The use of geothermal energy in co-generated heat and power production in Poland – a case study

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Abstract: The paper presents the results of energy and environmental evaluation of geothermal CHP plant. The variant of CHP plant based on Organic Rankine Cycle (ORC) has been taken into consideration as the most favorable for the geothermal conditions prevailing in Poland. The existing geothermal well located in the city of Konin in Greater Poland (Wielkopolska) voivodship has been chosen as the case study. The conceptual design of CHP plant has been proposed and evaluated from energy and environmental point of view. The non-renewable primary energy consumption has been chosen as energy performance criterion. In the case of environmental performance carbon dioxide emission has been taken as evaluation criterion. The analysis has been performed for different operating conditions and three working fluids. The best energy performance can be spotted for working fluid R123, for which the reduction varies between 15200 and 11900 MWh/a. The working fluid R134a has a worse energy performance, which allows for the reduction of fossil fuels energy consumption in the range of 15000 and 11700 MWh/a. The total reduction of CO_2 emission is the highest for working fluid R123: 5300 to 4150 $MgCO_2$/a, the medium one for working fluid R134a: 5200 to 4100 $MgCO_2$/a and the lowest for working fluid R227: 5000 to 4050 $MgCO_2$/a. It has been shown that the construction of geothermal CHP plants based on Organic Rankine Cycle can be reasonable solution in Polish conditions. It is important concerning the need of reduction of fossil fuels primary energy consumption and carbon dioxide emission.

Introduction

The increase in use of renewable energy resources in Poland is crucial due to the poor performance of the Polish energy system, based on the supply of high carbon content fossil fuels: coal and brown coal. In consequence Poland was responsible for 9.3% of annual European Union carbon dioxide (CO_2) emission in 2019 (Poland – 292.9 Mt CO_2, EU_{28} – 3150.9 Mt CO_2). According to the International Energy Agency (IEA) reports the annual ratio of carbon dioxide emission to the annual fossil fuels primary energy use in Poland is one of the largest in Europe and in 2019 reached the value of 2.85 Mt CO_2/Mtoe (for France it is 1.23 and for Germany 2.17) [1].

The weakest part of the Polish energy system is electricity production which basically takes place in traditional condensing power stations fired with hard and brown coal. The average annual energy efficiency of electricity production is only 0.33 [2], thus the generation of 1 kWh of electricity causes the unacceptable emission of more than 1 kg of CO_2. In order to improve this situation two actions have to be undertaken: (i) the increase of energy efficiency of electricity production, and (ii) the substitution of high carbon content fossil fuels by renewable energy resources. The utilization of renewable energy resources in electricity production in Poland has significantly increased within last years, which is mainly linked to the installation of wind turbines and PV solar panels [3]. Unfortunately, those electricity production systems are not stable and strongly depend on climatic conditions, solar irradiation and wind conditions. Despite of relatively high installed capacity in 2019 the electricity production from wind turbines (installed capacity 5800 MW) was 15006 GWh and from PV solar panels (installed capacity over 300 MW) 712 GWh only. At the same time period the coal based electricity production was more than 120000 GWh [3].

In order to provide stable production of usable energy forms, including electricity, the geothermal energy supply is taken into consideration [4]. The intensity of heat flow in the earth shell in Poland is relatively low, thus geologically confirmed geothermal energy resources in Poland are limited to low and medium temperature geothermal water [4, 5]. Average heat flux of those resources varies between 25 mW/m² and 90 mW/m² [6]. They are located in West European tectonic

plate and are formed by underground water pools of the Carpathian Mountains, the Sudety Mountains, and Western Pomerania and Podhale regions – Figure 1 [5].

The utilization of geothermal energy in Poland is limited to: (i) low temperature heat production in heating station, (ii) heating the pools in water recreation centers, (iii) balneotherapy, and (iv) aquaculture – Atlantic salmon's farms. In 2018 there were six medium scale district heating (DH) geothermal systems under operation – Fig 1. The total geothermal heating capacity of those systems in 2018 was 74.6 MW and it is expected that the growth of that capacity till 2025 will be by the factor of two [5]. There are neither geothermal power plants nor co-generated heat and power plants under operation for now in Poland.

In general, the temperature of geothermal water in Poland does not exceed 70–80°C, what makes the power production or co-generated heat and power (CHP) production in the direct solutions inefficient from the economical point of view [7]. It may be changed by the application of Organic Rankine Cycle (ORC) which enables utilization of low grade heat for the production of different usable energy forms. The use of low grade geothermal resources for co-generated heat and power production can help to improve the energy efficiency of energy systems and in consequence reduce the carbon dioxide emission.

