Sustainable Utilization of Low Enthalpy Geothermal Resources to Electricity Generation through a Cascade System

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Abstract: The article presents an assessment of the potential for using low temperature geothermal water from the C-PIG-1 well (Małopolskie Voivodship, southern Poland) for electricity generation, as the first stage in a geothermal cascade system. The C-PIG-1 well is characterised by a temperature of geothermal water of 82 °C and a maximum flow rate of 51.22 kg/s. Geothermal water is currently only utilised for recreation purposes in swimming pools. In such locations, with the potential to use renewable energy for energetic purposes, the possibility of comprehensive management of the geothermal waters extracted should be considered both in the first stage of the cascade and after recreational use. Thermodynamic calculations were conducted assuming the use of the Organic Rankine Cycle (ORC) or Kalina Cycle. Two variants were analysed—the use of the maximum flow rate of geothermal waters and partial use with an assumption of a priority for recreational/heating purposes. The analysis and calculations indicate that the gross capacity in the most optimistic variant will not exceed 250 kW for the ORC and 440 kW for the Kalina Cycle. As far as the gross electricity generation is concerned, for ORC this will not exceed 1.9 GWh/year and for the Kalina Cycle it will not exceed 3.5 GWh/year.

Keywords: geothermal resources; sustainable utilisation of water; geological conditions; electricity generation; cascade systems

1. Introduction

The use of renewable and ecological energy sources, including geothermal energy, forms the basis for the development of modern energy systems right across the world. Since other renewable sources can give an unstable energy production during the day or through the seasons, geothermal energy can guarantee its continuous use, regardless of changing weather conditions. Geothermal energy is in line with the idea of sustainable development and respect for the natural environment, so that can be a reasonable use of geothermal waters [1]. The variety of possible applications, together with the corresponding temperature demand, is illustrated by the Lindal diagram shown in Figure 1. By cascading exploitation of the heat accumulated in utilising geothermal water we mean a multi-variant and comprehensive use of resources.

Depending on specific geological, hydrogeological, and thermo-physical conditions such as temperature, flow rate, and geothermal waters mineralisation, prevailing in an area to be analysed, there are a number of possibilities for the industrial and economic utilisation of the heat energy accumulated in geothermal waters. They range from electricity generation, through its use in industrial
processes, use for heating purposes, agricultural and recreational use, to the use of so-called low temperature geothermal energy by heat pumps. In the case analysed, the outflow temperature of geothermal water at the well-head is 82 °C, which allows it to be used cautiously to generate electricity using the Organic Rankine Cycle (ORC) or Kalina Cycle. In view of the need to seek ecological solutions that fit into the idea of sustainable economic growth, this is a natural policy direction, especially in a situation where the geothermal well has been drilled and is in operation.

![Modified Lindal diagram](image)

**Figure 1.** Modified Lindal diagram (based on [1,2]).

It should be emphasised that the temperature of the geothermal water is not the only parameter determining the possibility of using ORC or the Kalina Cycle, although a key one. The temperature of the geothermal water supplying the geothermal power plant is of key importance for its power and efficiency. Both parameters are growing up with the increase of geothermal water temperature. Apart from the outflow geothermal water temperature, this is the second key parameter affecting the power of the geothermal power plant. As the value of the geothermal water stream directed to the geothermal power plant increases, the amount of heat supplied grows, directly causing the volume of the working medium stream circulating in the closed power plant system, and thus the amount of energy that is accumulated in the steam that makes the turbine blades move.

As with geothermal heating plants, the lowest possible mineralisation of geothermal waters is desirable for a power plant. In the technological context, an important role is also played by the water reaction and direct relations between the components present in it. They may play a role in the occurrence of corrosion processes. Mineralisation of water has an additional impact on two basic parameters: Specific heat and geothermal water density, taken into account in thermodynamic
calculations that allow estimating the efficiency and power of a geothermal power plant based on ORC technology and the Kalina Cycle.

