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Possibilities of electricity generation in the Republic of Croatia from medium-temperature geothermal sources

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ABSTRACT

In the Republic of Croatia, there are several sources of medium-temperature geothermal water in the range of 90–140 °C, with which it is possible to produce electricity in binary plants, either with the Organic Rankine Cycle (ORC) or with the Kalina cycle. In the literature, the Kalina cycle is viewed as more thermodynamically favourable than the ORC; i.e., the Kalina cycle has a higher thermal efficiency and produces more power. However, the Croatian experience with a medium-temperature geothermal source with the relatively high temperature of geothermal water (Velika Ciglena, 175 °C) is that the ORC is thermodynamically better than the Kalina cycle. In this paper, a comparison between the ORC and the Kalina cycle is performed based on energy analysis results for a medium-temperature geothermal source with a relatively lower temperature (Lunjkovec–Kutnjak, 140 °C). Additionally, in this case the ORC has better thermal efficiency (First Law efficiency) – 13.5% vs. 12.8% – and accordingly higher net power – 2225.5 kW vs. 2101.4 kW. This difference is explained by the relatively high average annual temperature of the cooling air in the condenser (15 °C), which has a more unfavourable influence on the condensing pressure in the Kalina cycle than in the ORC (6.35 bar vs. 0.68 bar).

1. Introduction

Geothermal energy is the energy contained in the Earth's interior. Generally, geothermal energy is a clean energy source, as it meets the criteria of two important concepts in energy source exploitation: renewability and sustainability. The increase in temperature with depth is referred to as a geothermal temperature gradient. A local geothermal gradient is essential for geothermal energy exploitation because it indicates the presence of geothermal resources at reachable depths [1]. Presently, an international standard on terminology for the classification of geothermal sources is not yet defined. The most widely used classification of geothermal sources is based on the temperature of the geothermal fluid. Geothermal sources are divided into low- (<100 °C), medium- (100–200 °C) and high-temperature sources (>200 °C) [2].

Currently, geothermal energy is used either indirectly (for electricity generation) or directly (in district heating, greenhouses, swimming pools, for medical purposes (spa), in fish farming and in various industrial processes), thus producing savings in the use of conventional energy sources. The total installed capacity of geothermal power plants in the world at the end of 2010 was approximately 10,700 MW [3], while the total installed capacity worldwide at the end of 2009 for direct geothermal utilisation was 50,583 MW [4]. Countries that are increasingly using geothermal energy sources for electricity production or for direct application include the United States, Iceland (where geothermal power accounts for 44% of the total energy consumption), Italy, New Zealand, France, Germany and Hungary [3,4].

In the Republic of Croatia, there is a several-centuries-old tradition of exploiting geothermal energy for medical purposes and for bathing. In addition to the use of geothermal energy in spas, techniques and technologies for obtaining geothermal energy from deep geothermal reservoirs were developed as a result of research into oil and gas resources. With the development of the oil industry in the Republic of Croatia and the comparative testing of certain geothermal wells, a technological basis was created for exploiting geothermal water for recreational–medical purposes, heating, production of fruits and vegetables in greenhouses, and for the subsequent industrial thermal processing of such products (e.g., drying and pasteurisation).

As early as 1998, the Energy Institute, Hrvoje Požar, prepared a Program of Geothermal Energy Usage in the Republic of Croatia [5]. This report showed that in the Republic of Croatia, there are several medium-temperature geothermal sources with a relatively lower temperature of geothermal water in the range of 90–140 °C, including Lunjkovec–Kutnjak (140 °C), Ferdinandovac (125 °C), Babina Greda (125 °C) and Rečica (120 °C), from which it is possible

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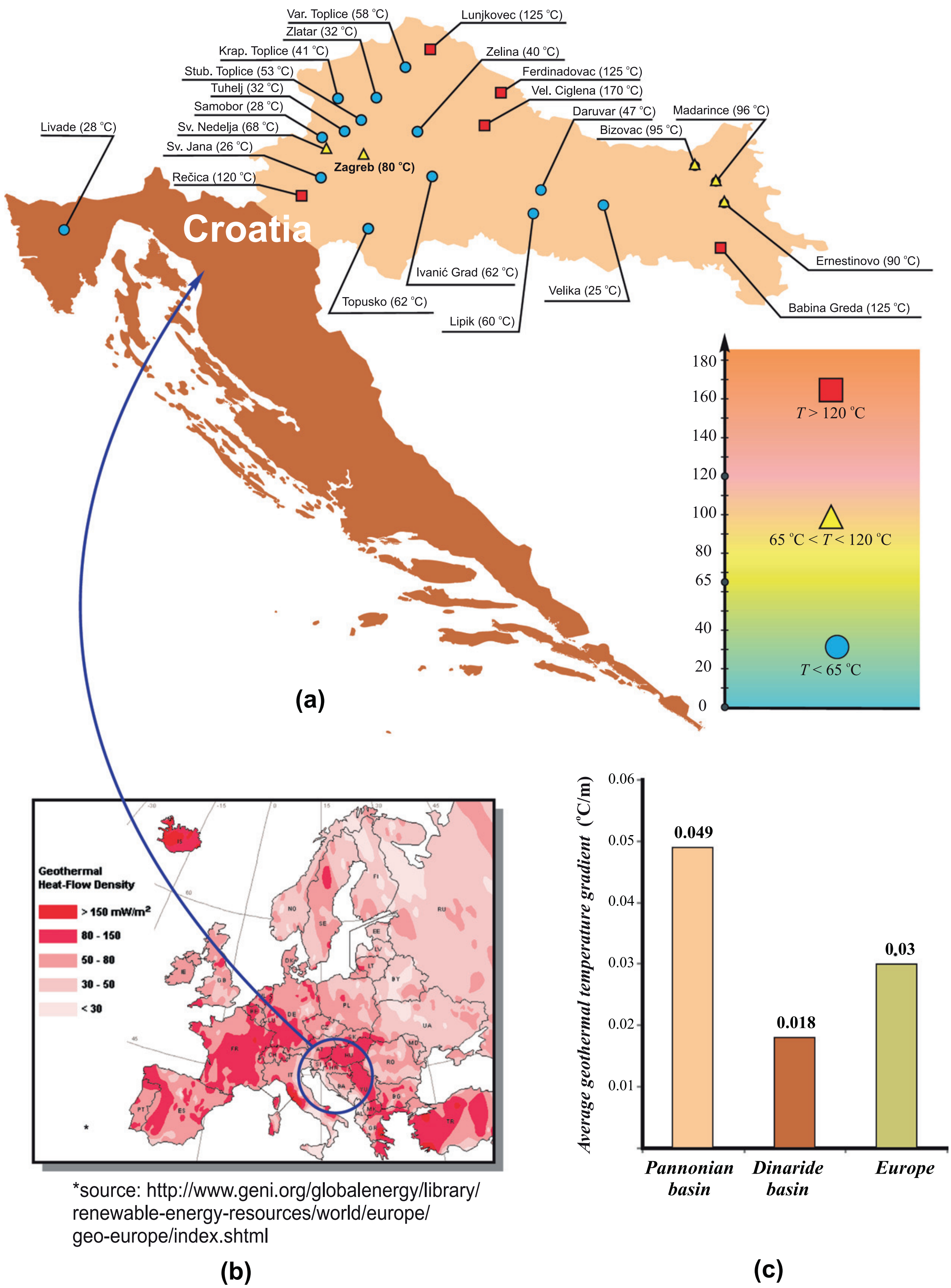


