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THE EXPLOITATION OF ULTRA-LOW-ENTHALPY GEOTHERMAL ENERGY IN AN ORC PROCESS IN COMBINATION WITH RES AND A HEAT PUMP

IZKORIŠČANJE ZELO NIZKOENTALPIJSKE GEOTERMALNE ENERGIJE V ORC PROCESU V KOMBINACIJI Z OVE IN S TOPLOTNO ČRPALKO

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Keywords: renewable energy resources, ORC process, energy analysis, economic analysis

Abstract

The paper presents a model of a binary-cycle hybrid power plant to be located in Topolšica, Šalek Valley, Slovenia. It is based on an ORC process and utilises several different renewable energy sources: geothermal energy, solar energy, and wood biomass energy. The portion of geothermal energy is so low that it is used in the system as a source of energy for a heat pump, thus increasing the inlet temperature of the ORC process. The model of the hybrid ORC power plant dealt with in this paper is intended only for electricity production.

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The energy source used first is geothermal water from a well, entering the heat pump to heat the heat pump working medium. Solar energy and wood biomass energy are sources of heat flow, additionally heating the ORC process working medium. The paper presents thermodynamic and economic analyses of this potential system.

Povzetek

Članek predstavlja model binarne hibridne elektrarne, ki bi bila postavljena v Topolšico, Šaleška dolina, Slovenija. Osnova je ORC proces, ki uporablja več različnih obnovljivih virov energije – geotermalno energijo, sončno energijo in energijo lesne biomase. Delež geotermalne energije je tako nizek, da jo v sistemu uporabimo kot vir energije za uporabo v toplotni črpalki in tako povečamo vstopno temperaturo v ORC proces. Model hibridne ORC elektrarne v članku je predviden samo za proizvodnjo električne energije. Energetski vir, ki je najprej uporabljen, je geotermalna energija iz vrtine, ki vstopa v toplotno črpalko, kjer segreje delovni medij toplotne črpalke. Sončna energija in energija lesne biomase sta izvora toplotnega toka, ki še dodatno segrejeta delovni medij ORC procesa. V članku sta predstavljeni termodinamična in ekonomska analiza takšnega potencialnega sistema.

1 INTRODUCTION

Global warming is a current crucial issue in the world and requires immediate action in order to reduce it. New, clean power generation technologies have to be explored. One very good option is the exploitation of renewable energy sources using hybrid technologies.

The so-called binary processes to increase system efficiency by exploiting the maximum amount of energy are used for the exploitation of low-enthalpy geothermal energy. According to the principles of thermodynamics, geothermal binary cycle power plants are the closest to the conventional thermoelectric or nuclear plants in that they have the working medium in a closed cycle, *[1]*.

An organic Rankine process (ORC) was chosen as a geothermal power plant model, i.e. a binary process, similar to the Rankine vapour power cycle in terms of thermodynamics, except that hydrocarbons are used as the working medium in the ORC instead of vapour, *[2]*, reaching the boiling temperature sooner and, consequently, being more suitable for processes of power generation from low-temperature sources, *[3]*.

The working medium chosen on the basis of thermodynamic properties for a specific system receives heat, evaporates and expands through the turbine, and then it is condensed and returns to the evaporator with a supply pump, *[1]*.

2 SYSTEM DESCRIPTION AND STRUCTURE

The geothermal power plant model is essentially an ORC system, in which the working medium is heated by various RES. First, we exploit geothermal energy through a heat pump, then solar energy and finally wood biomass energy. Three different RES will be used for the system with the advantage being to utilise the available RES potential as much as possible. This will provide greater operational reliability of the system and, consequently, reduce the oscillation of electricity production. Figure 1 shows the heat pump/ORC system diagram with all its elements.