Electricity generation using geothermal energy undoubtedly fits into the strategy of creating a low emission energy market structure that is to become the basis of a modern economy [3,4]. Therefore, the method of geothermal water management should be optimised and rationalised. It is especially important in cases where they have the potential to be used for energy sector purposes. Unfortunately, in some cases geothermal waters are only used for recreational purposes. Such an example is provided by the waters captured by the C-PIG-1 geothermal well, which was selected for the analysis of the use of the ORC and Kalina Cycle technology as the first stage of a cascade. In this particular case, the method of using geothermal waters results in the lack of a district heating network infrastructure and the difficulties in its implementation determined by technical and economic factors. In such locations, the possibility of comprehensive management of the geothermal waters extracted should be considered both in the first stage of the cascade and after recreational use.

Global experience resulting from the work of geothermal power plants based on the ORC and Kalina Cycle technology [5,6] indicates that the generation of electricity always takes place in combination with the production of thermal energy. The only exception is one installation in Chena Hot Springs (USA), due to the low temperature of the geothermal source.

Of the two technologies proposed for analysis, the Organic Rankine Cycle is more popular [5,6]. This does not mean, however, that no research has been done or is not being conducted in the context of using the Kalina Cycle to generate electricity from low enthalpy geothermal resources. They indicate that this technology may be more effective than ORC not only when using conventional geothermal water resources [7,8] but also enhanced geothermal systems [9,10]. In addition, attention should be paid to research aimed at optimising the Kalina Cycle in order to increase its efficiency [11–13], and also that in the case of installations with a low installed capacity, the investment and operational costs point out to the Kalina Cycle [14].

Considering both technologies in terms of ease of implementation and experience resulting from previously implemented projects, ORC may have an advantage over the Kalina Cycle. This technology is still being developed and optimised both in terms of a system configuration and optimisation [15–17], as well as the operating working fluids used [18,19]. It is important that the selection of the right working fluid plays a key role in the efficiency of electricity generation [20]. It should be added that large possibilities of ORC application result from the relatively simple system configuration, its reliability, and flexibility [21]. Taking into account the conditions related to the use of geothermal waters for recreational purposes in the locations considered, the calculations presented in this paper were provided for the generation and management of both electricity and heat.

When analysing the priorities for the use of the thermal water after the electricity generation stage and after its use for recreational purposes, balneotherapeutic goals and broadly understood cosmetology should be considered. In this context, further detailed consideration can be made based on the results of the performance, temperature, mineralisation, and prognosis of the physical and chemical properties of the water [22–24]. In this context, it should be noted, however, that the factors determining the use of the water are mainly the total content of the dissolved mineral components indicated, but also the type of dominant components and their biochemical properties (Cl\(^-\), Na\(^+\), Ca\(^{2+}\), Mg\(^{2+}\), SO\(_4^{2-}\), HCO\(_3^-\)) also in addition, in a balneotherapeutic context, the content of specific medicinal components (J\(^-\), F\(^-\), H\(_2\)SiO\(_3\), S\(^2-\), Rn, Fe\(^{2+}\)). According to the general indications for medicinal purposes, the limit mineralisation of water is assumed to be 50 g/dm\(^3\) and the temperature 28–42 °C [25]. The acceptance of higher temperatures and mineralisation of water in balneotherapeutic and therapeutic procedures results from health and organisational issues, as the treatments should take place under medical supervision. Sodium chloride waters will be most useful for balneotherapy purposes, because the basic action of these ions determines the beneficial processes in the surface layers of the skin, resulting in reduced pain. The idea of managing the geothermal resources described above is schematically presented in Figure 2.
2. Characteristic of the Studied Area