Fig. 1. Geothermal data: (a) geothermal sources in the Republic of Croatia, (b) geothermal heat-flow density in Europe and (c) average geothermal temperature gradient in the Republic of Croatia.

to produce electricity (see Fig. 1a). However, concrete initiatives for the construction of geothermal power plants have only recently been taken.

For the production of electricity from medium-temperature geothermal sources, binary power plants, which use either the ORC or the Kalina cycle, are the most common. In this paper, a comparison between the ORC and the Kalina cycle will be performed on the basis of energy analysis results for the geothermal field at Lunjkovec–Kutnjak (140 °C). The objective of the comparison is to recommend the most suitable binary plant, using either the ORC or the Kalina cycle, for medium-temperature geothermal sources in the Republic of Croatia with relatively lower temperatures of geothermal water.

2. Geothermal potential and the future of geothermal power plants in the Republic of Croatia

As shown in Fig. 1a, there are approximately 28 geothermal fields, out of which 18 are in use. For space heating, a total of 36.7 MW of heating power is installed, with an annual usage of heating energy of 189.6 TJ. For bathing, 77.3 MW of heating power is used, with an annual usage of heating energy of 492.1 TJ. Until now, geothermal energy has not been used for the production of electricity [5].

Two sedimentary basins cover almost the entire territory of the Republic of Croatia: the Pannonian basin and the Dinarides basin, as shown in Fig. 1a and c. Large differences in the geothermal potential of these two basins have been discovered during oil and gas explorations.

In the Dinarides basin, the average geothermal temperature gradient and the heat flux are 0.018 °C/m and 29 mW/m^2, respectively [5], as shown in Fig. 1a and c.

Unlike the Dinarides basin, which has no relevant geothermal potential, in the Pannonian basin, the average geothermal temperature gradient and the heat flux are much greater: 0.049 °C/m and 76 mW/m^2, respectively [5], as shown in Fig. 1a and c. Because the geothermal temperature gradient in the Pannonian basin is considerably greater than the European average value, as shown in Fig. 1c, the discovery of new fields is to be expected in this region.

The geothermal sources in the Republic of Croatia can be divided into three groups: medium-temperature sources with a temperature of 100–200 °C, low-temperature sources with a temperature of 65–100 °C, and geothermal sources with a water temperature below 65 °C (see Fig. 1a) [5].

In the period from 2000 to 2006, the direct consumption of electricity in the Republic of Croatia had an average annual growth rate of 4.1% [6]. Fig. 2 shows the structure of electricity production in the Republic of Croatia in 2006 [6]. Despite the energy efficiency measures and the replacement of electricity used for heating purposes with other forms of energy, particularly natural gas and renewable energy sources, it is estimated that the average annual growth of direct consumption of electricity will exceed 3.7% [6]. Thus, the average consumption per capita in the Republic of Croatia in 2020 will reach today's average electricity consumption in EU 27.

Because of the sustained development of the electricity sector and the aspirations for the use of domestic energy sources for electricity production and to stimulate domestic energy and services, the Republic of Croatia has set a goal that until 2020, the share of electricity generation from large hydro power plants and renewable energy sources in the total electricity consumption will be maintained at the present levels and that in 2020, it will be 35% [6].

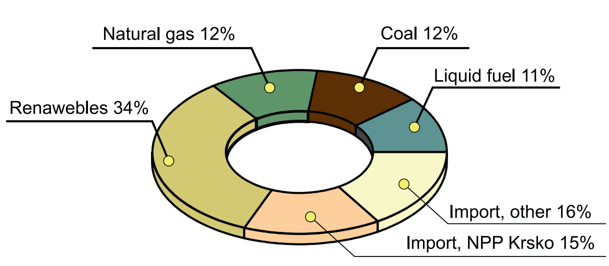


Fig. 2. The structure of electricity production in the Republic of Croatia in 2006 [6].

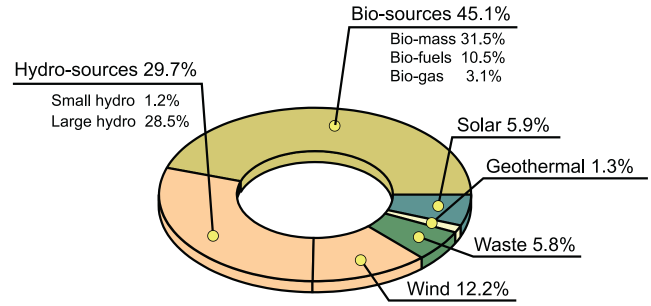


Fig. 3. Projection of the expected structure of electricity production from renewable energy sources in the Republic of Croatia in 2020 [6].

Because the increase in electricity generation from large hydro power plants will be significantly lower than the increase in total electricity consumption, achieving the goal of having 35% of the total production coming from large hydro and renewable energy sources requires an extremely high rate of growth in electricity production from renewable energy sources (e.g., wind, biomass, small hydro, solar power, municipal waste, geothermal) by 2020. Fig. 3 presents the projection of the expected structure of electricity production from renewable energy sources in 2020 [6]. As can be observed, the share of electricity generated by geothermal power plants will be 1.3% [6].

3. Types of geothermal power plants

The production of mechanical power to generate electricity from geothermal energy requires steam to drive steam turbines. Steam from natural sources can be either wet or dry, or it can be obtained by flashing the geothermal water. If no natural sources of steam can be found, steam can be produced artificially in hot, dry rocks (so-called advanced geothermal systems) [1,7]. At lower temperature levels, steam for turbine operation can be produced using the heat from a geothermal fluid (water) to evaporate a fluid with a lower boiling point than water. Such cycles are known as Organic Rankine Cycles (ORCs) because originally, organic substances such as toluene (C_7H_8), pentane (C_5H_{12}), propane (C_3H_8) and other hydrocarbons were used as the working fluids [8]. A more recent cycle in experimental use is the so-called Kalina cycle, which uses a mixture of water and ammonia (NH_3) as the working fluid [8,9].

