	885.26	49410.90	31618.83
9	NH_3–H_2O mixture, 88.5%	35.72	314.08	0.80	1254.40	4.73	876.33	44803.40	31299.88
10	NH_3–H_2O mixture, 88.5%	35.72	294.82	0.80	316.54	1.60	872.07	11305.86	31147.72
11	NH_3–H_2O mixture, 88.5%	35.72	295.36	2.80	319.98	1.60	875.09	11428.73	31255.59
12	NH_3–H_2O mixture, 88.5%	35.72	322.46	2.80	451.07	2.03	879.61	16110.87	31417.03
13	Geothermal water	83.00	449.17	7.00	748.72	2.09	129.39	62143.76	10739.37
14	Geothermal water	83.00	342.20	7.00	294.80	0.94	19.27	24468.40	1599.33
15	Geothermal water	83.00	448.20	2.00	741.82	2.09	123.36	61571.06	10238.88
16	Cooling air		288.15	0.10	290.34	6.85	0.17	0.00	0.00
17	Cooling air		297.04	0.10	299.35	6.88	0.00	0.00	0.00

7. Conclusion

In the Republic of Croatia there are several medium temperature geothermal sources which could produce electricity: Velika Ciglena, Lunjkovec, Ferdinandovac, Babina Greda and Rečica. Based on the world experiences, the binary power plants with the ORC or the Kalina cycle come to the fore. Therefore, the example of the most prospective geothermal field in Croatia, Velika Ciglena, has been used to make the comparison of binary plants with the ORC and the Kalina cycle. The ORC has proven to be thermodynamically better, which can be explained by relatively high temperatures of geothermal water (175°) and of air for cooling (15 °C). At the other geothermal sources with lower temperatures (120–125 °C) the advantages of the Kalina cycle will be more marked. As the results of comparison performed in [12] for similar temperatures (108–122 °C) show actual increase of 3% for the Kalina cycle over the ORC, and not 30–50% as referenced in literature [19], and considering the problems which all the new technologies experience in the starting phase of application, thus not only for geothermal field Velika Ciglena but also for other geothermal sources with lower temperatures in Croatia (Lunjkovec, Ferdinandovac, Babina Greda and Rečica) the application of the binary plants with ORC are proposed.

Appendix

Thermodynamic modelling is necessary for the calculation of all parameters in a power plant and for making models for each power plant before design of a power plant can be started. Thermodynamics of the conversion processes in single components of the binary plants is given in Refs. [1,7–11]. Denotations in the next equations correspond to those in Fig. 3a and b and Table 1 for the ORC and Fig. 4a and b and Table 2 for the Kalina cycle.

The power of the turbine in the ORC is given by:

$$\dot{W}_{\mathrm{t}} = \dot{m}_{\mathrm{ORC\text{-}wf}}(h_1 - h_2) = \dot{m}_{\mathrm{ORC\text{-}wf}}\eta_{\mathrm{t}}(h_1 - h_{2\mathrm{is}}) \tag{A1}$$

In the case of the Kalina Cycle $\dot{m}_{\mathrm{ORC\text{-}wf}}, h_1, h_2, h_{2\mathrm{is}}$ (Table 1) has to be replaced by $\dot{m}_{\mathrm{KC\text{-}vap}}, h_3, h_5, h_{5\mathrm{is}}$(Table 2).

The heat that must be rejected from the working fluid (isopentane) to the cooling fluid (air) in the condenser AC in the ORC is found from:

$$\dot{Q}_2 = \dot{m}_{\mathrm{ORC\text{-}wf}}(h_2 - h_3) \tag{A2}$$

In the case of the Kalina Cycle $\dot{m}_{\mathrm{ORC\text{-}wf}}, h_2, h_3$ (Table 1) has to be replaced by $\dot{m}_{\mathrm{KC\text{-}mix}}, h_9, h_{10}$ (Table 2).