The C-PIG-1 well was drilled in 1989–1990 [26] and is located in Witów (Małopolskie Voivodeship), in the western part of the Podhale Basin (Figure 3). It is one of the most promising structures in southern Poland from the point of view of electricity generation. This area (a dozen kilometres wide), is a vast asymmetric depression at the foot of the Tatra Mountains, being part of the Central Carpathian Paleogen Basin. This basin is composed of the Reglowa and Wierchowa nappes and a crystalline massif of the Tatra Mountains with sediment cover [27–30]. The Tatra Mountains have the functions of a supply area and of a barrier to the South, while an impermeable northern boundary of the basin is the Pieniny Klippen Belt. The insulating cover is the Podhale Flysch. The eastern border of the Podhale basin is the Ružbachów fault and the western fault of Krowiarki [29,31].
The Podhale Basin paleogene floor consists of the bands of nummulite Eocene formations with a thickness from a few to several tens of metres up to 300–320 m [32], represented by conglomerates of land origin (mainly formed from carbonate pebbles). Above, there are dolomite sandstones and higher nummulite limestones with a thickness up to 30 m [30]. The insulating layer is composed of Podhale Flysch with a thickness of 2500–3000 m, which was divided into oligocene Szaflary layers, Zakopane layers, Chocholów layers, and the youngest late oligocene-early miocene Ostyrskie layers [33–37]. In the area considered, the Chocholów, Zakopane, and Szaflary layers are characteristic of the abovementioned. In the C-PIG-1 borehole the thickness of the Chocholów layers is 466 m (at a depth of 9–475 m). The Zakopane layers have a thickness of 1553 m (at a depth of 475–2028 m) and the Szaflary layers of 968 m (at a depth of 2028–2996 m) [38,39].

The thermal flow in the area of the Podhale Geothermal System ranges from 55 to 60 mW/m² and the geothermal gradient ranges from 1.9 to 2.3 °C/100 m. Geothermal waters at a depth of 2–3.2 km are characterised by a temperature of about 80–95 °C (geothermal water temperature rises with increasing depth northward from the supply zone, which is the Tatra Mountains), with a flow rate of 50–550 m³/h. The reservoir has an artesian character; the maximum static head pressure is up to 29 bar. The mineralisation of geothermal waters in the study area is approx. 3 g/dm³ [29].

The C-PIG-1 borehole, with a total depth of 3572 m, provides geothermal waters associated with carbonate deposits of the Middle Triassic (depth 3218–3572 m) with an approved maximum capacity of 51.22 kg/s at a maximum temperature of 82 °C. The thermal and lithostratigraphic profile of the borehole is presented in Figure 4. The geothermal water extracted by the C-PIG-1 is sulphate-calcium-sodium-magnesium, silicic compounds, sulphide (fluoride) water, and its mineralisation is 1.24 g/dm³ [28]. Due to its mineralisation, the temperature, metasilicic acid content (77.4–78.12 mg/dm³), and hydrogen sulphide (7.6 mg/dm³), it can be classified as potentially therapeutic water. Some analyses have also shown that the content of fluorides is sufficient to allow them to be considered as a specific component (2.2 mg/dm³) [40].
Geothermal waters produced by the C-PIG-1 borehole are currently used for recreational purposes in Chochołowskie Termy, which is one of the largest thermal complexes in Podhale. The facility is managed by the Chochołowskie Termy Sp. z o.o. company, established in 2006. The opening of the facility took place on 1 June, 2016. The total surface of the water table is almost 3000 m². The depth of the thermal pools is in the range of 1–1.2 m. The thermal complex consists of eight pools with thermal water at 36 °C, one whirlpool with brine water at 36 °C, an outdoor pool with water at 36 °C, a lower outdoor pool with water at 36 °C, a salt cave, a textile dry sauna, a 16 × 8 m internal sports swimming pool with 30 °C water, and a 25 × 10 m outdoor swimming pool with 30 °C water. In addition, geothermal water is used in the so-called thermal barrels—bath tubs with raw, sulphuric thermal water at a temperature of 36 °C and in a thermal pool with iodised brine water at 32 °C.

Under operating conditions in accordance with the approved performance, the physico-chemical parameters have a relatively stable character. An analysis of the results of tests performed on the water, as well as of land development and the state of the environment in the vicinity of the C-PIG-1 intake, indicated that it should be expected that the water collected will have a stable chemical composition and good bacteriological status [26].
3. Materials and Methods

Two alternative cases were considered when analyzing the potential for using the ORC and the Kalina Cycle. The criterion was the geothermal water temperature leaving the evaporator (after the first stage of the cascade, which is the geothermal power plant). In variant A, it was assumed to be 60 °C (Δt = 22 °C) and in variant B 70 °C (Δt = 12 °C). The adoption of two different temperatures of geothermal water leaving the power plant results from the need to adapt this system to the currently functioning recreational facility and its energy demand.