The principle of Organic Rankine Cycle (ORC) operation is similar to the operation of Rankine Cycle (RC) based on water as working fluid [8]. The main difference lays in working fluids which in the case of ORC are organic substances characterized by high molecular weight, lower temperature of evaporation and higher pressure of steam phase. It allows

for the utilization of low temperature heat as driving energy, operation in lower pressure and application of turbines with lower rotation speed [9]. From the technological point of view ORC is less complicated in comparison to traditional RC, it can use only one heat exchanger for heating, evaporating and overheating of working fluid. The additional heat regenerator is sometimes used for preheating liquid phase of working fluid [10]. Depending on the low temperature heat source characteristics the working fluid has to be precisely selected. The cost, market availability and thermal stability of working fluid have to be considered [8, 11, 12, 13, 14]. The Organic Rankine Cycle attracted a lot of attention. This may be due to its contribution to mitigating the degradation of the ecosystem [15, 16]. One of the main topics of investigations related to ORC is energy efficiency evaluation. It is not an easy task due to the lack of adequate instrumentation, inaccurate measurements and uncertainty related to the thermodynamic properties of working fluids. This can have a significant impact on the final results of calculations, especially for complex fluids, with a small temperature drop in expansion [17, 18].

The use of waste heat as the driving force for ORC in power production is well documented [19]. Less attention has been paid to the application of that technology in the case of geothermal heat sources, due to the limited temperature of those sources [20, 21, 22]. ORC supplied by geothermal water is rather seldom used for co-generated heat and power production [22].

The existing low temperature geothermal energy source located in the city of Konin, Poland has been the basis for conceptual design of ORC based co-generated heat and power plant. In order to evaluate the energy and environmental
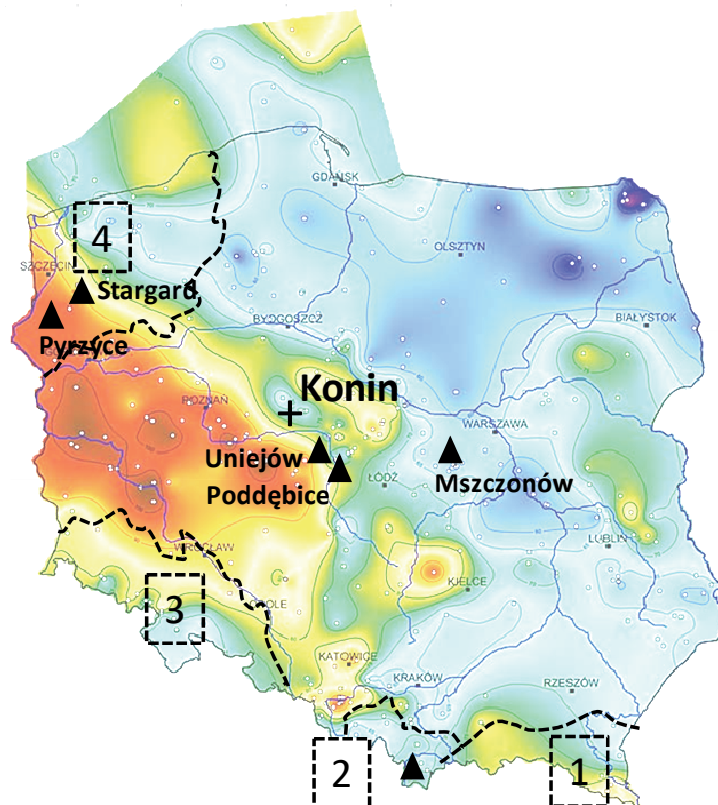

Fig. 1. Location of geothermal energy resources and its direct utilization in Poland [5],
1 – Carpatia Mountains, 2 – Podhale, 3 – Sudety Mountains, 4 – Western Pomerania, ▲ – existing DH geothermal systems

performance of that plant, two criteria have been proposed. The non-renewable primary energy consumption has been chosen as energy performance criterion. In the case of environmental performance carbon dioxide emission has been taken into account. The analysis has been performed for different operating conditions and three working fluids.

Materials and methods

The conceptual design of geothermal CHP plant has been settled on the existing geothermal well located in the city of Konin in Greater Poland (Wielkopolska) voivodship, central part of Poland. The basic data of the source are listed in Table 1.

The flow diagram of the proposed geothermal CHP plant based on ORC is shown in Fig. 2. It consists of ORC part responsible for electricity production and heat exchanger located downstream from evaporator responsible for useable heat production.

In order to evaluate the energy and ecological performance for the proposed ORC based CHP plant the set of energy balance equations for the system components has been formulated. It allowed for the calculation of heat and net power

production and finally the reduction of non-renewable energy consumption and carbon dioxide emission reduction.

Energy balance analysis

The calculations performed were settled on the First Law of Thermodynamics and energy balance equations derived for control volumes (CVs) covering main system elements.