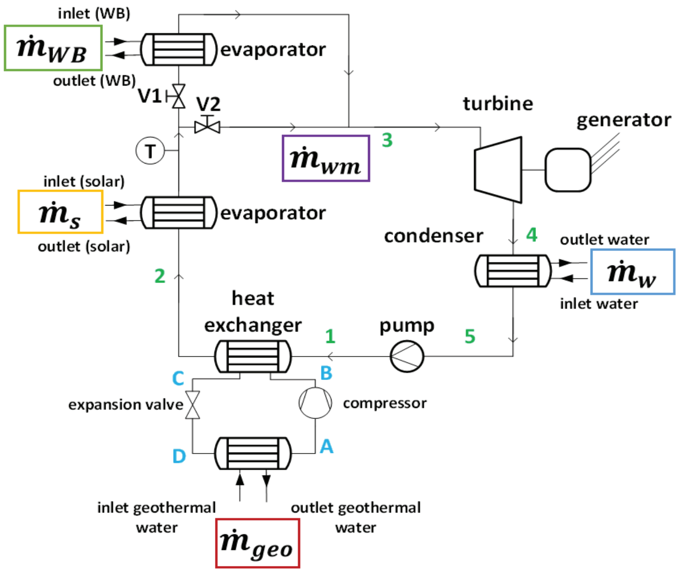

Figure 1: *Heat pump hybrid system diagram*

Geothermal energy enters the system as a medium that heats the heat pump medium in the heat pump evaporator. Then we look at the ORC process and see that in State 1 the working medium enters the heat exchanger, which is in fact a heat pump condenser, where it receives the heat from the heat pump working medium and passes to State 2. The working medium then enters the evaporator from State 2, where it is additionally heated by the heat from a solar subsystem. Immediately after this stage, a temperature sensor is placed in the system, which measures the temperature of the working medium. If the sensor detects a lower temperature than desired, valve V2 closes and valve V1 opens, thereby allowing the working medium to pass into another evaporator to be additionally heated by the heat from the wood biomass subsystem, where it is heated to the desired temperature, which is State 3. In State 3, the working medium enters the steam turbine, where it expands to State 4. The ORC process working medium then enters the condenser, where it releases the heat to the coolant, i.e. water in our case, and passes to State 5. In the last step of the cycle, the working medium passes through the pump from State 5 to State 1, *[4].*

The correct working fluids must be chosen for both the ORC process and the heat pump, because the choice of the working fluid has a great impact on the efficiency of the processes. According to *[5],* R245fa is an optimum choice of the working medium. Considering its thermodynamic properties and environmental characteristics, it is suitable for a number of applications in industry, *[6].* R134a is chosen as the heat pump working medium, also widely used in similar processes, *[7].*

3 INPUT DATA AND DIAGRAMS

In system modelling, some parameters need to be defined, some are assumed and some are obtained from the data. The basis for the ORC process calculation is the p-h diagram in Figure 2, *[7],* showing the changes to the states of R245fa in the ORC process.

