The usage of shallow groundwater heat by heat pumps in a high-temperature district heating system

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The general tendency in district heating (DH) is the lowering of grid temperatures. To achieve this, heat pumps (HPs) are necessary technology that has an important role in very low (below 60 ºC) and ultra-low (below 45 ºC) DH supply temperatures. A significant variation in outdoor temperatures during the heating season in the climate of Serbia makes the implementation of HPs in the high-temperature DH systems possible. The goal of the paper is to analyze the implementation of HPs that extract heat from the shallow groundwater to satisfy a part of heat requirements in a boiler room of a DH system. This is a superheated water system with a nominal capacity of 37.728 MW and a nominal temperature regime 130/75ºC that belongs to the PUC Toplana in Kraljevo. The city is placed at an alluvial plane rich with shallow groundwater with temperatures in the range of 12 to 18ºC. The analysis is carried with two operating modes: (i) present, with an everyday stoppage between 9 PM and 5 AM, and (ii) continuous operation with limited overnight heating. Not to endanger the inflow, the maximal extraction of the heat from groundwater of 755 kW was assumed. The present operating mode would have seasonal COP 3.87 and negative economic indicators, whereas the continuous operation would lead to a sustainable project with a financial rate of return of 10.5%, benefit-cost ratio of 1.192, and the reduction of CO_2 emissions of 201 t/year. The seasonal COP of the HPs would be 4.29.

Keywords: district heating, water source heat pumps, shallow groundwater, cost-benefit analysis

1. INTRODUCTION

In the second decade of the XXI century, Lund et al. [1] defined the 4th generation of the DH systems. The tendency in the development of the DH systems is the lowering of supply and return temperatures and integration of cogeneration and trigeneration systems, renewable energy sources, and heat pumps (HPs). Actually, from the beginning of the DH development, the general tendency is the lowering of supply and return temperatures. This is in accordance with the 2nd law of thermodynamics. In the past few years, a new concept of the development of DH systems emerged. It is called the 5h generation of DH systems and represents a thermal energy supply grid that uses water or brine as a carrier medium and hybrid substations with water source heat pumps (WSHP) [2]. These systems use ultra-low temperature regimes. In these emerging DH systems HPs are the key technologies because [3]:

- they can act as a balancing technology when electrical production fluctuates.
- HPs phase out fossil fuels from the energy system.
- HPs make it possible to use very low (below 60 °C) and ultra-low (below 45°C) temperatures in the district heating grid.
- HPs make it possible to minimize grid losses in the district heating grid.

The subject of the paper is an existing DH system with superheated water with a nominal temperature regime 130/75ºC and a nominal capacity of 37.728 MW in the "Nova kolonija" boiler room. For this class of the systems, the analyzed DH system is very efficient and belongs to the PUC Toplana in Kraljevo, Serbia. Although the temperature regime does not favor WSHPs, their usage is possible because of a significant variation in outdoor temperatures during the heating season. The climate is characterized by several cold waves during the winter, whereas during the rest of the heating season mild weather suitable for the implementation of WSHPs prevails.

The goal of the paper is to analyze the implementation of WSHPs that extract heat from the shallow groundwater to satisfy a part of heat requirements in a boiler room of a DH system. The paper should answer: (i) what should be the capacity of the WSHPs, (ii) should the DH company change its operational schedule, and (iii) is the implementation of the WSHPs economically beneficial for the DH company? The city is placed at an alluvial plane rich with shallow groundwater [4] with temperatures in the range of 12 to 18ºC. The boiler room "Nova kolonija" has an excellent position suitable for shallow groundwater usage.

To investigate the impact of the temperature regimes and the electricity tariff system, the analysis is carried with two operating modes: (i) present, with an everyday stoppage between 9 PM and 5 AM, and (ii) continuous operation with limited overnight heating. In the second operational mode, only 15% of the nominal load is supplied in the period between 9 PM and 5 AM and the supply temperatures do not exceed 50 ºC. Low electricity tariffs in this period as well as low temperatures should support the usage of HPs. As a basis for decision-making, a cost-benefit analysis (CBA) of the analyzed system is performed.