Energy balance calculations for evaporator (CV1):

$$\dot{Q}_{evap} = \dot{m} \cdot (h_1 - h_4)$$
$$\dot{Q}_{evap} = \dot{m}_{geo} \cdot (h_{G1} - h_{G2}) \quad\quad (1)$$
$$\dot{Q}_{evap} = \dot{m}_{geo} \cdot c_w \cdot (t_{G1} - t_{G2})$$

where:

$\dot{m}$ – mass flow of ORC working fluid, kg/s
$\dot{m}_{geo}$ – mass flow of geothermal water, kg/s
$h_{G,i}$ – specific enthalpies of geothermal water, kJ/kg
h_i – specific enthalpies of ORC working fluid, kJ/kg
$t_{G,i}$ – temperatures of geothermal water, °C
c_w – specific heat of geothermal water, kJ/kg°C
$\dot{Q}_{evap}$ – heat flux of evaporator, kW

Table 1. Basic data of geothermal heat source in the town of Konin [26]

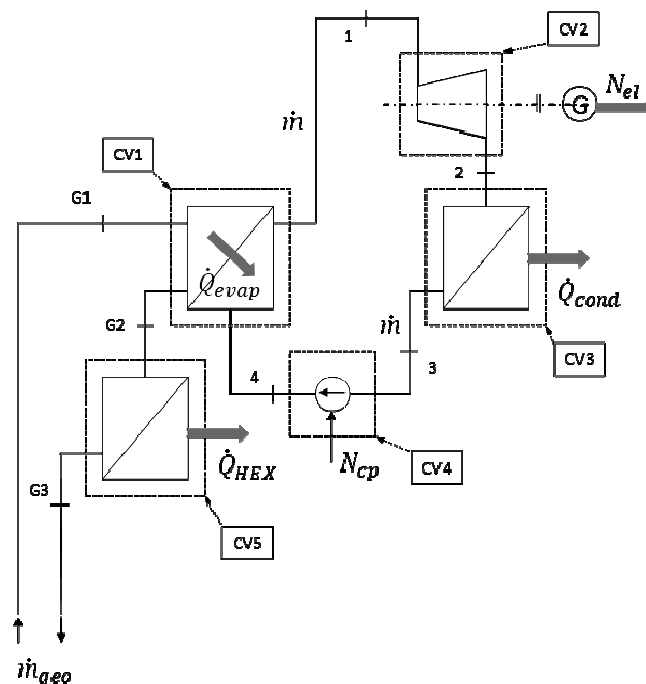| Depth of geothermal well	[m]	2660
Temperature of geothermal water in the layer	[°C]	97,5
Temperature of geothermal water on the surface	[°C]	92,0
Mineralization of geothermal water (Cl-Na)	[%]	15,04
Mineralization of geothermal water (Cl-Na)	[g/kg]	150,4
Specific heat of geothermal water	[kJ/kg K]	3,549
Geothermal water flow	[m³/h]	114,0

Fig. 2. Flow diagram of geothermal CHP plant based on ORC

Energy balance calculations for turbine (CV2):

$$N_i = \dot{m} \cdot (h_1 - h_2)$$
$$N_i = \dot{m} \cdot \eta_i \cdot (h_1 - h_{2s}) \qquad (2)$$
$$N_{el} = \dot{m} \cdot \eta_i \cdot (h_1 - h_{2s}) \cdot \eta_{em} = N_i \cdot \eta_{em}$$

where:
N_i – internal power of ORC turbine, kW
N_{el} – electrical power of ORC turbine, kW
η_i – internal energy efficiency of ORC turbine
η_{em} – electro-mechanical energy efficiency of ORC turbine

Energy balance calculations for condenser (CV3):

$$\dot{Q}_{cond} = \dot{m} \cdot (h_2 - h_3) \qquad (3)$$

where:
$\dot{Q}_{cond}$ – heat flux of condenser, kW

Energy balance calculations for circulation pump (CV4):

$$N_{cp,i} = \dot{m} \cdot (h_4 - h_3)$$
$$N_{cp} = N_{cp,i}/\eta_{cp,em} = \dot{m} \cdot v \cdot (p_4 - p_3)/(\eta_{cp,i} \cdot \eta_{cp,em}) \qquad (4)$$

where:
$N_{cp,i}$ – internal power of ORC circulating pump, kW
N_{cp} – electrical power of ORC circulating pump, kW
$\eta_{cp,i}$ – internal energy efficiency of ORC circulating pump,
$\eta_{cp,em}$ – electro-mechanical energy efficiency of ORC circulating pump,
v – specific volume of ORC working fluid, m³/kg
p_i – pressure of ORC working fluid, kPa

Energy balance calculations for heat exchanger (CV5):

$$\dot{Q}_{HEX} = \dot{m}_{geo} \cdot (h_{G2} - h_{G3})$$
$$\dot{Q}_{HEX} = \dot{m}_{geo} \cdot c_w \cdot (t_{G2} - t_{G3}) \qquad (5)$$

where:
$\dot{Q}_{HEX}$ – heat flux of district heating heat exchanger, kW

The set of energy balance equations listed above has been solved and used as energy analysis tool for the proposed ORC cogenerated heat and power plant.