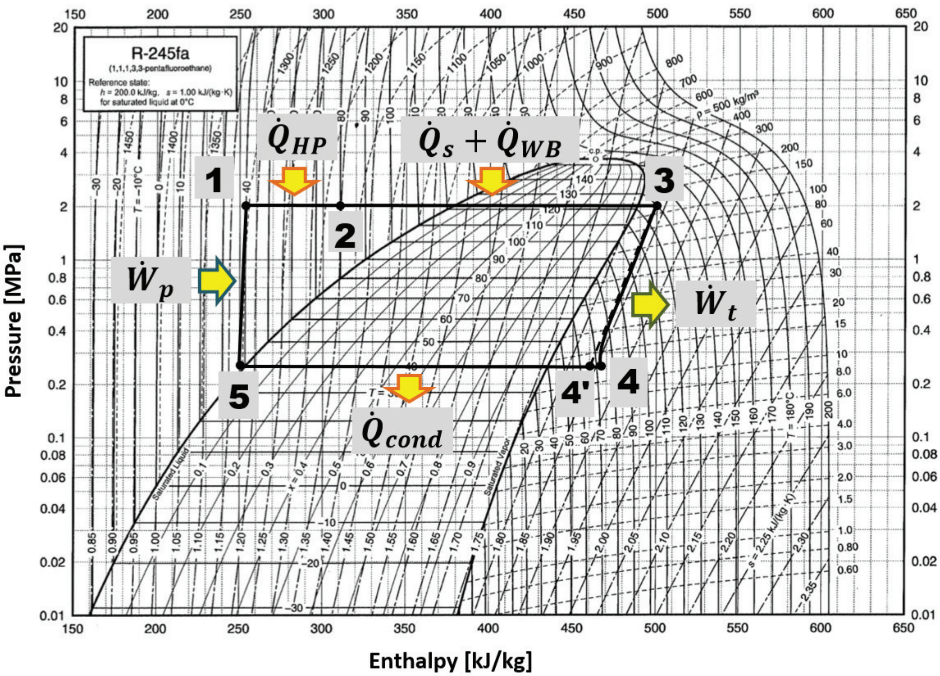

Figure 2: *p-h diagram R245fa*

The input data was provided by two geothermal wells in the area of Topolšica (Šalek Valley, Slovenia). The total average geothermal water flow from the two wells is 50 l/s and the maximum temperature 40 °C, *[8].* The collected input data for the ORC system is indicated in Table 1.

Table 1: *Data for the ORC system calculation*

Parameter	Value	Parameter	Value
$c_{p,w}$, $c_{p,geo}$	4.18 kJ/kgK	H	3.4 kWh/kg
G	1,250 kWh/m²	ΔT_{geo}	8 K
h_1	255 kJ/kg	ΔT_w	8 K
h_2	310 kJ/kg	$\dot{V}_{geo}$	50 l/s
h_3	500 kJ/kg	η_b , η_t	0.8
h_4	468 kJ/kg	ρ_{geo}	1,250 kg/m³
h_5	250 kJ/kg	ρ_{wm}	1,350 kg/m³

Before carrying out the ORC system calculation, the calculation of the heat pump has to be provided. The result of the heat pump calculation is used as the input data for the calculation of the ORC process indicated below.

The geothermal water temperature is too low to enter the ORC system and, therefore, it has to be heated. We decided to install a heat pump using R134a as a working medium. The Solvay program was used for the calculation of the heat pump performance. Table 2 contains the input parameters, output parameters, and results of the calculation. Figure 3 illustrates the p-h diagram of the heat pump, *[7].*

Table 2: *Heat pump parameters*

Element, parameter	Value
Evaporator	T = 30 °C, superheating 5 K, $\dot{Q}_{geo}$ = 2,090 kW
Condenser	T = 90 °C, subcooling 0 K, $\dot{Q}_{HP}$ = 3,040 kW
R134a mass flow	$\dot{m}_{R134a}$ = 27.22 kg/s
Point A (see Figure 3)	p = 7.7 bar, T = 35 °C, h = 419.88 kJ/kg, s = 1.7311 kJ/kgK
Point B (see Figure 3)	p = 32.44 bar, T = 104.33 °C, h = 454.52 kJ/kg, s = 1.7449 kJ/kgK
Point C (see Figure 3)	p = 32.44 bar, T = 90 °C, h = 343.08 kJ/kg, s = 1.4391 kJ/kgK
Point D (see Figure 3)	p = 7.7 bar, T = 30 °C, h = 343.08 kJ/kg, s = 1.4775 kJ/kgK
Compressor efficiency	85%
Compressor power	$\dot{W}_{HP}$ = 943 kW