As can be concluded from the discussion above, geothermal power plants presently in operation can be divided into three basic types: plants with dry steam, flash plants (single and double), and binary plants. The type of plant that is installed depends on the type of source. Fig. 4 shows the ranges of application of various types of geothermal power plants, depending on the unit power and the geothermal fluid temperature [8].

Dry-steam-rich geothermal sources produce dry steam with a minimal amount of water. This type of steam may be used directly in the turbine of the geothermal power plant, where it expands, producing useful mechanical power and driving an electric generator, as shown in Fig. 5. After expansion, the steam condenses in a condenser. A portion of the condensate can be used in the plant cooling towers, while the majority is pumped back into the underground reservoir for replenishment and to maintain the reservoir pressure.

For electricity production from hot-water-rich geothermal reservoirs, single- or double-flash power plants are used. The hot geothermal fluid evaporates in one or two evaporators (at one or two pressure levels, respectively), and the produced steam expands in

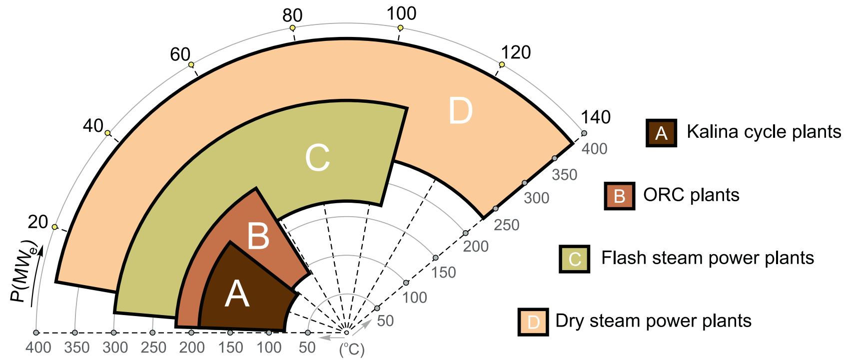


Fig. 4. Application ranges of various types of geothermal power plants [8].

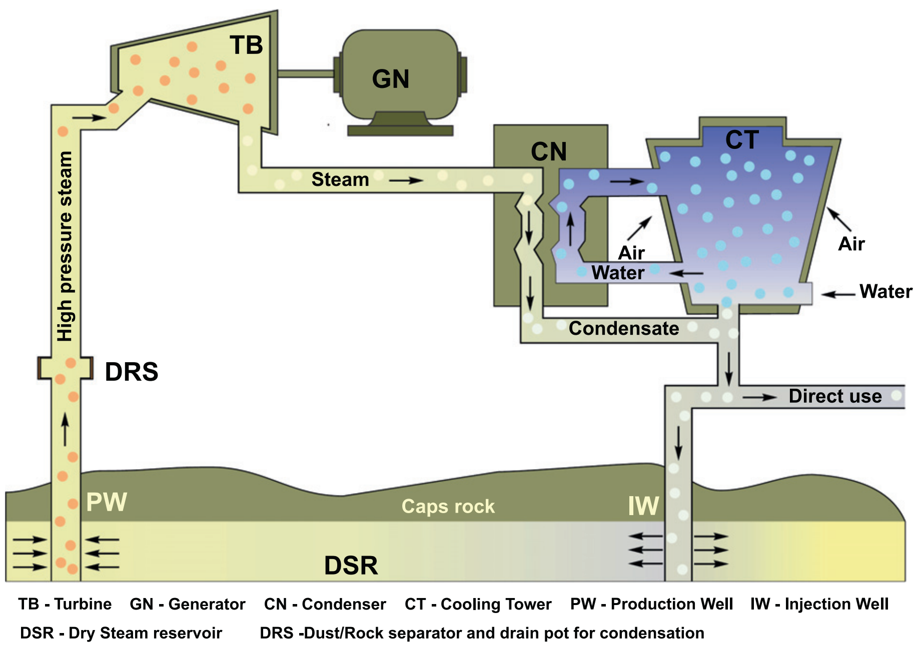


Fig. 5. Geothermal power plant with dry steam.

one or two turbines. Following expansion, the steam condenses, and the condensate is pumped back into the reservoir, as in dry-steam power plants. Fig. 6 shows a double-flash geothermal power plant.

Medium- and low-temperature geothermal reservoirs, with temperatures between 85 and 150 °C, produce fluids that are not hot enough to vaporise. However, these sources can be used for power generation in a binary geothermal plant using an ORC, as shown in Fig. 7. In binary plants, the geothermal fluid passes through a heat exchanger, where its heat is transferred to a secondary fluid with a low boiling point. The secondary fluid evaporates, and the steam expands in the turbine, producing useful mechanical energy to drive an electric generator. After expansion, the steam is fed to the condenser, and the condensate is fed through circulating pumps to return to the heat exchanger. Unlike in geothermal power plants using dry steam and in flash plants, in binary plants the geothermal fluid does not come in contact with the turbine or other elements of the plant apart from the heat exchanger. This relatively new technology has made possible the exploitation of numerous geothermal resources with lower fluid parameters and mass flows by using binary systems of smaller capacity and selecting favourable working fluids. A further advantage of having a large number of small units is that the cascade operating mode facilitates the optimal use of resources according to the current energy demand. Binary plants with the Kalina cycle improve the thermal efficiency of energy conversion because they use a mixture of water and ammonia (NH_3), which changes temperature while evaporating, unlike pure fluids that evaporate at a constant temperature. Therefore, the heat transfer between the geothermal fluid and the working fluid occurs with a smaller temperature difference between the fluids [10,11].

A detailed description of the various types of geothermal power plants is presented in [1,2,7,11].

4. Case study of geothermal power plant Lunjkovec–Kutnjak

The study "Concept and feasibility of the program for economic geothermal energy exploitation at the location Lunjkovec–Kutnjak" [12] presents, for the first time in the Republic of Croatia, a comprehensive program of economic exploitation of geothermal energy on a single site, with a detailed analysis of all relevant factors necessary for its concrete realisation.