The relationship between the flow rates of the working fluid and the cooling fluid is:

$$\dot{m}_{\mathrm{cf}}(h_{11} - h_{10}) = \dot{m}_{\mathrm{ORC\text{-}wf}}(h_2 - h_3) \tag{A3.a}$$

or

$$\dot{m}_{\mathrm{cf}}\bar{c}_{\mathrm{cf}}(T_{11} - T_{10}) = \dot{m}_{\mathrm{ORC\text{-}wf}}(h_2 - h_3) \tag{A3.b}$$

since the cooling fluid has a constant specific heat $\bar{c}$ for a small temperature range.

In the case of the Kalina cycle $\dot{m}_{\mathrm{ORC\text{-}wf}}, h_2, h_3$ (Table 1) has to be replaced by $\dot{m}_{\mathrm{KC\text{-}mix}}, h_9, h_{10}$ (Table 2).

The power imparted to the working fluid from the feed pump is:

$$\dot{W}_{\mathrm{p}} = \dot{m}_{\mathrm{ORC\text{-}wf}}(h_4 - h_3) = \dot{m}_{\mathrm{ORC}}(h_{4\mathrm{is}} - h_3)/\eta_{\mathrm{p}} \tag{A4}$$

In the case of the Kalina cycle $\dot{m}_{\mathrm{ORC\text{-}wf}}, h_4, h_3, h_{4\mathrm{is}}$ (Table 1) has to be replaced by $\dot{m}_{\mathrm{KC\text{-}mix}}, h_{11}, h_{10}, h_{11\mathrm{is}}$ (Table 2).

The relationship between the flow rates of the working fluid and the geothermal fluid in the heat exchanger (in preheater PH and evaporator EV) in the ORC is:

$$\dot{m}_{\mathrm{gf}}(h_6 - h_8) = \dot{m}_{\mathrm{ORC\text{-}wf}}(h_1 - h_4) \tag{A5.a}$$

or

$$\dot{m}_{\mathrm{gf}}\bar{c}_{\mathrm{gf}}(T_6 - T_8) = \dot{m}_{\mathrm{ORC\text{-}wf}}(h_1 - h_4) \tag{A5.b}$$

The following equation may be used to determine the working fluid flow rate in ORC:

$$\dot{m}_{\mathrm{ORC\text{-}wf}} = \frac{\dot{m}_{\mathrm{gf}}\bar{c}_{\mathrm{gf}}(T_6 - T_8)}{h_1 - h_4} \tag{A6}$$

The preheater PH and evaporator EV may be analyzed separately:

$$\dot{m}_{\mathrm{gf}}\bar{c}_{\mathrm{gf}}(T_7 - T_8) = \dot{m}_{\mathrm{ORC\text{-}wf}}(h_5 - h_4) \tag{A7.a}$$

$$\dot{m}_{\mathrm{gf}}\bar{c}_{\mathrm{gf}}(T_6 - T_7) = \dot{m}_{\mathrm{ORC\text{-}wf}}(h_1 - h_5) \tag{A7.b}$$

The pinch–point temperature difference is generally known from the manufacturer's specifications and T_7 can be found from the value for T_5.

In case of the Kalina cycle (Fig. 4a and b and Table 2) the governing equations for the separator SP are:

$$\dot{m}_{\mathrm{KC\text{-}mix}}x_2 = \dot{m}_{\mathrm{KC\text{-}vap}}x_3 + \dot{m}_{\mathrm{KC\text{-}liq}}x_4; \tag{A8.a}$$

$$\dot{m}_{\mathrm{KC\text{-}mix}}h_2 = \dot{m}_{\mathrm{KC\text{-}vap}}h_3 + \dot{m}_{\mathrm{KC\text{-}liq}}h_4, \tag{A8.b}$$

for the mixer MX:

$$\dot{m}_{\mathrm{KC\text{-}mix}}x_8 = \dot{m}_{\mathrm{KC\text{-}vap}}x_5 + \dot{m}_{\mathrm{KC\text{-}liq}}x_7; \tag{A9.a}$$

$$\dot{m}_{\mathrm{KC\text{-}mix}}h_8 = \dot{m}_{\mathrm{KC\text{-}vap}}h_5 + \dot{m}_{\mathrm{KC\text{-}liq}}h_7, \tag{A9.b}$$

for the low temperature recuperator LTR:

$$\dot{m}_{\mathrm{KC\text{-}mix}}(h_8 - h_9) = \dot{m}_{KC-mix}(h_{12} - h_{11}), \tag{A10}$$

for the high temperature recuperator HTR:

$$\dot{m}_{\mathrm{KC\text{-}liq}}(h_4 - h_6) = \dot{m}_{\mathrm{KC\text{-}mix}}(h_1 - h_{12}) \tag{A11}$$

for the evaporator EV:

$$\dot{m}_{\mathrm{gf}}(h_{13} - h_{14}) = \dot{m}_{\mathrm{KC\text{-}mix}}(h_2 - h_1) \tag{A12.a}$$

or

$$\dot{m}_{\mathrm{gf}}\bar{c}_{\mathrm{gf}}(T_{13} - T_{14}) = \dot{m}_{\mathrm{KC\text{-}mix}}(h_2 - h_1) \tag{A12.b}$$

Cycle net power for ORC and Kalina cycle:

$$\dot{W}_{\mathrm{net}} = \dot{W}_{\mathrm{t}} - \dot{W}_{\mathrm{p}} \tag{A13}$$

The supplied heat in ORC and Kalina cycle:

$$\dot{Q}_1 = \dot{m}_{\mathrm{gf}}(h_6 - h_5) = \dot{m}_{\mathrm{gf}}(h_{13} - h_{14}) \tag{A14.a}$$

or

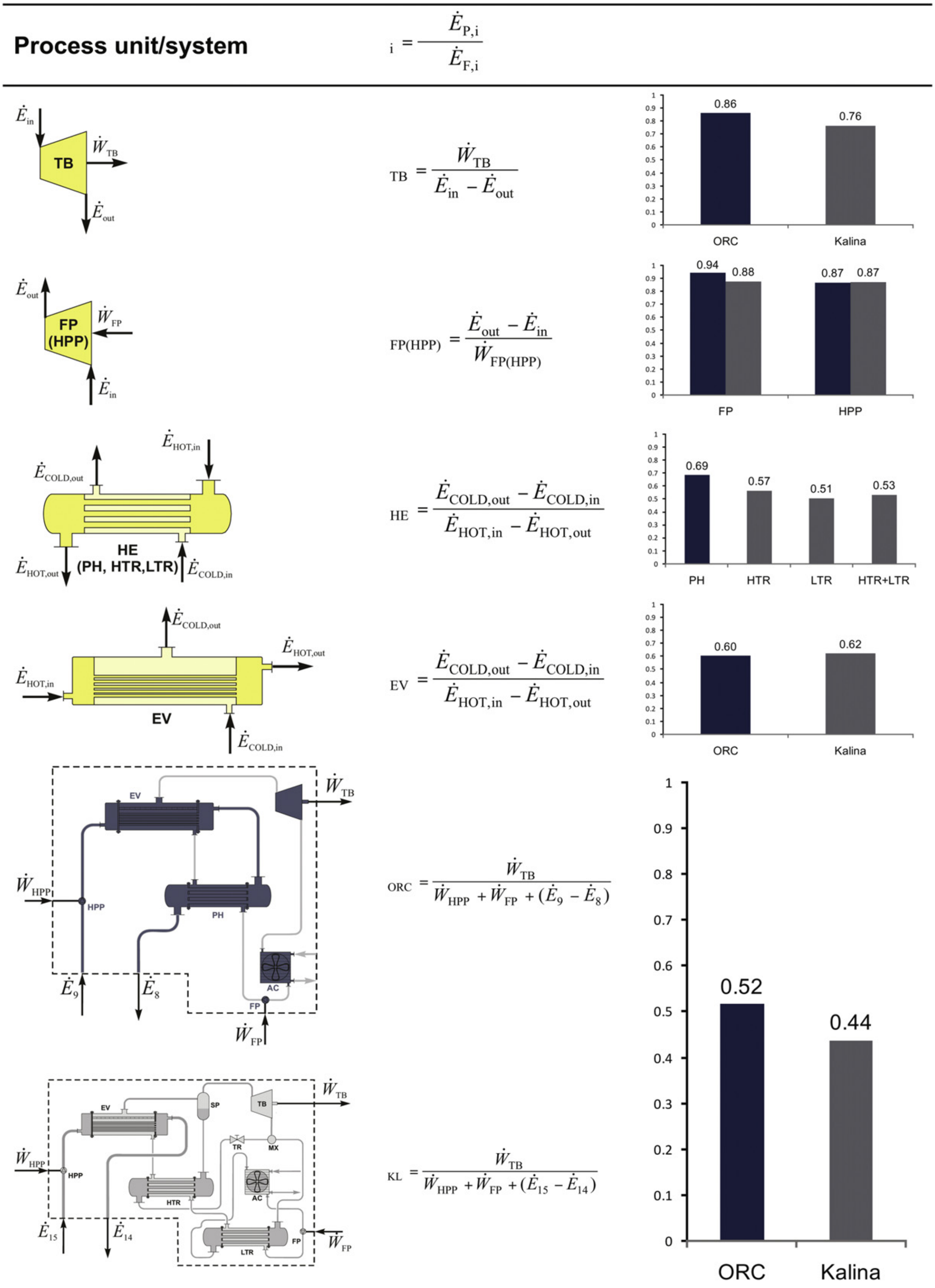
$$\dot{Q}_1 = \dot{m}_{\mathrm{gf}}\bar{c}_{\mathrm{gf}}(T_6 - T_5) = \dot{m}_{\mathrm{gf}}\bar{c}_{\mathrm{gf}}(T_{13} - T_{14}) \tag{A14.b}$$