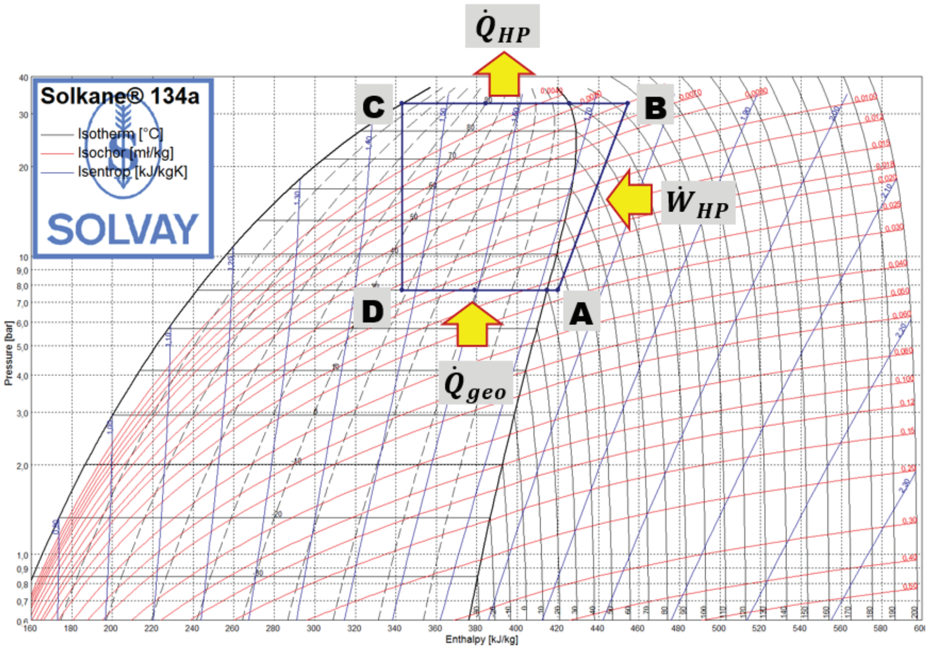

Figure 3: *p-h diagram R134a*

4 THERMODYNAMIC AND ECONOMIC CALCULATION

The following equation was used to calculate the geothermal water heat flow:

$$\dot{Q}_{geo} = \dot{V}_{geo} \cdot \rho_{geo} \cdot c_{p,geo} \cdot \Delta T_{geo} \tag{4.1}$$

This heat flow enters the heat pump in order to heat R134a in the heat pump evaporator and R134a then heats R245fa (see Figure 1). Examining the diagram in Figure 2, we calculated how much heat flow was required from the heat pump working medium to change State 1 to State 2. For further calculation, Equation 4.2 is used:

$$\dot{Q}_{HP} = \dot{Q}_{wm} \tag{4.2}$$

It was assumed that the total heat flow was transferred to the R245fa working medium – heat exchangers have the efficiency of 100%. Equation 4.3 is used to calculate the working medium mass flow.

$$\dot{m}_{wm} = \frac{\dot{Q}_{wm}}{h_2 - h_5} \tag{4.3}$$

In the next step, we will calculate how much additional heat flow is required to heat R245fa to the desired 130 °C (see Figure 2). The additional heat flow is divided into two components: the heat flow from the solar subsystem and the heat flow from the wood biomass subsystem, as can be described by Equation 4.4:

$$\dot{Q}_{add} = \dot{Q}_s + \dot{Q}_{WB} \tag{4.4}$$

The value of the additional heat flow to reach State 3 (see Figure 2) will be calculated by using Equation 4.5:

$$\dot{Q}_{add} = \dot{m}_{wm} \cdot (h_3 - h_2) \tag{4.5}$$

Furthermore, Equation 4.5 will be used to calculate the turbine power by using enthalpies in States 3 and 4 rather than enthalpies in States 2 and 3 (see Figure 2). When calculating the turbine power, the isentropic efficiency of 80% has to be taken into account, *[4].*

A similar calculation is made for the condenser heat flow. The enthalpy difference used in Equation 4.5, is now the difference between States 4 and 5 (see Figure 2), *[7].*

The next step is the calculation of the water mass flow by taking into consideration the equality as in Equation 4.2; nevertheless, the water heat flow is now equal to the ORC system condenser heat flow. Equation 4.6 is used to calculate the water heat flow:

$$\dot{Q}_w = \dot{m}_w \cdot c_{p,w} \cdot \Delta T_w \tag{4.6}$$

Water mass flow may be calculated according to Equation 4.3 by taking the values and data for water.

The necessary pump power to raise the pressure from 2.5 to 20 bar is calculated according to Equation 4.5 by using, however, the enthalpy difference between States 1 and 5 (see Figure 2).

The COP number of the heat pump will be calculated using Equation 4.7.

$$COP = \frac{\dot{Q}_{HP}}{\dot{W}_{HP}} \tag{4.7}$$

Finally, the ORC system thermodynamic efficiency is calculated according to Equation 4.8:

$$\eta_{TD} = \frac{\dot{W}_t - \dot{W}_p}{\dot{Q}_{HP} + \dot{Q}_{add}} \tag{4.8}$$

Furthermore, the system contains a solar subsystem. Various parabolic trough solar collectors are used, more specifically the PTMx-36 model manufactured by Soltigua. The value of solar irradiation on a horizontal surface (G) in the area of the potential site is taken as the input data. The basis for the calculation using all the equations required to calculate the solar subsystem complies with *[9].*