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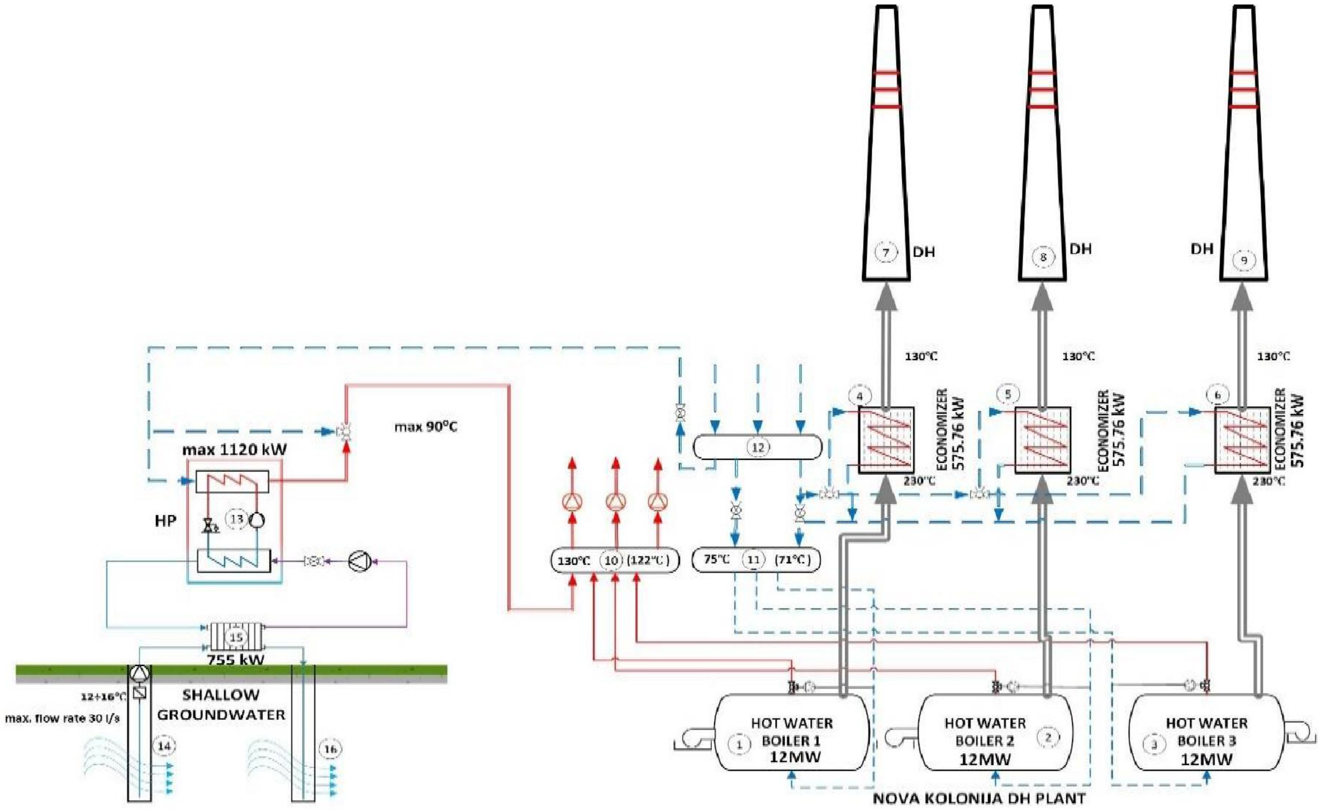

Figure 1: Integration of the groundwater HPs (13) into the “Nova kolonija” plant. Shallow groundwater (14÷16) is the heat source for HPs (13), which work in parallel with the boilers (1÷3) whenever their work is financially profitable. In the figure: 1 ÷ 3- hot water (superheated water) boilers, 4÷6 economizers, 7÷9 – each boiler has its chimney, 10 - supply manifold, 11- return manifold (2nd stage), 12 – return manifold (1st stage), 13 – heat pump(s), 14 – supply well, 15 – plate heat exchanger, 16 – return well.

Figure 1 shows a simplified scheme of the analyzed system. The system utilizes shallow groundwater (14÷16 in Fig. 1) as the heat source for the HPs (13) to supply a part of the required heat in the DH plant “Nova kolonija”. The figure is simplified and shows the parallel connection of the boilers and the HPs. In practice, by a proper design, both series and parallel connections would be used. Additionally, safety and expansion equipment as well as many other details regarding valves, air separators, etc., are omitted from the figure. The analyzed system is dimensioned to limit the maximal flow of groundwater to 30 l/s. The system has the following features:

- Kraljevo is situated at an alluvial plane rich with shallow groundwaters [4]. The position of the plant suits the exploitation of the shallow groundwater. Based on the study and several conversations with geological engineers a modest flow rate of 30 l/s for the location is taken in the analysis. Figure 2. shows the location of the DH plant as well as the potential area for the wells.
- The system should work only when the plant operates, i.e., 180 days per year.
- Depending on the water quality, which has not been analyzed, the direct heat exchange in HPs (13) or with an indirect circuit (as in Figure 1.) would be used.
- Two variants (case studies) are analyzed. They depend on the operational mode of the DH company and are: 1. operation as usual, i.e., from 5 AM to 9 PM, and 2. continuous operation with limited overnight heating.
- The HPs have been implemented in many DH companies, especially in Scandinavian countries because of the low-temperature regimes [5].