The thermal efficiency (the First Law efficiency) for ORC and Kalina cycle:

$$\eta_{\mathrm{th}} = 1 - \frac{\dot{Q}_2}{\dot{Q}_1} = \frac{\dot{W}_{\mathrm{net}}}{\dot{Q}_1} \tag{A15}$$

The heat rejection ratio for ORC and Kalina cycle:

$$\frac{\dot{Q}_2}{\dot{W}_{\mathrm{net}}} = \frac{1}{\eta_{\mathrm{th}}} - 1 \tag{A16}$$



$${}_{\mathrm{i}} = \frac{\dot{E}_{\mathrm{P,i}}}{\dot{E}_{\mathrm{F,i}}}$$

$$\mathrm{TB} = \frac{\dot{W}_{\mathrm{TB}}}{\dot{E}_{\mathrm{in}} - \dot{E}_{\mathrm{out}}}$$

$$\mathrm{FP(HPP)} = \frac{\dot{E}_{\mathrm{out}} - \dot{E}_{\mathrm{in}}}{\dot{W}_{\mathrm{FP(HPP)}}}$$

$$\mathrm{HE} = \frac{\dot{E}_{\mathrm{COLD,out}} - \dot{E}_{\mathrm{COLD,in}}}{\dot{E}_{\mathrm{HOT,in}} - \dot{E}_{\mathrm{HOT,out}}}$$

$$\mathrm{EV} = \frac{\dot{E}_{\mathrm{COLD,out}} - \dot{E}_{\mathrm{COLD,in}}}{\dot{E}_{\mathrm{HOT,in}} - \dot{E}_{\mathrm{HOT,out}}}$$

$$\mathrm{ORC} = \frac{\dot{W}_{\mathrm{TB}}}{\dot{W}_{\mathrm{HPP}} + \dot{W}_{\mathrm{FP}} + (\dot{E}_{9} - \dot{E}_{8})}$$

$$\mathrm{KL} = \frac{\dot{W}_{\mathrm{TB}}}{\dot{W}_{\mathrm{HPP}} + \dot{W}_{\mathrm{FP}} + (\dot{E}_{15} - \dot{E}_{14})}$$

Fig. A1. Exergy efficiencies of the most important cycle units and both cycles.

Exergy analysis of ORC and Kalina cycle is performed by the use of REFPROP program special routine on models of the most important cycle units and both cycles developed on the basis of Res. [1,12–17] and are presented in Fig. A1. The exergy balance considered $T_0 = 298.15$ K and $p_0 = 101325$ Pa as the dead state conditions for the calculation of physical exergy, and neglected the kinetic, potential and chemical exergy of the streams. Exergy efficiencies of the most important cycle units and both cycles are also presented in Fig. A1.

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