The wood biomass system starts operating as soon as solar irradiation is insufficient for the operation of the solar subsystem. From the data and parameters, it is possible to calculate how much heat can be obtained annually from the solar subsystem, whereas the remaining amount of the total annual heat needed must be obtained from the wood biomass system. On the basis of the required amount of heat from wood biomass, we can calculate the quantity of wood chips needed per year for such a system; see Equation 4.9.

$$m_{wch} = \frac{Q_{WB}}{H \cdot \eta_b} \tag{4.9}$$

An economic analysis of the ORC process will also be carried out. In order to calculate certain economic indicators, the input data selected on the basis of experience, by the companies, according to the laws and guidelines in Slovenia, is needed.

The estimate of revenues and expenditure was made on the basis of initial investment costs, operating costs and maintenance costs, as well as potential revenues and the revenues arising from energy savings.

The initial investment costs were divided into funding investment, construction work, equipment with installation, and unforeseen work.

Funding investment is divided into costs for land and costs for documentation and engineering. The costs for land are assessed on the basis of previous experience, namely €5/m², whereas the costs for documentation and engineering work are assessed to 2% of the costs for solar collectors and 7% of the costs for the other equipment. The construction costs are divided into the costs of geological surveys, costs of well excavation, costs of soil preparation and costs of the facility and ancillary buildings. The costs of equipment and installations are mainly estimated on the basis of previous experience with certain data provided by manufacturers (Siemens, Hurst Boiler Inc., Soltigua). Regarding unforeseen work, the costs are assessed to 5% of the costs of equipment and installations.

The operating costs comprise all the data on the disbursements foreseen for the purchase of goods and services, which are not of an investment nature since they are consumed within each accounting period. The operating costs are divided into direct costs of production, administrative and general costs, as well as expenses arising from sales and distribution. The direct costs of production are divided into the costs of wood chips, estimated at €75/t (since a large quantity of wood chips is required, a 25% discount may also be taken into consideration), and the geothermal water consumption costs. Administrative and general expenses are estimated at 8% of staff costs. Costs of sales and distribution, however, are divided into staff costs, i.e. costs of salaries for four full-time employees and power distribution costs. Maintenance costs are estimated at 5% of investment costs.

The revenues are estimated according to the price of power generated from renewables, in particular from geothermal energy, for medium-sized units in Slovenia. The estimated useful life of a power plant taken into consideration was 25 years.

The revenues arising from energy saving are estimated in accordance with the price of CO_2 coupons, given that wood biomass may be regarded as CO_2 neutral. For the sake of comparison, lignite was taken instead of wood chips.

All the values described above are summarised in Table 3, *[7].*

Table 3: *Economic parameters*

Investment costs		
Category		Costs (€)
Funding investment	Land	525,990
	Documentation and engineering	632,572
Construction	Geological research	150,000
	Soil preparation	500,000
	Wellbore	1,300,000

	Building and supply buildings	100,000
Equipment with installation	Heat pump	2,081,230
	Pumps	199,925
	Heat exchangers	377,086
	Steam turbine	600,000
	Biomass boiler	1,203,218
	Solar collectors	11,726,000
	Pipelines and tubes	1,225,000
Unforeseen work		870,623
Operating and maintenance costs		
Category		Costs (€) per year
Direct production costs	Wood chips	1,032,304
	Geothermal water consumption	40,000
Administrative and general expenditures		7,520
Sales and distribution expenditures	Staff costs	94,000
	Distribution expenditures	350,000
Maintenance costs		1,074,582
Revenues and energy savings		
Category		€ per year
Energy savings		134,426
Category		Revenues (€)
Total revenues in 25 years of operation		26,503,716