The geothermal field at Lunjkovec–Kutnjak is situated in Koprivnica-Križevci County, in the municipalities of Legrad and Mali Bukovec. The geothermal field has a surface of 83 km^2, and

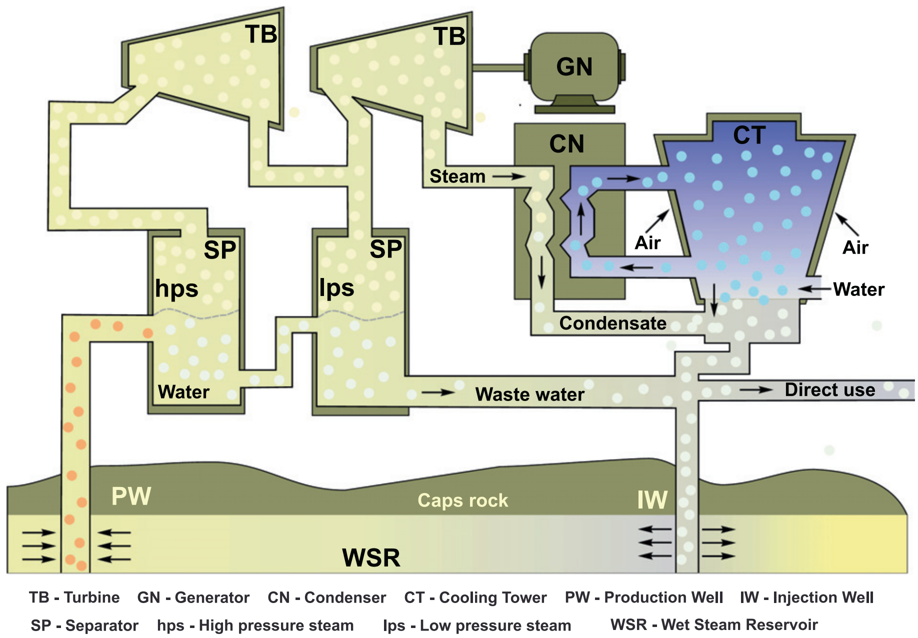


Fig. 6. Double-flash geothermal power plant.

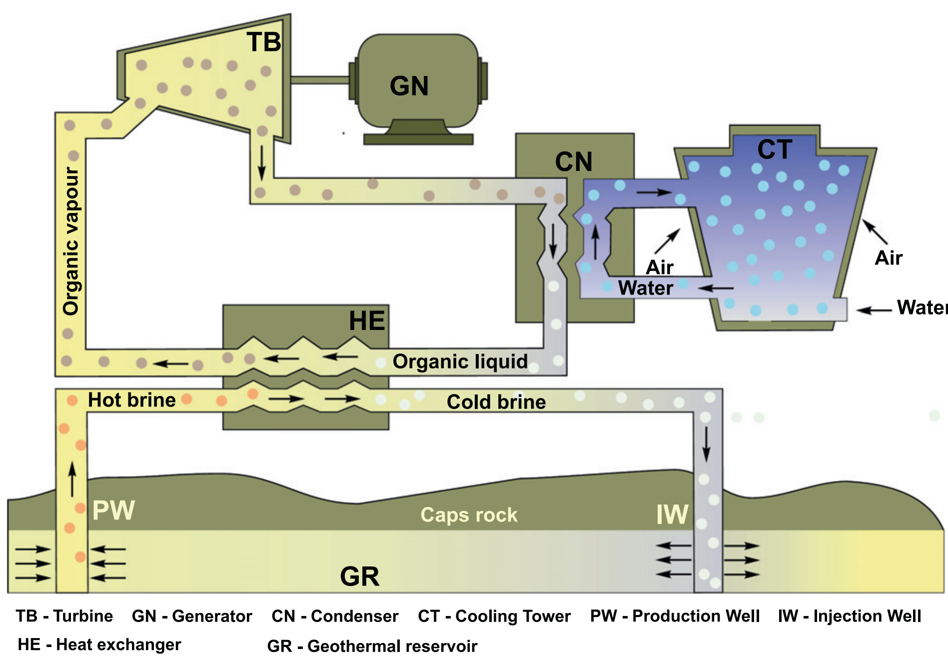


Fig. 7. Geothermal power plant with binary cycle.

the reservoir depth is 2010 m, with an average thickness 117.5 m. The volume of the geothermal fluid is 687,670,000 m^3. According to the categorisation of geothermal resources, the reservoir belongs to the medium-temperature category [12].

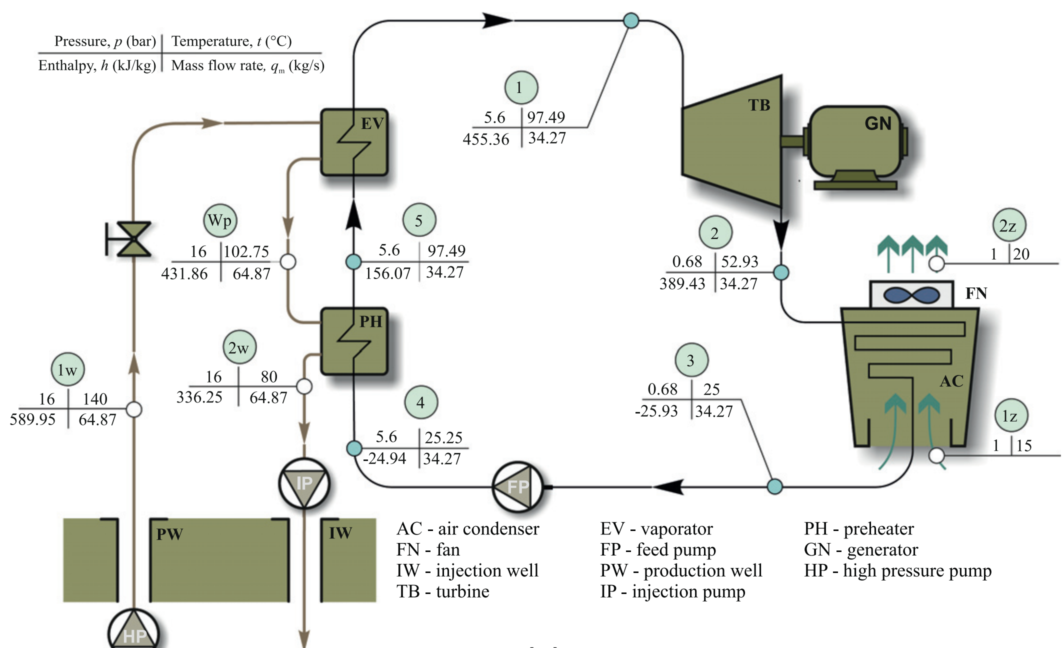
The geothermal reservoir is a closed hydro-geological entity without natural replenishment, so it is expected that during exploitation, the exhausted geothermal fluid will be injected back into the reservoir to ensure the sustainability of the geothermal system. Based on proven features of existing wells drilled by INA (a Croatian oil company), well Kutnjak 1 (Kt-1), with a depth of 2430 m, is defined as the production well, and well Lunjkovec 1 (Lun-1), with a depth of 2201 m, is defined as the injection well [12]. The temperature at the mouth of the production well is 140 °C, the pressure is 6 bar, and the flow is 53 l/s for a natural outflow or 70 l/s with a submerged booster pump. The distance between the injection and the production wells is 4.3 km [12].