Energy and environmental evaluation

In order to evaluate energy and ecological performance of ORC based geothermal CHP plant two criteria have been employed. As energy performance criterion the avoided fossil fuels chemical enthalpy consumption has been chosen. In the case of environmental performance avoided carbon dioxide (CO_2) emission has been used.

As the reference energy system the cogenerated heat and power plant fired with hard coal (gross energy efficiency η_{CHP}) has been taken into consideration. Annual use of fossil fuels for reference energy system has been calculated for equivalent

number of hours of full load operation of electricity generator (net value) – τ_{EL} [h/a], and heat exchanger – τ_{HEX} [h/a].

Avoided annual use of fossil fuels chemical enthalpy has been calculated using the following equation:

$$H_{ch,HC} = H_{ch,El} + H_{ch,Heat} = \tau_{EL} \cdot (N_{el} - N_{cp})/\eta_{CHP} + \\ + \tau_{HEX} \cdot \dot{Q}_{HEX} /\eta_{CHP} \qquad (6)$$

where:
$H_{ch,HC}$ – avoided annual use of hard coal for reference energy system, MWh/a

Avoided annual emission of carbon dioxide has been derived using CO_2 emission factor for hard coal used in reference energy system – $e_{CO2,HC}$ [$MgCO_2$/MWh], for heat and electricity production.

$$E_{CO2} = E_{CO2,El} + E_{CO2,Heat} = e_{CO2,HC} \cdot (H_{ch,El} + H_{ch,Heat}) = \\ = e_{CO2,HC} \cdot H_{ch,HC} \qquad (7)$$

The analysis has been performed for different operating conditions and three working fluids.

Results and discussion

Energy balance analysis

The calculations have been performed using the Excel based calculation tool [24]. It has been assumed that the temperatures of geothermal water entering and leaving evaporator (CV-1) are $t_{G1} = 90°C$ and $t_{G2} = 75°C$. It has been also assumed that the overall efficiency of turbine and generator is 80% as for radial inflow turbines [25, 26] and overall efficiency of working fluid and geothermal water pumps is 70%. The calculations have been performed for three working fluids: R123, R134a, and R227, which have been chosen on the basis of former findings published by Saleh et al. [27] and Wang et al. [28].

In order to evaluate the production capability of the system the following operational parameters have been changed in calculations: evaporation temperature $t_1 = 75°C$ and $t_1 = 70°C$, condensation temperature $t_{2''} = 25°C$ and $t_{2''} = 30°C$ temperature of geothermal water leaving the heat exchanger $t_{G3} = 30°C$ and $t_{G3} = 40°C$ .The thermodynamic properties of working fluids in characteristic points of ORC have been imported from Solkane 8.0 selection software. Figure 3 presents the example of energy balance analysis for working fluid R123 and the following thermal parameters $t_1=75°C$, $t_{2''} = 25°C$, $t_{G3} = 30°C$.

Figure 4 presents the example of energy balance analysis for working fluid R134a and the following thermal parameters $t_1=75°C$, $t_{2''} = 30°C$, $t_{G3} = 35°C$.

Figure 5 presents the example of energy balance analysis for working fluid R227 and the following thermal parameters $t_1=70°C$, $t_{2''} = 25°C$, $t_{G3} = 40°C$.

Table 2 summarizes the energy balance calculation results for all working fluids and operating parameters.

The influence of the temperature of geothermal water leaving heat exchanger (CV-5) on the heating capacity of district heating heat exchanger is shown in Table 3.

The calculation results show that for all three working fluids the highest production of electrical power refers to

the evaporation temperature and condensation temperature t_1=75°C and condensation $t_{2''}$ = 25°C. The differences are rather small, for R123 and R134a the electricity production is a little bit higher comparing with R227 working fluid. It is worth to emphasize that significant part of electricity production would be used for covering self-energy requirements of district heating system and ORC CHP plant.

In the case of heat the increase of temperature of geothermal water leaving heat exchanger significantly decreases the production of that form of useable energy. It has been assumed

that geothermal CHP plant is capable to cover full requirements of heat end users.