5 RESULTS

The geothermal water inlet temperature is very low (40 °C), and it had to be preheated in a heat pump. The geothermal water heat flow that heated R134a in the heat pump amounts to 2,090 kW. As a result, the ORC system inlet heat flow amounts to 3,040 kW. This heat flow directly defines the mass flow of the ORC system working medium (R245fa), which is 55.27 kg/s. The desired turbine inlet temperature was 130 °C, which means that a large amount of additional heat flow has to be supplied to the system from the solar subsystem chosen as the first option. The quantity of additional heat flow is 10,501.3 kW. If the solar subsystem is not capable of producing such heat flow (depending on solar irradiation and weather conditions), R245fa as the working medium will be additionally heated in the wood biomass subsystem so as to finally reach 130 °C. The expansion of R245fa occurs in the turbine to a state of 2.5 bars and 73 °C in the range of overheated vapour (see Figure 2). Considering Figure 1, the working medium has to get to State 5 in which it enters the pump. It reaches State 5 by passing through the condenser in which it moves through a mixed area to the liquid phase. In the condenser, 12,048.9 kW of heat flow is removed from the water. The water used as a refrigerant must have its inlet temperature lower than the outlet temperature of the working medium in State 5. The water inlet temperature is 15 °C and outlet temperature 23 °C, which means that a relatively high water mass flow is required: 390.3 kg/s. The necessary power of the pump in the ORC system is 276.35 kW.

The total input heat flow is 13,541.3 kW, of which 22.45% from the heat pump and 77.55% is from additional sources. In the condenser, 12,048.9 kW of heat flow is released. Electrical power generated from the ORC system amounts to 1,768.64 kW, with 15.63% (276.35 kW) of it consumed by the pump and, therefore, the net recovered electrical power amounts to 1,492.3 kW. Another option is that the pump takes the power for its operation from the grid. Thermal efficiency is the ratio between the net generated power and the invested heat flow; it amounts to 11.02%. Figure 4 shows the power flows in the ORC system. The COP of a heat pump as the ratio of heat output to the amount of energy input of a heat pump amounts to 3.22.

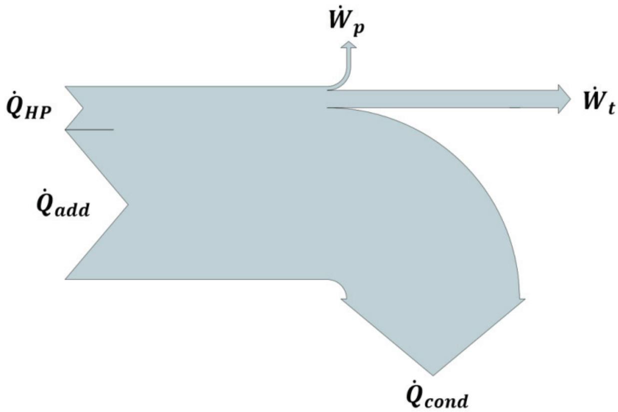

Figure 4: *ORC system power flow diagram*

To provide additional heating of the R245fa working medium in the ORC system, 10,501.3 kW of heat flow is needed. This is a rather large amount of heat and as a consequence, 286 units of PTMx-36 solar collectors are needed and approximately 5.5 hectares of land for their installation. The solar subsystem calculation was made on the basis of a fixed solar irradiation value. However, we know that the amount of solar irradiation changes throughout the day and, therefore, another subsystem is installed in the ORC system, i.e. the wood biomass system, which in our case requires quite a large quantity of wood chips per year. Since we know that we need approximately 10.5 MW of additional heat flow, we need 18,434 tons of wood chips per year for this purpose. The wood biomass system would operate mostly in winter and at night, when there are low levels of solar irradiation or none at all. All the above-described calculated values are indicated in Table 4.

Table 4: *Calculation results*

Parameter	Value	Parameter	Value
$\dot{m}_w$	390.3 kg/s	$\dot{Q}_{HP}$	3,040 kW
m_{wch}	18,434 t	Q_s	23,452 MWh
$\dot{m}_{wm}$	55.27 kg/s	Q_{WB}	50,141 MWh

N	286	S	55,198 m²
Q	73,593 MWh	$\dot{W}_p$	276.35 kW
$\dot{Q}_{add}$	10,501.3 kW	$\dot{W}_t$	1,768.64 kW
$\dot{Q}_{cond}$, $\dot{Q}_w$	12,048.9 kW	η_{TD}	0.1102
$\dot{Q}_{geo}$	2,090 kW	COP	3.22

The results of the economic analysis are not encouraging since the costs exceed the revenues. The investment was estimated at €21,491,644. The funding of the system with the estimated lifetime of 25 years would be provided through own sources. The cash flow plan was calculated on the basis of the estimated expenses and revenues (see Table 3). The ORC system has a negative cumulative cash flow, as shown in the diagram in Figure 5. Figure 5 shows a negative range throughout the diagram. By the 10th year of the operation, the slope of the graph is slightly less steep, because higher state subsidies for power production from renewables were taken into consideration. After the 10th year of the operation, however, the slope of the graph is even steeper, which means that a 100% return on investment cannot be expected due to the fact that the revenues are too low in relation to the current expenditure or in other words: the annual revenues fail to reach or exceed the annual revenues resulting in losses increasing one year after another.