According to the study, the majority of heat from the geothermal fluid will be used for electricity production, starting at the highest temperature level of the source (from 140 °C). After use in the power plant, the cooled geothermal fluid will still have a sufficient temperature (80 °C) for use in other processes (direct use): a system of heat distribution to a nearby fruit and vegetable drying plant, a spa (an outdoor swimming pool and a hotel with a pool), greenhouses (flowers and vegetables) and fish farming [12].

In the second phase of the project, the construction of additional wells is envisaged, providing a flow of an additional 300 l/s of geothermal fluid at a temperature of 140 °C to two additional units for electricity production. The additional amount of heat obtained from the new wells will be used to meet the increased demand for thermal energy from all the existing consumers at the location and possibly to supply thermal energy to the city of Koprivnica for district heating [12].

On a geothermal field with maximum fluid temperature of 140 °C, the production of electricity requires the application of a binary power plant [1,2,7,11,13]. Evaporation of the geothermal fluid produces a very small quantity of steam with low parameters that would not allow efficient power generation. Therefore, the proposed technology for electricity production at the site Lunjkovec–Kutnjak is a binary plant using either the ORC or the Kalina cycle. Therefore, these two technologies will be compared using the results of thermodynamic calculations; i.e., an energy analysis based on the First Law efficiency. Thermodynamic calculations are performed on a computer using a model of a binary plant with both the ORC and the Kalina cycle, as presented in [14,15], where the thermodynamic properties of the working fluids are determined by the REFPROP program [16].

For both cycles, an optimisation of the main cycle parameters is performed. For the ORC, the main cycle parameter is the upper cycle pressure, and for the Kalina cycle, it is the concentration of ammonia [15]. The presumed turbine isentropic efficiencies are



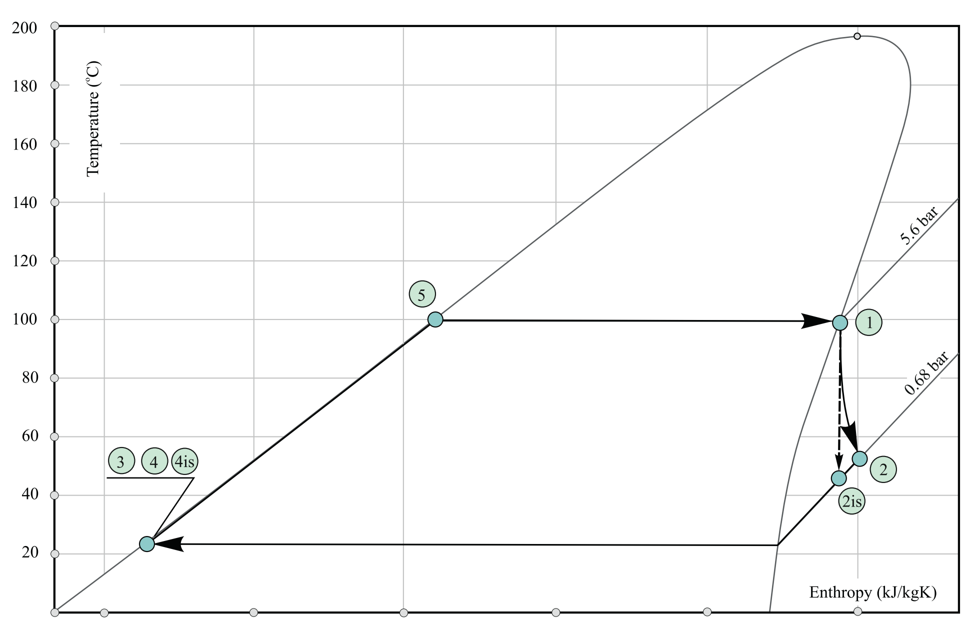


Fig. 8. Thermodynamics of the geothermal power plant at Lunjkovec–Kutnjak with the ORC (working fluid: isopentane): (a) process flow chart and (b) *T–s* diagram [15].

0.85 for the ORC (dry turbine) and 0.80 for the Kalina cycle (wet turbine). In both cases, the presumed efficiencies for the feed pumps are 0.8. Air-cooled condensers are used, whose thermodynamic calculations have been performed assuming an average annual air temperature of 15 °C. Air cooling is the only feasible method at the Lunjkovec–Kutnjak location because the large amount of cooling water needed for a water-cooled condenser is not available. In the thermodynamic calculations, special attention is given to the values of pinch points that are not below 5 °C.

4.1. ORC

A binary power plant with an ORC consists of a preheater, an evaporator, a steam turbine with a generator, a feed pump and an air-cooled condenser with fans; the process flow chart of such a power plant is presented in Fig. 8a [15]. The working fluid parameters (states) at the characteristic points of the cycle, obtained by thermodynamic calculations and presented in Fig. 8a, are for the design operating regime.

Based on the results presented in [17–22], isopentane is recommended as the working fluid in the ORC for the medium-temperature geothermal resources because among all the refrigerants and the hydrocarbons that come into consideration, it shows the best properties: low specific volumes, high efficiency (net power), moderate pressures in the heat exchangers, low cost, low toxicity, low ODP (ozone depletion potential), low GWP (global warming potential) and a low pinch-point temperature.

The geothermal fluid (state 1w, 2w) transfers its heat to the working fluid – isopentane – inside the evaporator and the preheater. In the preheater, the condensed isopentane (state 4) is heated to the boiling point (state 5) and transforms into dry saturated steam (state 1) within the evaporator. Dry saturated steam expands in the turbine (from state 1 to state 2), providing mechanical work to drive the electric generator. After expansion in the steam turbine, the steam is fed to the air-cooled condenser. The condensation heat is transferred to the environment by the forced convection of the air (state 1z, 2z). The condensate (state 3) is brought to the initial pressure (state 4) by the feed pump and returns to the preheater and the evaporator.

Dry fluids such as isopentane are characterised by a positive slope of the saturated vapour curve in the *T–s* diagram (overhanging saturation line), as shown in Fig. 8b [15]. Because of this characteristic, dry fluids do not need to be superheated. The reason is that after expansion, the saturated vapour remains in the superheated region (states 1–2) [23–28]. Additionally, problems related to the flow of wet steam through a turbine are excluded. Thus, preventing problems such as erosion of the turbine blades, droplet separation, condensate draining and similar problems is not necessary, which simplifies the turbine design [28].