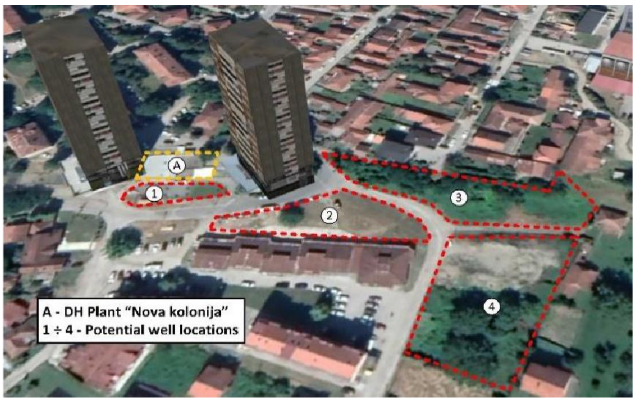

Figure 2: The locations of the “Nova kolonija” DH plant together with the potential locations for the wells.

2. METHODOLOGY

The main points of the methodology sequentially applied are:

- Meteorological data. The energy calculations in the study were performed for the average meteorological days during the heating season. The data were taken from the Republic Hydrometeorological Service of Serbia for the period 1990-2010 [6].

- Heat requirement and production. The heat produced in the "Nova kolonija" plant was simulated on the average meteorological days for each month during the heating season [6]. The daily variation of temperature was obtained by the average temperatures at 7 AM, 2 PM, and 9 PM. The data regarding the performance of the DH system were provided by the company PUC Toplana. It was assumed that the temperature of the shallow groundwater changes in the range from 13°C during the winter to 15°C during the summer months.
- Sizing and performance of the HP(s). The HP efficiency is averaged from the available data provided by the manufacturers and was determined based on the previously explained temperature profiles. Constant heat extraction from the groundwater of 755 kW and the maximum heat delivery to the DH system at 85ºC of 1120 kW were assumed [7].
- Cost-benefit analysis is carried by the Guide to Cost-Benefit Analysis of Investment Projects [8].
- The same methodology is applied to two variants. The continuous work was taken because it favors the electricity usage by HPs during the low electricity tariffs.

3. METEOROLOGICAL DATA AND PERFORMANCE OF THE DH SYSTEM

3.1 Meteorological data and heating requirements

The energy calculations in the study were performed for the average meteorological days during the heating season [6]. The average monthly days with their temperature profiles that are shown in Figure 3 were used in the study.

The temperature profiles were then used to calculate supply and return temperatures in the DH system. Figure 4. shows the temperature profiles for the DH system for the present mode of operation whereas Figure 5 shows the daily temperature profiles for the continuous mode of operation with limited overnight heating obtained by the usage of data provided by Todorović [9]. The continuous mode of operation estimates around a 5% reduction in the energy usage for DH heating. The average overnight supply and return temperatures are shown in Table . Based on measurements provided by the PUC Toplana, and by assuming linear dependence between the heating requirements and outdoor temperature the required thermal energy necessary to fulfill the requirements of all consumers of the "Nova kolonija" plant is:

$$Q[kW] = -555.5 \cdot t + 11110, \qquad (1)$$

where t is the outdoor temperature [°C].

For the average meteorological data, the previous equations give the thermal energy needs that are shown in Table 1.

Table 1: Heating requirements for the hospital and the DH company.

The energy required for DH heating in the "Nova kolonija" plant [kWh/day] – with an overnight stoppage of operation							
	January	February	March	April	October	November	December
	165283	146427	92259	40637	37386	112714	155834
The energy required for DH heating in the "Nova kolonija" plant [kWh/day] – continuous heating							
05-20	136318	120089	72352	29551	27654	91935	128977
20-05	19882	18291	14837	8853	7677	14585	18293