In addition, in each of the cases considered, two variants of the system operation were assumed: I—using the maximum flow rate of geothermal water it is possible to obtain, II—partial use of the flow rate, assuming the possibility of the developing part for the generation of thermal energy and recreation. In total, four additional cases were analysed for variants A and B, for a mass flow of geothermal water of 20, 30, 40, and 51.22 kg/s. Similar to the criterion for the temperature of geothermal water leaving a power plant, the change in the stream of geothermal water used for electricity generation results from the need to take into account the energy needs of existing infrastructure in Chochołowskie Termy.

On this basis, the mass flow of the working fluid circulating in the power plant and the mass flow of the cooling water directed to the condenser were calculated. The condensation temperature of the working fluid was assumed to be a constant value of 30 °C, as well as the superheating temperature of the working fluid in the ORC system was 3 °C [41]. The amount of gross electricity was calculated from the gross power and an operational time of 4000 h per annum [42].

In the calculation regarding ORC technology, six operational fluids were analysed: R227ea, R600a, R236fa, R245fa, R1234yf, and R134a. In the case of the Kalina Cycle, the calculations were conducted for mixtures with an ammonia content of 82% to 92% in relation to water [41]. At the research stage, it was found that for the temperature range of the geothermal water analysed the optimal range of the percentage share of ammonia in the mixture is from 85% to 89%. To determine this range, a thermodynamic analysis was carried out by trial and error using the NIST REFPROP software (Version 9.1, National Institute of Standards and Technology, Gaithersburg, Washington, USA) for an ammonia content of the mixture from 75% to 90%. Optimum results have been obtained for mixtures with an ammonia content in the range of 85%–89%, hence the results obtained for three types of mixture with an ammonia content of 85%, 87%, and 89%. Each time the pressure on the turbine was selected from the range of 1500–3000 kPa, in order to obtain optimal results [41]. Specific enthalpy, entropy, pressure, and temperature values at the individual stages of the ORC and Kalina Cycle technologies were also determined using the NIST REFPROP 9.1 software.

The methodology of calculation was adopted from [43–45]. The gross power for the ORC was calculated based on Equation (1) and the efficiency of the geothermal power plant was calculated based on Equation (2):

$$ W_{gross\ ORC} = Q_d \times \eta_{ORC} = m_{wf} \times (h_{wf1} - h_{wf4}) \times \eta_{ORC} $$

(1)

$$ \eta_{ORC} = 1 - \frac{h_{wf2} - h_{wf3}}{h_{wf1} - h_{wf4}} $$

(2)

where:

- $W_{gross\ ORC}$ — gross power of the ORC [W];
- $Q_d$ — heat flux supplied to the superheater, evaporator, and preheater [W];
- $\eta_{ORC}$ — thermal efficiency of the ORC [-];
- $m_{wf}$ — mass flow of the working fluid [kg/s];
- $h_{wf1} - h_{wf4}$ — difference between specific enthalpy of the evaporation process [kJ/kg];
- $h_{wf2} - h_{wf3}$ — difference between specific enthalpy of the condensing process [kJ/kg].
Based on the same assumptions, the gross power (Equation (3)) and efficiency (Equation (4)) were calculated for the Kalina Cycle [26,31]:

$$W_{\text{gross Kalina}} = Q_d \times \eta_{\text{Kalina}} = m_{wf1} \times (h_{wf1} - h_{wf8}) \times \eta_{\text{Kalina}}$$  (3)

$$\eta_{\text{Kalina}} = 1 - \frac{h_{wf4} - h_{wf5}}{h_{wf9} - h_{wf8}}$$  (4)

where:

- $W_{\text{gross Kalina}}$ gross power of the Kalina Cycle [W];
- $Q_d$—heat flux supplied to the evaporator [W];
- $\eta_{\text{Kalina}}$—thermal efficiency of the Kalina Cycle [-];
- $m_{wf1}$—mass flow of the working fluid [kg/s];
- $h_{wf1}$—$h_{wf8}$—difference between the specific enthalpy of evaporation and separation process [kJ/kg];
- $h_{wf4}$—$h_{wf5}$—difference between the specific enthalpy of condensing process [kJ/kg];
- $h_{wf9}$—$h_{wf8}$—difference between the specific enthalpy of evaporation process [kJ/kg].