On the other hand, because the vapour remains largely superheated after expansion, this has a negative influence on the cycle efficiency; i.e., the superheated vapour first has to be cooled in the condenser. In this manner, the heat content of the superheated vapour is dissipated in the condenser along with the condensation heat itself. Therefore, a regenerator is often used to increase the cycle efficiency [25–28]. The superheated vapour is first cooled closer to the condensation temperature in the regenerator by preheating the liquid fluid exiting the feed pump. A drawback of a regenerator is that geothermal sources cannot be cooled as much as they could be in a cycle without a regenerator [28].

4.2. Optimisation of the ORC

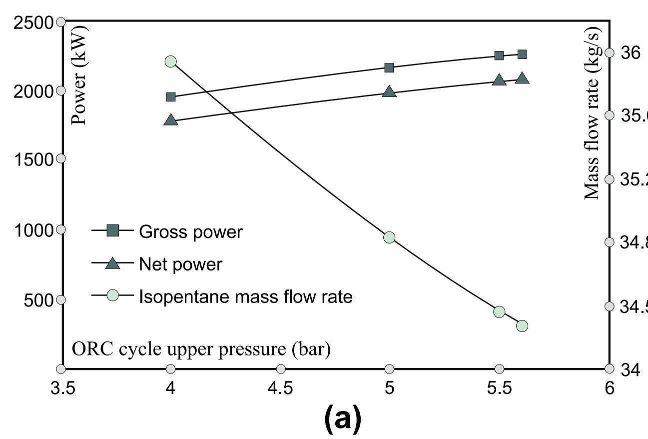
Once set up, the mathematical model of the ORC allows the optimisation of the cycle by changing its main parameter: the upper cycle pressure (pressure of evaporation).

In a model with a fixed output temperature of the geothermal fluid (for secondary consumers), the heat exchanged in the preheater/evaporator is constant. When the upper cycle pressure changes, the evaporation temperature of the isopentane changes, which determines the mass flow of the isopentane that can be evaporated by the exchanged heat (see Fig. 9a) [15]. At lower pressures, the evaporation process starts earlier, evaporating a larger mass of isopentane with the same amount of heat, but the temperature, as well as the pressure, of the steam obtained is lower.

From the comparison shown in Fig. 9a, it can be observed that more power is generated by steam with a higher pressure, regardless the corresponding lower mass flow. A pressure increase thus leads to an increase in output power. The limit to the pressure increase is represented by the minimal temperature difference between the geothermal fluid and the isopentane at the heat exchanger's pinch point. The optimum pressure is considered to be the maximum pressure at which the pinch-point difference reaches an agreed minimum of 5 °C. Cycles with an upper pressure above 5.6 bar are therefore not feasible, based on the aforementioned assumption.

The power required for feed pumps increases with the increase in the cycle upper pressure, while the required cooling fan power decreases. However, their mutual effect on the net output power of the plant is approximately constant (as can be observed from the parallel lines of turbine gross power and net output power in Fig. 9a).

In cases where there are no secondary heat consumers at a certain location, and the aim would be to produce the maximum



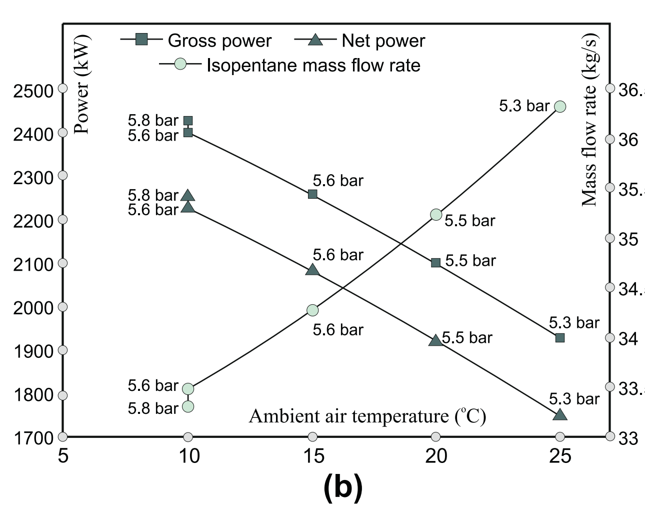


Fig. 9. Comparison of ORCs: (a) with upper cycle pressures of 4.5, 5.5 and 5.6 bar (optimum), and (b) for ambient air temperatures of 10, 15, 20 and 25 °C [15].

amount of electricity from the geothermal fluid, a small adaptation of the mathematical model would be necessary. The output temperature of the geothermal fluid would be taken as a variable, and the order of the equations would be modified. Furthermore, the optimal upper cycle pressure would not necessarily be the maximum possible pressure.

The mathematical model of a cycle with a fixed output temperature of the geothermal fluid additionally allows an analysis of plant operations that depend on a variable temperature of the ambient air. The plant is optimised to operate at an average annual air temperature of 15 °C, but operation of the plant at temperatures