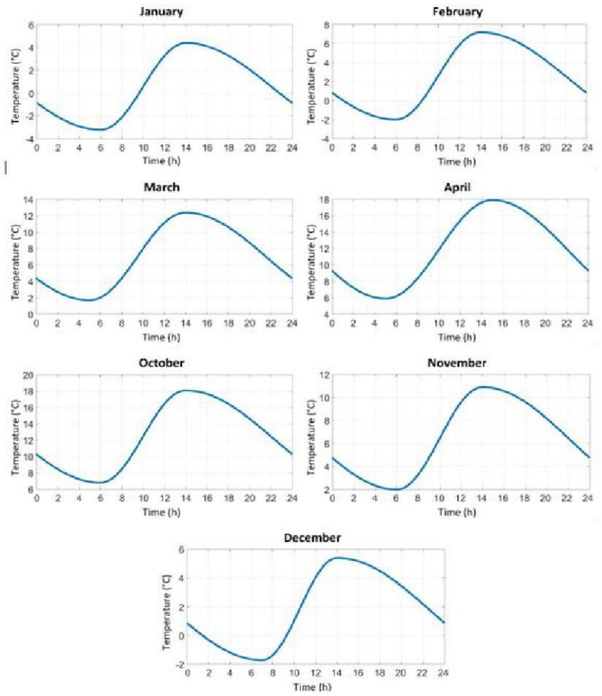

Figure 3: Temperature profiles for the average days during the heating season in Kraljevo.

Figures 4 and 5 show the temperature profiles that fulfill heating requirements on the average days in the DH company from the "Nova kolonija" plant.

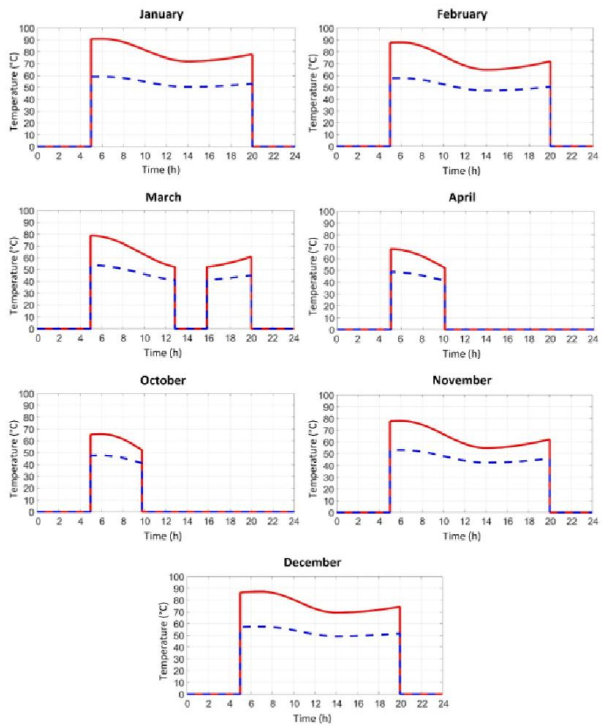

Figure 4: Temperature profiles (supply and return lines) in the DH system for the average month days. The present mode of operation (overnight stoppage).

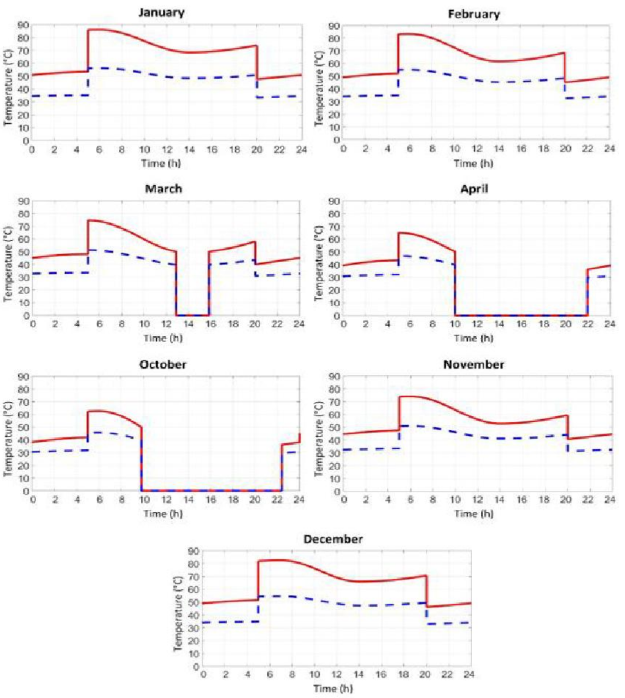

Figure 5: The daily temperature profiles (supply and return lines) in the DH system for the average month days for the continuous mode of operation with limited overnight heating.