As mentioned above, the C-PIG-1 geothermal well is characterised by a maximum temperature of the geothermal water of 82 °C and maximum flow rate of 51.22 kg/s, the remaining key parameters of geothermal water are shown in Table 1.

Table 1. List of parameters of the C-PIG-1 geothermal well included in the calculations.

| Geothermal Water Parameter                  | Unit | Value       | Variant AI, AII | Variant BI, BII |
|--------------------------------------------|------|-------------|-----------------|-----------------|
| Temperature of geothermal water before power plant | °C   | 82          | 82              |
| Temperature of geothermal water after power plant | °C   | 60          | 70              |
| Mineralisation                             | g/dm³| 1.2440      | 1.2440          |
| Density                                    | kg/m³| 970.5046    | 970.5046        |
| Specific heat                              | kJ/kg K | 4.1895    | 4.1895          |
| Flow rate of geothermal water              | kg/s | 20–51.22    | 20–51.22        |

4. Results

The results obtained during the calculations for the Organic Rankine Cycle indicate, in the case of gross power, the achievable range from 190 to 234 kW in the AI variant and from 101 to 125 kW in the BI variant (Table 2). The difference in the obtained values is the effect of reducing the temperature difference of the geothermal water supplying and leaving the geothermal power plant from 22 to 12 °C. It affects directly into the amount of thermal energy that can be received from geothermal water in the evaporator, and thus into less power that can be installed. In the case of efficiency, the effect of changing the temperature parameters of the geothermal water leaving the power plant is not visible, in both variants it ranges from 5.8% to 7.5% (Figure 5). Although for wet working fluids, efficiency is almost 2% higher than for dry working fluids, this does not have a major impact on the amount of gross energy available to generate—these values range from 761 to 936 MWh in the AI variant and from 404 to 500 MWh in the BI variant (Figure 6).

In the case of ORC technology, the analysis of organic working fluids showed that the highest gross power of the plant can be obtained in variant AI for dry working fluid R245fa—226 kW, with an efficiency of 5.9% and for wet working fluid R134a—234 kW, with an efficiency of 7.5%. The lowest power values in variant AI were obtained for dry working fluid R227ea—190 kW, with an efficiency of 5.8% and for wet working fluid R1234yf—193 kW, with an efficiency of 7.5%. In variant BI the same working fluids are
characterised by the highest and lowest values. The highest value of the gross power was calculated for R245fa—121 kW and R134a—125 kW, the lowest for R227ea—101 kW and R1234yf—103 kW.

The highest gross electricity production that it is possible to obtain was calculated in variant AI for the working fluid R134a and totalled 936 MWh. Comparable results for both gross power and electricity generation showed that the dry working fluid R245fa produced an estimated electricity generation of 906 MWh. The decrease in the amount of electricity generated in variant BI compared to variant AI is for individual working fluids: R227ea—46.91%, R600a—46.85%, R236fa—46.55%, R245fa—46.58%, R1234yf—46.84%, R134a—46.58%.

Table 2. Results of thermodynamic calculations for variants I and II with organic Rankine cycle (ORC) technology.

| Working Fluid | Efficiency [%] | Gross Power [kW]/Gross Energy [MWh] (Temperature of Geothermal Water after the Evaporator 60 °C) | Gross Power [kW]/Gross Energy [MWh] (Temperature of Geothermal Water after the Evaporator 70 °C) |
|---------------|----------------|---------------------------------------------------------------------------------|---------------------------------------------------------------------------------|
|               | Flow rate of geothermal water [kg/s] | AI   | 40  | 30  | 20  | 20  | 30  | 20  | 20  | 20  |
| R227ea        | 5.8             | 761  | 149/761 | 111/446 | 74/297 | 101/405 | 324/243 | 41/162 |
| R600a         | 5.9             | 888  | 173/888 | 131/520 | 87/347 | 118/473 | 95/378 | 71/189 |
| R236fa        | 5.9             | 853  | 167/853 | 125/500 | 83/333 | 114/454 | 91/363 | 68/284 |
| R245fa        | 5.9             | 906  | 177/906 | 133/531 | 88/354 | 121/482 | 96/386 | 72/193 |
| R1234yf       | 7.5             | 775  | 189/775 | 113/454 | 76/303 | 103/413 | 83/330 | 62/182 |
| R134a         | 7.5             | 936  | 228/936 | 137/548 | 91/366 | 125/499 | 100/399 | 75/199 |