Energy and environmental evaluation

Performing energy and environmental evaluation of ORC based geothermal CHP plant it has been assumed that the ORC circulating pump is supplied from electricity produced in ORC cycle – net electricity production has been used in order to calculate the avoided primary energy consumption and avoided CO_2 emission. In the case of other devices (geothermal water

Fig. 3. Print screen of Excel calculation tool for working fluid R123 and thermal parameters: t_1=75°C, $t_{2''}$=25°C, t_{G3}=30°C

Fig. 4. Print screen of Excel calculation tool for working fluid R134a and thermal parameters: t_1=75°C, $t_{2''}$=30°C, t_{G3}=35°C

pump, control systems) it has been assumed that the reference energy system (hard coal fired cogenerated heat and power plant) has the congenial energy consumption for the supply of internal circuit pumps and control systems.

The gross energy efficiency for reference energy system – cogenerated steam heat and power plant fired with hard coal has been taken equal to $\eta_{CHP} = 80\%$ [29]. Electrical net power

production and heat flux production have been the same as for geothermal CHP plant. The emission of carbon dioxide has been derived for hourly and annual conditions. It has been assumed that energy system has to operate for $\tau_{EL} = 8760/a$ in the case of electrical power production (whole year operation) and for $\tau_{auHEX} = 2000\ h/a$ in the case of heat production (typical value for climatic condition in the city of Konin location). The
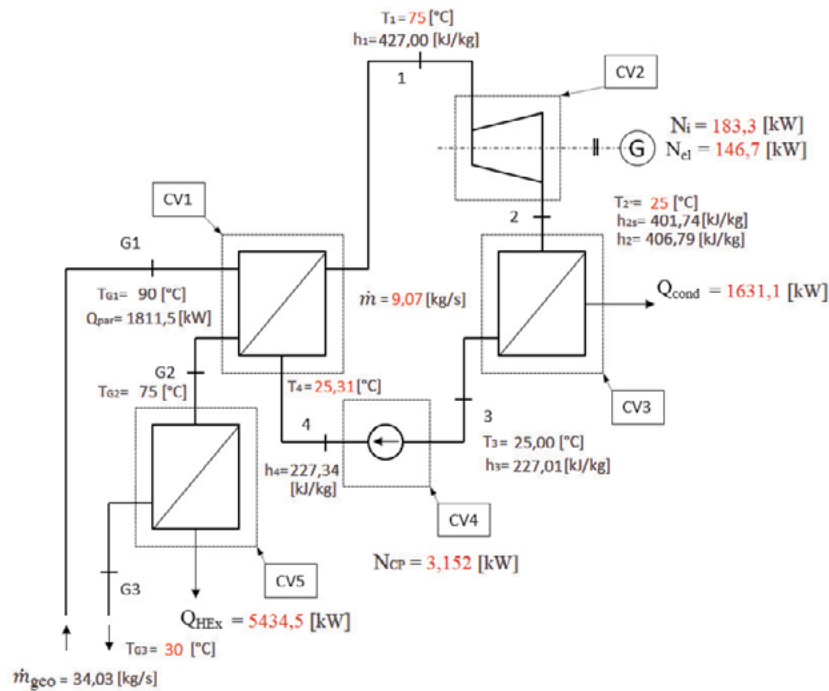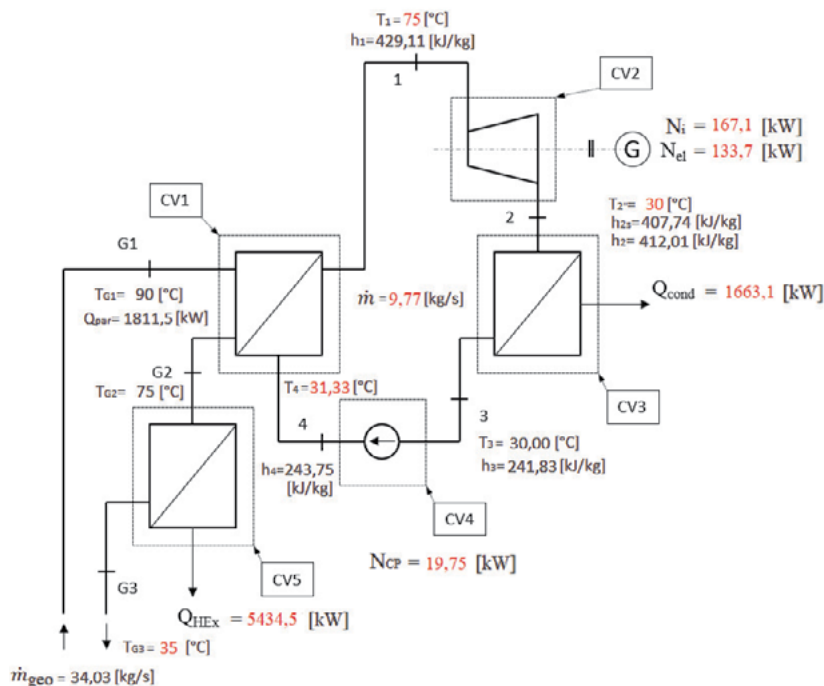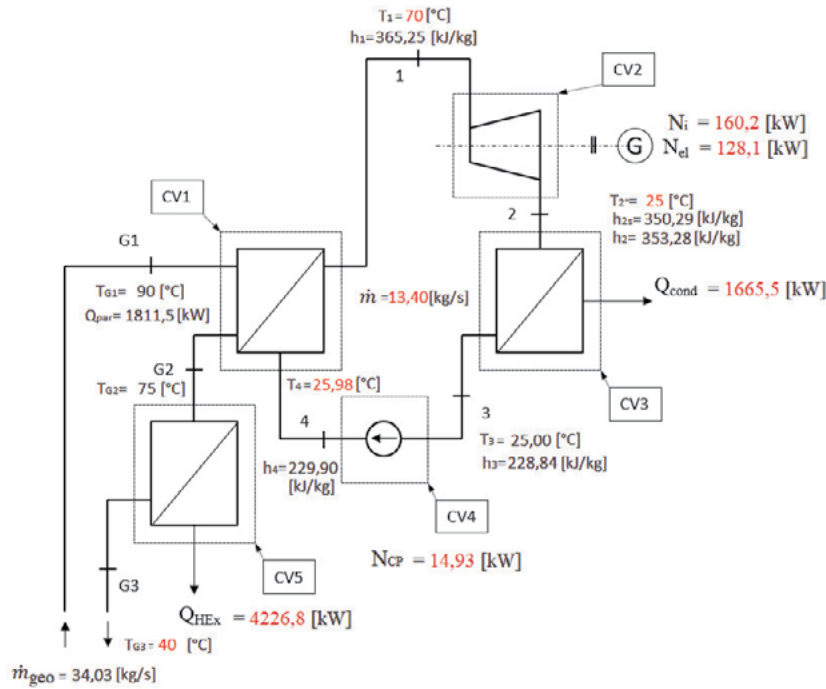