3.2 HP efficiency

The efficiency of the HP was calculated based on the data provided by HP manufacturers [10] and the fact that the HP efficiency is between 0.5 and 0.6 of the Carnot cycle [11]. The HP efficiency was determined by:

$$COP = 0.618 \cdot \frac{(T_{H-SINK} + 5)}{(T_{H-SINK} - T_{EVAPORATION} + 10)}, \quad (2)$$

where: COP [-] is the heat pump efficiency, T_{H-SINK} in [K] the highest temperature of the heat sink at an instant, in this case, DH water, $T_{EVAPORATION}$ in [K] is the temperature of evaporation. In our case, the temperature is in the range of 306 to 310 K.

4. ENERGY BALANCES

Table 2. shows the basic data for the energy and CBA analyses, whereas in the rest of the heading energy balances are presented for both variants of the project. All calculations in this section were done based on the average monthly temperatures.

Table 2: The basic data for the study.

The average emissions of CO_2 from the natural gas combustion	1.9	[kg/m³]
The average emissions of CO_2 from the natural gas combustion	9.564	[kWh/m³]
Fuel unit cost for the DH company	0.344	[€/m³]
Fuel unit cost for the DH company	0.036	[€/kWh]
Higher daily tariff for electricity	0.0899	[€/kWh]
Lower night tariff for electricity	0.0517	[€/kWh]
Thermal energy cost from DH system	0.04	[€/kWh]
Thermal power of NG fired hot water boilers in "Nova kolonija" plant	3 x (12+0.575)	[MW]
The efficiency of the DH boilers	95.13%	[%]

In Table 2, the values for average emissions of CO2 are taken from the literature [13], fuel unit cost was provided by PUC Toplana, Kraljevo. The electricity price for the higher daily tariff was calculated from the electricity bill for January 2021. All prices exclude VAT and the taxes for overconsumption and renewable energy. Similarly, the electricity price for the lower night tariff was calculated. The thermal power of natural-gas-fired hot water boilers in the "Nova kolonija" plant and their efficiencies were based on the data provided by the manufacturer Buderus.

4.1 Variant 1 – the present mode of operation (overnight stoppage).

Tables 3 and 4 show the energy balance and the main outcomes of the proposed project.

Table 3: Energy balance of the analyzed system in the present mode of operation (overnight stoppage).

Month	Temperature regime [°C]	Groundwater temperature [°C]	COP	Thermal power from underground water P_{ugw} [kW]	Heat delivered to DH [kW]	Electricity consumption HP [kWh]	Electricity consumption circulation pumps [kWh]	Total electricity consumption [kWh]
January	82.3/55.3	12.5	2.8	755	508653	134173	9123	143296
February	77.3/53.1	12	2.9	755	454192	115952	8240	124192
March	65.8/47.8	12	3.3	755	486902	112422	9123	121546
April	52.7/41.3	12	4.0	755	301506	59906	5886	65792
October	52.7/41.3	14	4.2	755	164529	31649	3237	34886
November	67.9/48.7	13.5	3.3	755	471503	109103	8829	117932
December	79.1/53.9	12.5	2.9	755	504360	129880	9123	139004
				TOTAL	2891645	693085		746648
					COPs	4.17		3.87

The temperature regime shown in Table 3 is the average value from Figure 4. COP is determined by Eq. (4), and the heat delivered by the HP $Q_{delivered}$ [kWh] is calculated by

$$Q_{delivered} = Q_{SGW} + \frac{Q_{SGW}}{COP}, \quad (3)$$

where Q_{SGW} in [kWh] is the heat extracted from shallow groundwater, and COP is calculated based on the temperature regimes and Eq. (2).

Electricity consumption is used for HPs and water circulation. Electricity consumption by HPs is $Q_{delivered}/COP$. The electricity consumption by water circulation pumps was calculated based on the following data:

- volume flow rate 30 l/s,
- total head 30 m,
- pump efficiency 48% (motor + impeller),
- 16 hours per day.

The electricity consumption for water pumping is not negligible as it accounts for 7.2% of the total electricity consumption. The energy required for water circulation reduces the seasonal COP by 0.3.

Table 4 shows that the majority of electricity is consumed during the high tariffs (between 7 AM and 10 PM).

Table 4: Electricity consumption and cost.

	Tariff	Electricity for the HPs [kWh]	Electricity cost [€]
January	HT	125384	11274
	LT	17912	926
February	HT	108668	9771
	LT	15524	802
March	HT	106352	9563
	LT	15193	785
April	HT	57568	5176
	LT	8224	425
October	HT	30525	2745
	LT	4361	225
November	HT	103191	9279
	LT	14742	762
December	HT	121628	10937
	LT	17375	898
TOTAL		**746648**	**63569**

The following table shows the financial and ecological benefits of the project, which improves energy efficiency, reduces natural gas (NG) consumption, and increases electricity consumption. The increase in electricity consumption and the cost of electricity reduce the benefits of the project.