Figure 5. Comparison of results obtained for gross power and efficiency in the AI and BI variants using ORC technology.
Table 3 and Figures 7 and 8 present the results of calculations of the gross power available to the plant, efficiency, and gross electricity generation for the Kalina Cycle. The results obtained for the gross power range from 382 to 432 kW in the AI variant and from 208 to 236 kW in the BI variant. The difference in the results obtained is an effect, as in the case of ORC, the temperature change of the geothermal water leaving the plant from 60 to 70 °C. In the case of efficiency, it ranges from 5.7% to 6.6%, which is similar to the results obtained with the use of ORC. For the amount of electricity that can be generated, the values range from 1526 to 1728 MWh in the AI variant and from 832 to 944 MWh in the BI variant. These results are much better than in the case of ORC.

The most favourable results were obtained for the mixture containing 87% ammonia—the gross power of the power plant in variant AI was 432 kW, with an efficiency of 6.6% and gross energy generation of 1728 MWh. The lowest gross power of the power plant was obtained for an ammonia content of 85% and in variant AI this totalled 382 kW, at 5.7% efficiency with electricity generation of 1526 MWh. In variant BI the highest value of gross power and gross energy was also calculated for the mixture with an ammonia content of 87%—236 kW and 943 MWh. The lowest values were calculated for “85% Ammonia”—208 kW and 833 MWh.

The temperature (82 °C) and flow rate (51.22 kg/s) of the geothermal water extracted from the C-PIG-1 well are among the highest in Podhale. The results of the thermodynamic analysis presented in the article indicate that there is the potential to implement such a solution, while in the case of ORC technology, the gross power of the plant will not exceed 240 kW, efficiency 6%, and the amount of gross energy possible to obtain 940 MWh. For the Kalina Cycle, these values will be respectively 430 kW, 7%, and 1730 MWh. These results were obtained assuming that the geothermal water temperature leaving the power plant will be 60 °C. In the variant of combined generation of electricity and heat for central heating and hot water, it will be more appropriate to adopt a scheme where the temperature of geothermal water leaving the power plant is 70 °C. For ORC technology, the maximum (assuming the use of the entire geothermal water flow rate) gross power and energy values are respectively 120 kW and 480 MWh. In the case of the Kalina Cycle, the results obtained are 240 kW and 950 MWh.
Table 3. Thermodynamic calculation for the Kalina Cycle.

| Working Fluid | Efficiency [%] | Gross Power [kW]/Gross Energy [MWh] (Temperature of Geothermal Water after the Evaporator 60 °C) | Gross Power [kW]/Gross Energy [MWh] (Temperature of Geothermal Water after the Evaporator 70 °C) |
|---------------|----------------|---------------------------------------------------------------------------------|---------------------------------------------------------------------------------|
|               |                | AI      | AII     | BI       | BII      | AI      | AII     | BI       | BII      |
| Flow rate of geothermal water [kg/s] |                | 51.22   | 40      | 30       | 20       | 51.22   | 40      | 30       | 20       |
| 85% Ammonia   | 5.7            | 382/1526| 298/1192| 223/894  | 149/596  | 208/833 | 163/650 | 122/488  | 81/325   |
| 87% Ammonia   | 6.6            | 432/1728| 337/1350| 253/1012 | 169/675  | 236/943 | 184/736 | 138/552  | 92/368   |
| 89% Ammonia   | 6.5            | 400/1601| 313/1251| 234/938  | 156/625  | 218/874 | 171/682 | 128/512  | 85/341   |

Figure 7. Comparison of results for gross power and efficiency obtained in variants AI and BI using the Kalina Cycle.

In addition, it should be noted how the gross energy values change when the geothermal water stream directed to the power plant changes, as shown in Figures 9 and 10. In the case of variant BII, assuming a temperature of 70 °C at the outlet of the geothermal power plant will be sufficient to meet other needs, mainly recreation. However, in the case of the AII variant, it is possible to use part of the geothermal water stream, and then direct it to a heat exchanger serving the recreation part and mix it with extracted water at 82 °C.
Figure 7. Comparison of results for gross power and efficiency obtained in variants AI and BI using the Kalina Cycle.