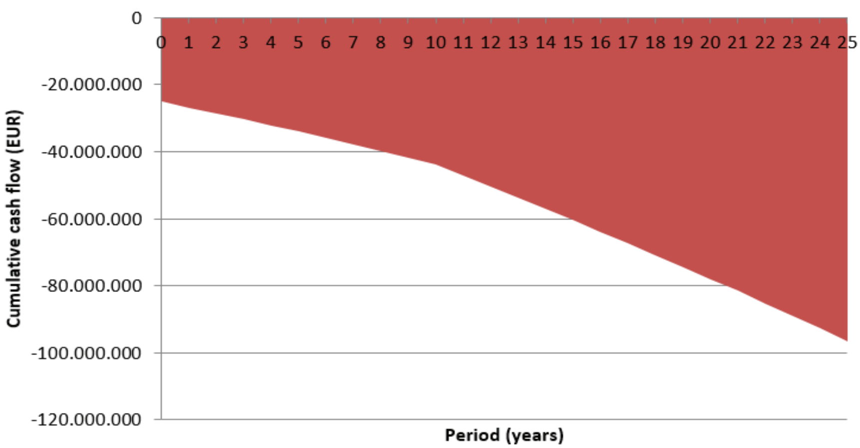

Figure 5: *Cumulative investment cash flow*

6 CONCLUSION

Currently, the use of RES is strongly encouraged. One of the options for their use is described in this paper: a system using three different renewable energy sources in combination with a heat pump. The temperature of the geothermal water from a wellbore, taken as the input data, is too low and had to be heated in a heat pump. The total input heat flow into the ORC process from the heat pump amounts to 22.45%, which is much more than if connecting the heat from geothermal water directly to the ORC process. However, we know that the temperature increases with the depth of the well, so it would probably make sense to choose a deeper well. The ORC system was modelled solely for electricity production and as a result, a considerable amount of additional heat flow had to be brought into the system from the solar subsystem and, consequently, many solar collectors are needed. If the desired amount of heat flow is not provided by the solar subsystem, a wood biomass subsystem is used to ensure the same required amount of additional heat flow. This system is not economically feasible. The ORC system with recuperation would be much more feasible, or geothermal water with such temperature would be used for heating and cooling systems. This paper presents an example of electrical energy production from a very low-enthalpy geothermal source in combination with other renewable energy sources and a heat pump. From an environmental aspect and, in view of the consequences of global warming, the use of these sources of energy will be crucial for electricity production in the near future.

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Nomenclature

(Symbols)	(Symbol meaning)
c_p	Specific heat capacity [kJ/kgK]
G	Solar irradiation [kWh/m^2]
h	Specific enthalpy [kJ/kg]
H	Heating value [kWh/kg]
$\dot{m}$	Mass flow [kg/s]
N	Number of collectors [-]
p	Pressure [bar], [Pa]
Q	Heat [kWh]
$\dot{Q}$	Heat flow [kW]
s	Specific entropy [kJ/kgK]
S	Surface area [m^2]
T	Temperature [°C], [K]
ΔT	Temperature difference [K]
V1, V2	Valves
$\dot{V}$	Volume flow [m^3/s]
$\dot{W}$	Power [kW]
η	Efficiency [-]
ρ	Density [kg/m^3]
(Subscripts)	(Subscript meaning)
add	Additional
b	Boiler
cond	Condenser
geo	Geothermal
HP	Heat pump
p	Pump
s	Solar
t	Turbine
TD	Thermodynamic

w	Water
WB	Wood biomass
wch	Wood chips
wm	Working medium
(Abbreviations)	(Abbreviation meaning)
COP	Coefficient of performance
ORC	Organic Rankine cycle
RES	Renewable energy source(s)