Table 5: The outcomes of the project.

NG reduction due to the use of HPs	317825	m^3/year
Cost reduction due to the decrease in NG consumption	109213	€/year
Increase in electricity consumption	746648	kWh/year
Cost of the additional electricity	63569	€/year
CO_2 reduction due to the NG reduction	604	t/year
CO_2 increase due to the additional electricity consumption	515	t/year
Net CO_2 reduction	**89**	**t/year**

4.2 Variant 2 – the continuous operation with limited overnight heating.

Tables 5-8 show the main outcomes for this variant. Compared with variant 1, the DH system operates in a lower temperature regime. In addition, overnight temperature regimes are lower and suitable for HP usage. Compared with variant 1: (i) the seasonal COP is larger because of the lower temperature regimes, (ii) water pumping is more influential to the seasonal COP, and (iii) there is substantial electricity usage during the low tariffs.

Table 6: Energy balance of variant 2 of the project.

Month	Temp. regime [°C]	Groundwater temperature [°C]	COP	Thermal power from underground water P_{ugw} [kW]	Heat delivered to DH [kW]	Electricity consumption by HP [kWh]	Electricity consumption circulation pumps [kWh]	Total electricity consumption [kWh]
January	78/52.8	12.5	2.9	755.0	502944	128464	9123	137588
	49.7/34.2	12.5	4.3	755.0	230858	43618	4866	48483
February	73.4/50.8	12	3.0	755.0	449354	111114	8240	119355
	47.4/33.5	12	4.4	755.0	207299	38179	4395	42574
March	62.7/45.9	12	3.5	755.0	482422	107942	9123	117065
	42.2/31.8	12	4.9	755.0	225294	38054	4866	42919
April	50.6/39.9	12	4.2	755.0	299371	57771	5886	63657
	36.4/29.8	12	5.7	755.0	142168	21368	3139	24507
October	50.6/39.9	14	4.4	755.0	163346	30466	3237	33703
	36.4/29.8	14	6.0	755.0	77509	11069	1727	12795
November	64.6/46.8	13.5	3.5	755.0	466982	104582	8829	113411
	433.2/32.1	13.5	5.0	755.0	217397	36197	4709	40906
December	75/51.5	12.5	3.0	755.0	498872	124392	9123	133515
	48.2/33.7	12.5	4.4	755.0	229684	42444	4866	47309
				TOTAL	**4193498**	**895658**		**977788**
					COPs	**4.68**		**4.29**

Table 7: Electricity consumption and cost for variant 2.

	Tariff	Electricity for the HPs [kWh]	Electricity cost [€]
January	HT	126450	11370
	LT	59621	3082
February	HT	109757	9869
	LT	52172	2697
March	HT	107797	9693
	LT	52187	2698
April	HT	58763	5284
	LT	29401	1520
October	HT	31090	2796
	LT	15409	797
November	HT	104347	9383
	LT	49969	2583
December	HT	122740	11036
	LT	58085	3003
TOTAL		**977788**	**75809**

The following table shows the financial and ecological benefits of variant 2 of the project. Compared with variant 1, the NG reduction is almost 50% larger, whereas the electricity cost is only 19.2% larger.

Table 8: The outcomes of variant 2 of the project.

NG reduction due to the use of HPs	460913	m^3/year
Cost reduction due to the decrease in NG consumption	158381	€/year
Increase in electricity consumption	977788	kWh/year
Cost of the additional electricity	75809	€/year
CO_2 reduction due to the NG reduction	876	t/year
CO_2 increase due to the additional electricity consumption	675	t/year
Net CO_2 reduction	**201**	**t/year**

5. CBA ANALYSIS

The economic advantages and disadvantages of the proposed project were assessed by the CBA carried out following the Guide to Cost-Benefit Analysis of Investment Projects [8].

The main points in the CBA analysis are:

- For this scenario, projections were made of all cash flows related to the operations in the project area for each year during the project lifetime, which was supposed to be 15 years.
- A counterfactual baseline scenario for the project would be the so-called "business as usual", i.e., the usage of hot water (superheated water) boilers with economizers in the DH systems.
- A long-term loan, under the following conditions, is assumed: (i) tenor of up to 12 years including the grace period of 2 years, and (ii) an upfront fee of 1%.
- Analysis was prepared and expressed in EUR, and all figures exclude VAT.
- A 4 % discount rate in real terms is used in the financial calculations, whereas a 2.5 % interest rate is used in the economic analysis.