Figure 8. Comparison of the amount of electricity it is possible to generate in the AI and BI variants using the Kalina Cycle.

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Figure 9. Comparison of the quantity of electricity it is possible to generate in the AII variant using the ORC Cycle.

Figure 10. Comparison of the amount of electricity it is possible to generate in the AII variant using the Kalina Cycle.
Depending on the stream of geothermal water, the decrease in gross electricity generation using the ORC varies from 21.96% at 40 kg/s to 33.41% for 20 kg/s. Comparing the decrease in gross energy generation for individual working fluids with a water stream of 40 kg/s, it ranges from 21.85%–21.96%, for 30 kg/s it is 24.89%–25.07%, and for 20 kg/s it is 33.21%–33.41%. The Kalina Cycle is characterised by similar variability, which indicates a relatively uniform effect of changing the water stream on the stability of electricity generation. Depending on the geothermal water stream, the decrease in the amount of energy generated for the Kalina Cycle ranges from 21.89% at 40 kg/s to 33.37% for 20 kg/s.

Due to the calculations made, there is a visible relationship between the decrease in the temperature of the geothermal water leaving the power plant, as well as the effect of reducing the stream of geothermal water directed to the power plant on the achievable gross power and the amount of electricity that can be generated. This allows the system to be adapted to the needs of the Chochołowskie Termy facility, taking into account the maximisation of the amount of electricity that can be generated. It is apparent that the investor can use the extracted geothermal stream and cool the water by 12 °C in the evaporator of the power plant, thus obtaining a gross power of 101 to 125 kW, and the amount of gross energy from 404 to 500 MWh for ORC technology (BI variant). On the other hand, similar values can be obtained in the AII variant, using 30 kg/s of geothermal water stream—111–137 kW of gross power and 446–548 MWh of gross energy. Results show that in the case of the Kalina Cycle for the BI variant it is 208–236 kW of gross power and 833–943 MWh of gross energy, and for the AII variant (30 kg/s) it is 223–234 kW and 894–112 MWh.

5. Discussion

The results of the calculations show that geothermal waters from the C-PIG-1 well could be used for geothermal electricity and heating/cooling purposes, and not only in the context of development for recreational purposes as it is now. Considering the possibility of using ORC technology or the Kalina Cycle as the first stage of the cascade, may be justified due to the fact that there is no infrastructure in the study area in the form of a heating network to which a potential geothermal heating plant could be connected. The construction of a completely new heating network is associated with high investment costs. However, this should not preclude deliberations and the possible development of a project based on a geothermal heating system in the future. Actually, local policies seem to be directed to the exploitation of geothermal energy for recreational facilities, through electricity generation as well as for heating/cooling and hot water production in the Chochołowskie Termy.

The results presented in the article indicate the possibility of using ORC and Kalina Cycle technology to generate electricity using low enthalpy geothermal resources. The results related to thermodynamic calculations of the potential gross power, the gross amount of electricity generated, and the efficiency. In the further analysis, attention should be also paid to the conclusions formulated by other authors indicating the high investment and operating costs [46–48]. The results regarding the efficiency of the process of heat-to-electricity conversion, which should be considered low, are consistent with the studies mentioned above. This does not mean, however, that the technologies investigated should not be used, as evidenced by a number of studies aimed at improving the efficiency of electricity generation processes [49–51]. The reason for this should be the benefits associated with the comprehensive use of geothermal energy on a regional/local scale.