Fig. 5. Print screen of Excel calculation tool for working fluid R227 and thermal parameters: $t_1=70°C$, $t_{2"}=25°C$, $t_{G3}=40°C$

Table 2. Energy performance of ORC for different working fluids

Working fluid	t_1	$t_{2"}$	$\dot{m}$	N_i	N_{el}	Q_{skr}	N_{cp}
	[°C]	[°C]	[kg/s]	[kW]	[kW]	[kW]	[kW]
R123	75	25	9,07	183,3	146,7	1631,1	3,15
	75	30	9,32	166,8	133,5	1647,7	3,14
	70	25	9,20	169,3	135,5	1644,7	2,71
	70	30	9,46	152,2	121,8	1661,7	2,59
R134a	75	25	9,41	182,7	146,2	1647,7	19,92
	75	30	9,77	167,1	133,7	1663,1	19,75
	70	25	9,42	169,4	135,5	1658,3	17,05
	70	30	9,78	153,1	122,5	1674,2	16,68
R227	75	25	13,21	172,3	137,8	1655,5	17,24
	75	30	13,80	158,0	126,4	1669,8	17,14
	70	25	13,38	160,2	128,1	1665,5	14,93
	70	30	14,00	145,2	116,2	1680,2	14,73

Table 3. Calculation results for heat exchanger (CV5) for different temperatures of water leaving HEx

t_{G2}	t_{G3}	$\dot{m}_{geo}$	c_w	$\dot{Q}_{HEX}$
[°C]	[°C]	[kg/s]	[kJ/(kg K)]	[kW]
75	30	34,03	3,549	5434,5
75	35	34,03	3,549	4830,7
75	40	34,03	3,549	4226,8

carbon dioxide emission factor for hard coal has been taken as $e_{CO2,HC} = 0.35$ $MgCO_2/MWh$. The calculation results have been presented below.

It can be seen (Tables 4 and 5) that construction of geothermal CHP plant can significantly reduce the chemical enthalpy of fossil fuels use and emission of carbon dioxide what is of greatest importance concerning poor performance of energy systems in Poland. The calculations have been performed for all three working fluids and 12 discrete temperature conditions listed in Table 6. Discrete temperature conditions (DTC) refer to different operating temperatures of main geothermal CHP plant components: evaporator, turbine, condenser and district heating heat exchanger. The change of those parameters allowed for the calculation of the range of avoided fossil fuels chemical enthalpy consumption and avoided CO_2 emission joined with geothermal CHP plant operation.