Two variants of the project were analyzed:

1. present operation mode, i.e., from 5 AM to 9 PM.

2. continuous operation mode with limited overnight heating. Period with limited heating from 9 PM to 5 AM.

- The cost of NG was taken to be as in the heating season 2019/2020. Additionally, the benefit due to the reduced NG cost should rise at a rate of 1.2% per year.
- Unite price for the electricity was assumed to be as in January 2021 and that the price would rise with a 2% rate yearly.
- The depreciation rate of 8% per annum was supposed to calculate the residual value for the equipment.
- The maintenance cost was assumed to be 1.5% of the total investment.
- Environment and climate change considerations were included in the economic analysis.
- The HP costs were obtained by an offer from Viessmann doo Belgrade [7].

Table 9 shows the investment cost of the project. The HPs are the most expensive item that makes 70% of the budget. In this phase of the project, a contingency of 10% was assumed.

Table 9. The investment cost for both variants of the project.

Project investment cost [€]	1	2-14	15
Planning/design fees	20000	0	
Land purchase	0	0	
Machinery and construction:		0	
Heat pumps	403050	0	
Heat exchanger 755 kW	13479		
Wells for shallow underground water+pump+pipelines	22813	0	
Electrical equipment in DH boiler room	12092	0	
Pumps, valves, piping, regulating equipment, automatic control, measuring equipment in the boiler room	30229	0	
Supervision during construction and implementation	16000	0	
Contingency	51776	0	
Residual value		0	-137899
TOTAL	569,428 €		(137,899) €

The financial net present value of investment (FNPV(C)) and the financial rate of return of the investment (FRR(C)) compare investment costs to net revenues and measure the extent to which the project net revenues can repay the investment, regardless of the sources or methods of financing [8]. Table 10 shows their values for both variants of the project. Compared with variant 1, variant 2 has positive financial indicators.

Table 10: The outcome of the CBA analysis for both variants

	Variant 1	Variant 2
Discount rate	4%	4%
FNPV(C)	-105176	290962
FRR(C)	1.4%	10.5%
B/C ratio	0.923	1.192
Social discount rate	5%	5%
ENPV	99,532 €	362,584 €
ERR	2%	14%
B/C ratio	0.92	1.26

Variant 2 of the project is financially sustainable. According to the assumptions made for the analysis, this variant of the project does not have the risk of running out of cash in the future, both during the investment and the operational stages. The cumulated net cash flow is negative only during the construction phase for all other considered years it is greater than zero.

The economic analysis is carried out to appraise the project’s contribution to the welfare [8]. This is the project that improves the energy efficiency of the DH system. The direct benefit of the project is the increase in energy efficiency. This induces two economic benefits and two costs. The two benefits are: (i) lower greenhouse gas emissions due to the reduced usage of natural gas, and (ii) substitution of the natural gas import. Consequently, the two costs are: (i) the usage of HP requires a larger domestic electricity production, which subsequently increases the greenhouse gas emissions.

The benefit from reduced CO_2 emissions is calculated as the net reduction of CO_2 emissions (see **Error! Reference source not found.Error! Reference source not found.**. and 7) multiplied by the unit cost of GHG emissions. The net reduction of CO_2 emissions is calculated as the difference between the decrease in natural gas consumption and the increase in electricity consumption. The equivalent CO_2 emissions for NG are 1.9 kg/m_N^3 whereas the equivalent emissions for the electricity production in the Republic of Serbia are 690 g/kWh. The unit cost of GHG emissions is taken from the Guide to Cost-Benefit Analysis of Investment Projects [8]. The central cost of 25 €/t-CO_{2e} was adopted with an annual adder of 1.

The benefit from the substitution of natural gas import is calculated by the use of the border price for the fuel of 155 \$/1000m^3. The economic cost of additional electricity usage

is calculated by assuming that the production and distribution cost of electricity is 4.8 c€/kWh. The electricity consumptions are shown in is shown in Tables 4 and 6.

Table 10 shows that compared to the financial indicators, the economic indicators are not substantially better because of the additional electricity usage that increases carbon dioxide CO_2 emission and electricity production cost.

6. SENSITIVITY ANALYSIS

To identify the crucial variables of the project, sensitivity analysis was carried out for the implementation of the HPs in the DH plant “Nova kolonija”. Both variants are covered with the analysis. Figure 6 and Figure 7 show the sensitivity analysis for variant 1 of the project. This project is the least sensitive to the variation of the investment cost, whereas it is the most sensitive to the total inflows. Consequently, it is the most sensitive to the number of working hours and the COP of the HPs.