Rubio-Maya et al. [52] note the increased profitability of a geothermal plant, maximised use of geothermal resources, local community development, as well as social and environmental benefits. This is important because the extraction and use of geothermal waters may be associated with a potential negative impact of the installations on the natural environment, as well as the need to protect the deposit itself. Therefore, if the process of extracting geothermal waters takes place, the widest possible spectrum of uses should be made of the heat energy that is accumulated within them. The purpose of protecting geothermal water resources is to maintain a constant chemical composition and physical properties, as well as the temperature at the outflow from the exploitation wells [53].
Unfortunately, some of the effects of exploiting geothermal energy are unavoidable, and they manifest themselves at a relatively short distance from geothermal CHP (combined heat and power) plants. However, their impact on the natural environment is much smaller when compared to other energy-generating technologies, especially with reference to conventional energy converting processes using fossil fuels \cite{43,54,55}. To assess the real environmental impact of a geothermal installation, it is appropriate to conduct a life cycle assessment of the use of geothermal energy \cite{56,57}. However, this is not widely performed. In addition, it is not possible to compare results from one location with another, because the complexity of the investment process means that the real impact on the environment will be different for each project. This is primarily due to changes in geological, hydrogeological, topographic, and environmental conditions. The main categories requiring definition during the life cycle assessment include land use, geological hazards, emissions to the atmosphere, water and rock mass, as well as water consumption, impact on biodiversity, noise and light emissions, and waste heat removal \cite{58,59}.

In addition, the proposed cascade of uses of the water in the study location may expand the offer of recreational and health benefits of the region in the future. Such activities are of particular importance in an age of widespread need to improve the quality of life. This aspect is also associated with the possibility of alternative management of the waste water via cosmetology, where the range of applications is not limited by the overall mineralisation of water, but rather makes use of the presence of specific components in the water and factors associated with technologies that enable the acquisition of appropriate concentrates, brines, or medicinal salts \cite{22,60,61}.

As emphasised, the beneficial effect of water on the human body can also be recognised based on an assessment of its chemical composition. This applies especially to waters in which the content of components important for physiological functions is significant, and the systematic drinking of these waters provides supplementary minerals to treat mineral deficiencies, e.g., magnesium, calcium, sodium, fluorine, iodine, iron (II), and chlorides or reduces the intake of some minerals, e.g., water with a low sodium content \cite{22,60,61}. It can be stated that for the study location, the possible use of geothermal waters as drinking water is not anticipated, which results from the physico-chemical composition of water. Such a use of the water could be considered if a high content of easily digestible ingredients is found in the water. However, due to its salinity, the water would certainly have to be diluted or in some way treated \cite{23,24,62}. It should also be noted that when micronutrients of therapeutic importance are present, dilution of the water usually generates a loss of value resulting from the increased content of specific components in the water. This is especially the case with iodide ions, which quickly evaporate from water and the dilution of the water results in their loss.

In relation to the recreational aspect of water management, such activities, although representing an aside due to the amount of water necessary for such purposes, may prove particularly interesting due to the attractiveness of local products, building a new brand, and the implementation of new policies for the rational and comprehensive use of natural resources.

Considering the issues of using geothermal energy in a broader aspect, not locally, but on a national scale, this method of electricity generation should be considered desirable. First of all, this is due to the fact that the energy generated using renewable energy sources, which is geothermal energy, should be considered as ecological. Secondly, it has a significant impact from the point of view of striving for energy self-sufficiency, diversification of energy sources, as well as the development of local communities.

6. Conclusions

Summing up, the use of a cascade system, in which the first stage would be the generation of electricity, could enable effective management of geothermal waters at different temperature levels. This solution is justified due to the sustainable use of geothermal resources. Moreover, it would allow to rationalise the use of natural resources from the point of view of environmental protection.
The results of the thermodynamic analysis indicate that there is the potential to implement such a solution as ORC or the Kalina Cycle. However, in the case of ORC technology, the gross power will not exceed 240 kW and the gross energy that is possible to obtain would be 940 MWh. For the Kalina Cycle, these values would be 430 kW and 1730 MWh, respectively. In the present situation, the development of geothermal water for electricity needs of the recreational facilities in the Chochołowskie Termy would seem to be an interesting direction for future policy.

The concept of managing low enthalpy geothermal waters for the purpose of electricity generation in the first stage of the cascade presented in the article may be reproduced in locations where there are no technical possibilities to build a heating network or it is unjustified from an economic point of view. In cases where geothermal water with a relatively high temperature is used only for recreational purposes, the potential of available geothermal resources should be considered as not fully utilised. The results obtained show that there is a technical possibility of using ORC or the Kalina Cycle for electricity generation in the first stage of cascade. Subsequently, future research should be focused on precisely determining the amount of net power and net energy that will be generated using the proposed technologies. It is also necessary to conduct an economic viability analysis and the environmental impact of the installation, e.g., using an environmental life cycle assessment.

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