Table 4. Avoided chemical enthalpy of hard coal use and carbon dioxide emission in production of electrical power for reference energy system

Working fluid	N_{el}	N_{cp}	$N_{el,net}$	$\dot{H}_{ch,El}$	$\dot{E}_{CO2,El}$	$H_{ch,El}$	$E_{CO2,El}$
	[kW]	[kW]	[kW]	[kW]	[kgCO$_2$/h]	[MWh/a]	[MgCO$_2$/a]
R123	146,7	3,15	143,5	434,9	152,2	1571,5	550,0
	133,5	3,14	130,3	395,0	138,2	1427,3	499,6
	135,5	2,71	132,8	402,3	140,8	1453,7	508,8
	121,8	2,59	119,2	361,1	126,4	1304,8	456,7
R134a	146,2	19,92	126,2	382,6	133,9	1382,5	483,9
	133,7	19,75	113,9	345,2	120,8	1247,4	436,6
	135,5	17,05	118,5	359,0	125,6	1297,2	454,0
	122,5	16,68	105,8	320,6	112,2	1158,5	405,5
R227	137,8	17,24	120,6	365,5	127,9	1320,7	462,3
	126,4	17,14	109,3	331,1	115,9	1196,4	418,7
	128,1	14,93	113,2	343,1	120,1	1239,8	433,9
	116,2	14,73	101,4	307,4	107,6	1110,8	388,8

Table 5. Avoided chemical enthalpy of hard coal use and carbon dioxide emission in production of heat in reference energy system

t_{G2}	t_{G3}	$\dot{Q}_{HEX}$	$\dot{H}_{ch,Heat}$	$\dot{E}_{CO2,Heat}$	$H_{ch,Heat}$	$E_{CO2,Heat}$
[°C]	[°C]	[kW]	[kW]	[kgCO$_2$/h]	[MWh/a]	[MgCO$_2$/a]
75	30	5434,5	5434,5	1086,9	13586,3	4755,2
75	35	4830,7	4830,7	966,1	12076,8	4226,9
75	40	4226,8	4226,8	845,4	10567,0	3698,5

Table 6. Discrete temperature conditions (DTC) for energy and ecological analysis of ORC CHP plant operation

DTC	t_1	$t_{2"}$	t_{G2}	t_{G3}
[–]	[°C]	[°C]	[°C]	[°C]
1	75	25	75	30
2	75	25	75	35
3	75	25	75	40
4	75	30	75	30
5	75	30	75	35
6	75	30	75	40
7	70	25	75	30
8	70	25	75	35
9	70	25	75	40
10	70	30	75	30
11	70	30	75	35
12	70	30	75	40

The results of calculations have been plotted in Fig. 6 and Fig. 7.

As shown in Fig. 6, the application of ORC based geothermal CHP plant can significantly reduce annual consumption of chemical enthalpy of fossil fuels. The best energy performance can be spotted for working fluid R123, for which the reduction varies between 15200 and 11900 MWh/a. The working fluid R134a has a worse energy performance, which allows for the reduction of fossil fuels energy consumption in the range of 15000 and 11700 MWh/a. The worst performance has been noted for working fluid R227 – the reduction between 14800 and 11600 MWh/a. The same relation concerning ecological performance, i.e., the reduction of carbon dioxide emission, can be found, see Fig. 7. The total reduction of CO_2 emission is the highest for working fluid R123: 5300 to 4150 $MgCO_2$/a, the medium one for working fluid R134a: 5200 to 4100 $MgCO_2$/a, and the lowest for working fluid R227: 5200 to 4050 $MgCO_2$/a.

In all the cases mentioned above the reduction can be considered as significant regarding energy and environmental performance of reference energy system. Therefore, it should be taken into consideration to expand the use of geothermal energy beyond the production of heat only.

Conclusions

The aim of the work was to propose the conceptual design of geothermal CHP plant that would be applicable in Poland. Bearing in mind the geothermal conditions prevailing in Poland the use of ORC seems to be the reasonable solution, allowing for the reduction of fossil fuels chemical enthalpy consumption and carbon dioxide emission.

The energy and environment evaluation of geothermal CHP plant based on ORC has been conducted. The evaluation referred to the existing geothermal well located in the city of Konin in Greater Poland (Wielkolpolska) voivodship, the
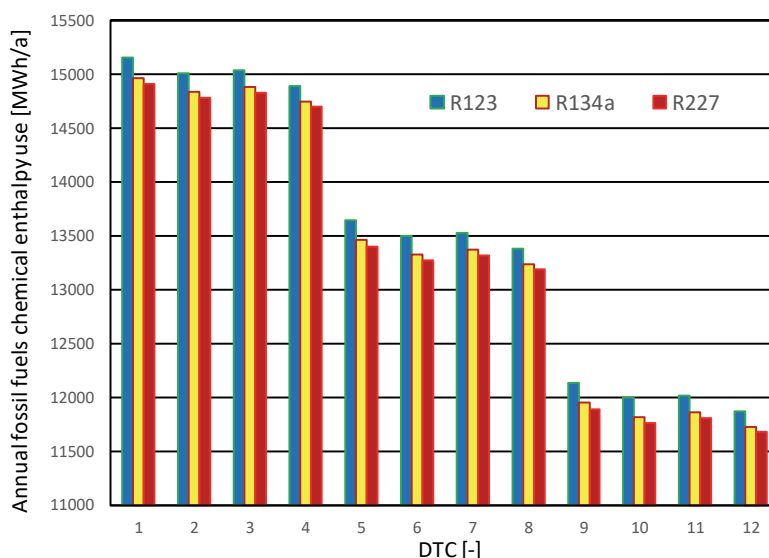