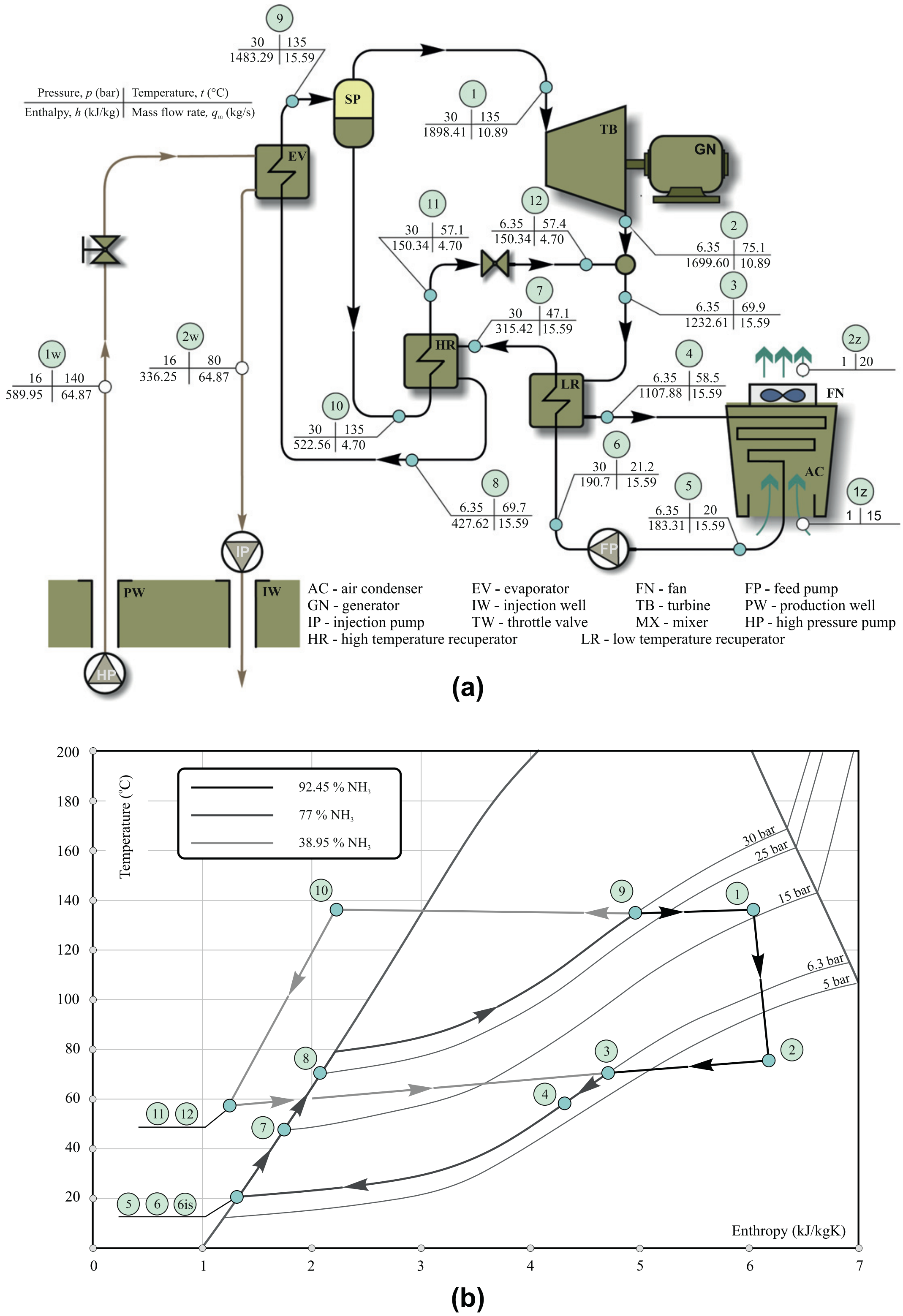


Fig. 10. Geothermal power plant at Lunjkovec–Kutnjak with the Kalina cycle: (a) process flow chart and (b) *T*–*s* diagram (saturation lines and constant pressure lines are for the basic mixture of 77% ammonia) [15].

of 10, 20 and 25 °C was additionally considered, along with the possible control of the cycle parameters [15].

The ambient air temperature determines the condensation pressure of the isopentane, where a lower temperature is more favourable to larger power outputs. For example, an increase in the power output of the plant from the design level of 2260–2400 kW occurs with a decrease of the ambient air temperature to 10 °C, without any control of the cycle. In unfavourable cases, when the air temperature is above the average, a significant decrease in the power output occurs. The process may then be controlled by reducing the upper pressure; i.e., the process is optimised to the new air temperature, as shown in Fig. 9b [15]. In addition, it is possible to increase the upper cycle pressure at an ambient temperature below the average, thus obtaining additional power. In Fig. 9b, optimised ORCs are shown for various ambient air temperatures. For an ambient air temperature of 10 °C, the case without pressure control is additionally presented (i.e., a pressure of 5.6 bar, the same as for the temperature of air at 15 °C).

Control of the upper cycle pressure reduces the power plant's dependence on ambient conditions.

4.3. Kalina cycle

A binary plant using the Kalina cycle consists of an evaporator, a vapour/liquid separator, a turbine with a generator, a throttle valve, a mixer, an air-cooled condenser, low- and high-temperature recuperators and a feed pump, as shown in the process flow chart in Fig. 10a [15]. The working fluid is a variable-concentration mixture of ammonia and water. The fluid parameters (states) at the characteristic points of the cycle that were obtained from thermodynamic calculations for the design operating regime are presented in Fig. 10a. Fig. 10b presents the *T–s* diagram of the Kalina cycle with saturation lines and constant-pressure lines for the basic mixture of 77% ammonia [15].

The geothermal fluid (state 1w, 2w) transfers heat in the evaporator for evaporation of the basic water–ammonia mixture (primary concentration, state 8) to the state of wet steam (state 9). Because of the different evaporation temperatures of ammonia and water, wet steam consists of a steam portion with an increased ammonia concentration and a liquid portion with a reduced ammonia concentration. In the separator, the steam is extracted, and the generated dry saturated steam with the increased ammonia concentration (state 1) is delivered to the turbine. In the turbine, the steam expands (from state 1 to state 2), performing mechanical work that is used to drive the electric generator. The boiling liquid with the reduced ammonia concentration (state 10) is separated in the separator and flows through the high-temperature recuperator, where part of its heat is used to preheat the condensate of the basic water–ammonia mixture. After passing through the high-temperature recuperator, the liquid (state 11) passes through the throttle valve, where its pressure is reduced to the pressure of the turbine exhaust (state 12). The liquid is then introduced to the mixer, along with wet steam from the turbine exhaust, forming wet steam of the basic ammonia concentration (state 3). Before entering the air-cooled condenser, the wet steam passes through the low-temperature recuperator, where a part of its heat is transferred to the condensate returning from the condensers. At the condenser entrance (state 4), the wet steam is therefore carrying less heat, so the heat that must be rejected by the air stream (state 1z, 2z) during condensation is reduced. The condensate (state 5) passes through the feed pumps, where its pressure rises to the initial value (state 6) and then enters the low-temperature recuperator, where it receives heat from the flow coming from the mixer. The condensate then passes through the high-temperature recuperator (state 7 to state 8), receiving heat from the liquid coming from the separator. The condensate is finally introduced to the evaporator (state 8).

The dry-saturated, ammonia-rich steam entering the turbine expands completely in the region of wet steam, so phenomena related to wet steam such as blade erosion, the need for separation and drainage of the condensate and a reduction in turbine efficiency occur in the turbine.

The influences of the geothermal fluid temperature and the ambient temperature on the upper and the lower pressures and on the concentration of ammonia in the mixture in the Kalina cycle can best be observed from the phase diagram in Fig. 11 [15]. According to the recommendation from [29] for the given temperature of the geothermal fluid (140 °C), the upper pressure was chosen to be 30 bar, and the concentration of the base mixture was chosen to be 77% NH_3. The range of possible values is between 75% and 90%, so that the temperature difference at the pinch point in the evaporator is at least 5 °C. The average temperature of the cooling air is 15 °C, and with an increase of 5 °C in the cooling air temperature, the air temperature at the outlet of the air condenser is 20 °C. A relatively high condensing pressure of 6.2 bar corresponds to this temperature and to the selected concentration of NH_3 in the mixture, which has an adverse impact on the cycle work.