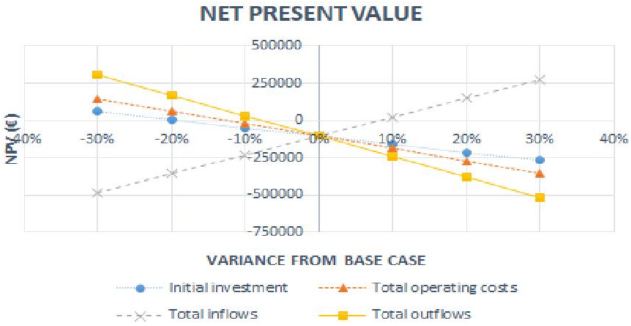

Figure 6: The sensitivity analysis of the net present value for variant 1 of the project.

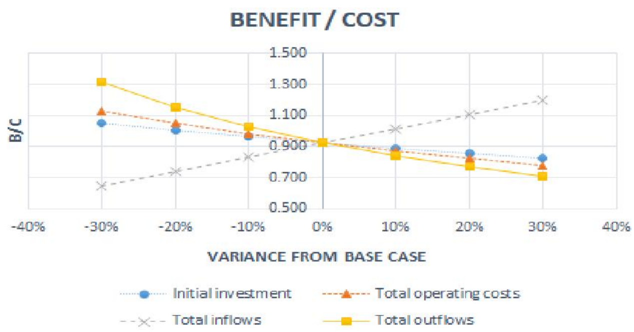

Figure 7: The sensitivity analysis of the BC ratio for variant 1 of the project.

Compared to variant 1, variant 2 of the project has equal sensitivity to the basic project parameters. However, financial and economic indicators for this variant are positive. The project is the most sensitive to total inflows, and consequently to the working hours and COP of the HPs. The second most important parameter of the project is the total outflows and consequently electricity and maintenance cost. The project can tolerate an increase in total outflows of 20%, an increase in the investment cost of over 30%, and a decrease in total outflows of less than 17%.

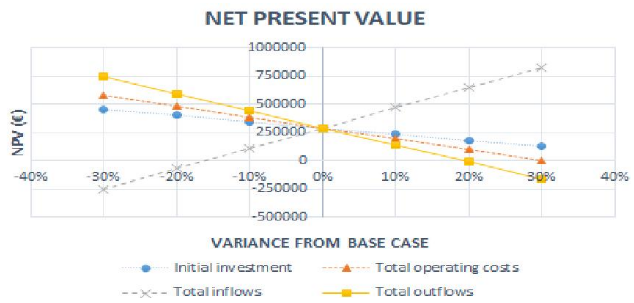

Figure 8: The sensitivity analysis of the net present value for variant 2 of the project.

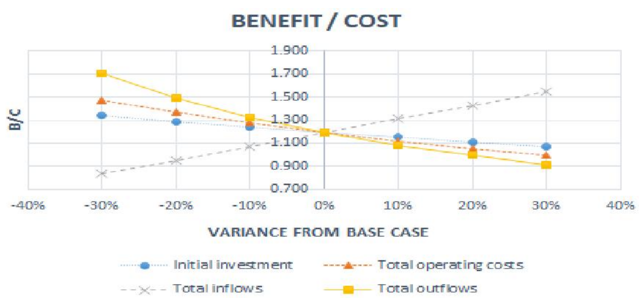

Figure 9: The sensitivity analysis of the BC ratio for variant 2 of the project.

7. CONCLUSIONS

The main conclusions of the study are:

- The analyzed HP system is financially and economically beneficial if the DH system works continuously with limited overnight heating. If the DH system works as in the present mode of operation with the overnight stoppage, it is not financially nor economically beneficial to implement the analyzed HPs.
- The stable operation of the analyzed system requires groundwater flow rates larger than 18 l/s.
- Assuming that the pumping power decreases the COP of the system by 0.3, and with the unit costs of electricity and NG as in Table 2, the HPs should work in the system if the COP is larger than 2.8 and 1.74 during higher and lower electricity tariffs, respectively.
- The project is the most sensitive to the total inflows and outflows during its realization. Compared with them, the project is less dependent on the variations of the total investment cost. Consequently, the operating hours, COP, and electricity cost are the most important variables in the project.
- To be implemented the project requires the transformation from the present to the continuous work with limited overnight heating. Additionally, it requires hydrological examinations and adequate placement of the wells.

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