Fig. 6. Total avoided annual use of fossil fuels for reference energy system
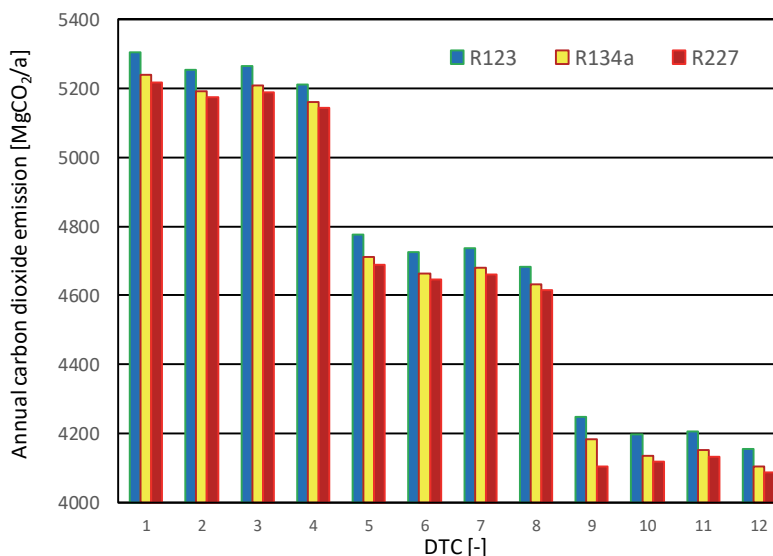

Fig. 7. Total avoided annual emission of carbon dioxide for reference energy system

central part of Poland. It has been assumed that the system is capable to cover heat and electrical power of energy end users, thus does not require additional energy sources. Such system is characterized by zero chemical enthalpy of fossil fuels use and zero carbon dioxide emission. Although the electrical power production is not high the use of ORC can significantly reduce the emission of carbon dioxide comparing with traditional energy systems based fossil fuels and separate production of heat and electrical power.

The amount of heat production highly depends on the thermal parameters of heat exchanger operation. The lower is the temperature of heat exchanger operation the higher is the production of heat. On the other hand, the decrease of that temperature determines the need of installation of low temperature heating systems in end users what can be difficult concerning economical and organizational aspects.

The proposed method of energy and ecological evaluation and achieved results may be also used for analysis of other energy systems in which energy supply is dominated by high carbon primary energy resources.

In order to make the final decision concerning the system application the future research work will have to be performed. It has to cover economic evaluation of the system – investment and total operating cost calculations, as well as ecological evaluation related to the global warming potential (GWP) of the working fluids available for the ORC based geothermal CHP plant.

Nomenclature

c_w – specific heat of geothermal water, kJ/kg°C
e_{CO2} – carbon dioxide emission factor for fossil fuel, kgCO$_2$/kWh
$\dot{E}$ – energy flux, kW
$\dot{E}_{CO2}$ – carbon dioxide emission, kg/h
H_{ch} – chemical enthalpy flux of fossil fuel, kW
$h_{G,i}$ – specific enthalpies of geothermal water, kJ/kg
m – mass flow, kg/s
$N_{cp,i}$ – internal power of ORC circulating pump, kW
N_{cp} – electrical power of ORC circulating pump, kW
N_i – internal power of ORC turbine, kW
N_{el} – electrical power of ORC turbine, kW
p_i – pressure of ORC working fluid, kPa
v – specific volume of ORC working fluid, m³/kg
$\eta_{cp,i}$ – internal energy efficiency of ORC circulating pump
$\eta_{cp,em}$ – electro-mechanical energy efficiency of ORC circulating pump
η_{em} – electro-mechanical energy efficiency of ORC turbine
η_i – internal energy efficiency of ORC turbine
τ_{EL} – equivalent number of hours of electricity production per year, h/year
τ_{HEX} – equivalent number of hours of heat production per year, h/year

Indices

cp – circulating pump
cond – condenser
em – electro-mechanical
evap – evaporator
geo – geothermal water
HC – hard coal
HEX – heat exchanger

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