4.4. Optimisation of Kalina cycle

Comparing the results of the Kalina cycle obtained for different concentrations of ammonia in the basic mixture (see Fig. 12 [15]), the optimum concentration of ammonia in the primary mixture is 77%, which is the lowest feasible concentration for the chosen pressure of 30 bar.

Fig. 12a clarifies this, simultaneously showing that, with respect to the given model assumptions (i.e., the steam parameters at the turbine entrance are equal for all cases), the mass flow of the steam slowly decreases when the concentration of ammonia is lower. In addition, the concentration decrease has a significant influence on the condensation pressure and thus on steam expansion in the turbine and the power, as can be observed in Fig. 12b.

The water serves primarily as a "moderator" for the evaporation and the condensation of the ammonia, modifying the vaporisation line of the mixture and bringing it closer to the cooling line of the geothermal fluid.

A lower ammonia concentration in the mixture is achieved with higher quantities of water, so the total mass flow in the cycle increases, as can be observed in Fig. 12a. Regardless of the larger amounts of water heated in the evaporator, roughly the same amount of ammonia is evaporated. Most of the quantity of water stays liquid, and it is removed in the separator, bypassing the

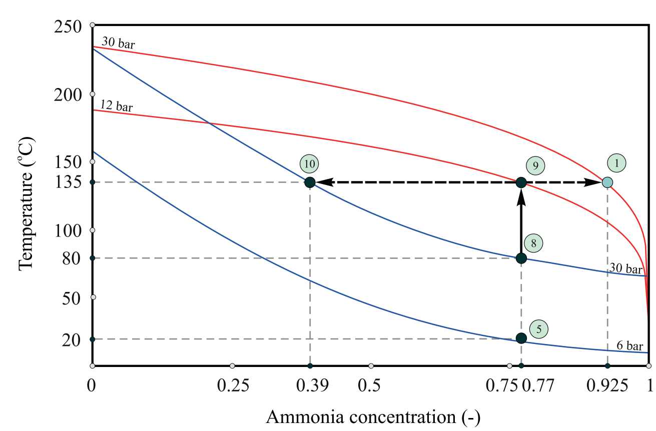
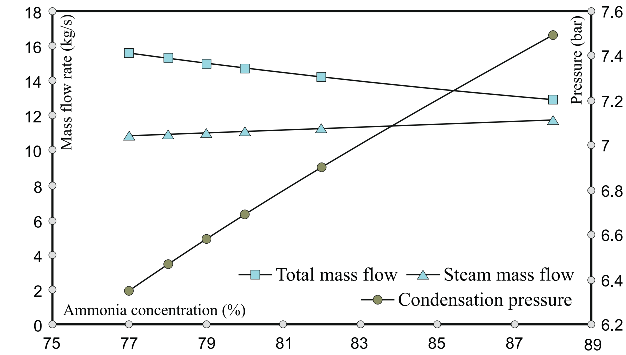


Fig. 11. Phase diagram of ammonia–water mixture [15].



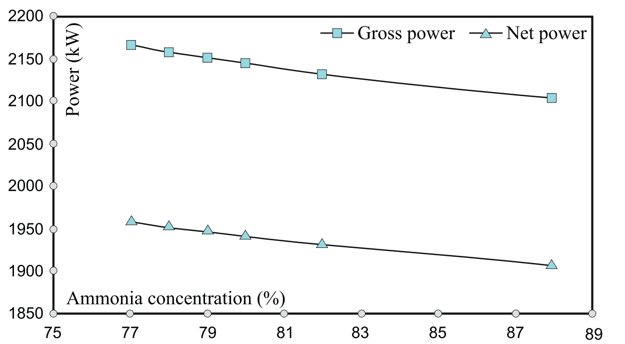


Fig. 12. Dependence of the Kalina cycle on NH_3 concentration: (a) mass flow and condensation pressure, and (b) power [15].

turbine. Additionally, most of the energy used to heat the water is regenerated, as it remains in the cycle because of the two recuperators. Therefore, increasing the water mass flow produces only limited negative effects. On the other hand, increasing the water mass flow changes the mixture concentration, lowering its condensation pressure and thus enabling the approximately constant flow of ammonia to produce more power in the turbine.

5. Discussion and conclusions

Thermodynamic calculations predict a gross power of 2259.4 kW with a mass flow rate of 34.27 kg/s for the ORC and a gross power of 2165.5 kW with a mass flow rate of 15.59 kg/s for the Kalina cycle. If the related power for the operation of the feed pumps, which is 33.9 kW in the case of the ORC and 64 kW in the case of the Kalina cycle, is subtracted from the gross power, the net power is obtained. The net power is 2225.5 kW for the ORC and 2101.4 kW for the Kalina cycle. The thermal efficiency (the First Law efficiency), calculated based on the net power obtained and the heat transferred from the geothermal fluid, is 13.5% for the ORC and 12.8% for the Kalina cycle.

In this case, where medium-temperature sources with a relatively lower temperature of geothermal water are used, the Kalina cycle is not thermodynamically better than the ORC. However, it is necessary to note that the difference in the thermal efficiencies of the ORC and the Kalina cycle is less than in the case of a medium-temperature source with high-temperature geothermal water (175 °C), as calculations in [14] show (14.1% vs. 10.6%). Again, relatively high-temperature cooling air in the condenser (15 °C) has a more unfavourable influence on the Kalina cycle than on the ORC, so the ORC is thermodynamically better than the Kalina cycle. In such conditions, the condensation pressure in the Kalina cycle is considerably higher than in the ORC (6.35 bar vs. 0.68 bar). It should be taken into account that, at the cited locations of geothermal sources in the Republic of Croatia, air cooling is the only feasible method of cooling.

However, it is necessary to additionally take into consideration that, at present, there is just one geothermal Kalina cycle power plant in operation (in Husavik, Iceland), although several more are under construction [30]. While there are reports [30] of problems during the start-up and the commissioning of the only plant in the world using the Kalina cycle, the ORC has a series of advantages [31]. Currently, the ORC is a mature technology with hundreds of megawatts of various types of plants installed throughout the world [32].

Because the ORC is thermodynamically better than the Kalina cycle for the given temperatures of the geothermal water and the cooling air, and given the problems that all new technologies encounter in their early phase of application (in this case, primarily due to the poor properties of the working fluid, ammonia, in the Kalina cycle such as toxicity, corrosion and erosion of turbine blades), the application of binary plants using the ORC cycle is proposed for all medium-temperature geothermal sources in the Republic of Croatia.

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