

Thermodynamic Evaluation and Working Fluid Selection for a Heat Pump Integrated into a Hydropower Plant HVAC System: A Case Study from Serbia

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Abstract *This paper presents a thermodynamic analysis of two types of heat pumps integrated into the heating, ventilation, and air conditioning (HVAC) system of the "Bajina Bašta" hydropower plant located in Serbia. The study aims to replace existing electric boilers with more energy-efficient solutions by utilising renewable heat sources. A comparative evaluation of water source heat pump (WSHP) and air source heat pump (ASHP) configurations was conducted using a custom-developed MATLAB model based on CoolProp data of working fluids. The analysis was supported by real data obtained through in situ measurements of air and water temperatures at the selected location, ensuring accurate input parameters for the simulations. Five refrigerants (R-410A, R-407C, R-134a, R-32, and R-1270) were used, and R-32 was selected as the optimal working fluid because of its high efficiency, moderate flammability, and low environmental impact. The lowest coefficient of performance (COP) for the WSHP was 3.27 in January, while the seasonal coefficient of performance (SCOP) reached 3.36, approximately 15.5 % higher than the ASHP counterpart (SCOP = 2.91). The study confirms that, upon analyzing the entire heating period, WSHP systems are technically and environmentally superior to ASHPs in the locations studied. The proposed configuration, based on real measured data and obtained results, can significantly improve energy efficiency and reduce internal electricity consumption in hydropower plants, thereby supporting the decarbonisation of large-scale renewable energy facilities. While most previous studies have focused on improving energy efficiency in buildings, this work demonstrates the substantial yet underexplored potential for efficiency improvements in the electricity production sector in Serbia. The study specifically examines hydropower plants in Serbia, where heating and air conditioning systems built in the 1960s remain highly energy inefficient. By quantifying the benefits of integrating WSHP and ASHP systems, the research highlights a pathway toward significantly enhancing the energy efficiency of hydropower infrastructures.*

Keywords *hydropower plant, heat pump, energy efficiency, COP, SCOP*

Highlights

- *A thermodynamic model, supported by in situ river and air temperature measurements, was used to compare WSHP and ASHP at the HPP.*
- *Refrigerant R-32 was chosen as the optimal working fluid.*
- *WSHP showed a 15.3 % higher seasonal COP than ASHP.*
- *The research shows a potential for improving energy efficiency within large-scale hydropower plants in Serbia.*

1 INTRODUCTION

The integration of heat pumps into energy systems has garnered increasing attention over the past three decades due to their potential to reduce primary energy consumption and greenhouse gas emissions significantly. As countries strive to meet ambitious climate targets and transition towards more sustainable energy systems, heat pumps offer a practical solution for improving energy efficiency, especially in sectors with high thermal energy demands. The European Union, through its Green Deal and climate neutrality goals by 2050, has identified heat pump technology as a key component of decarbonising the heating and cooling sector [1,2]. Many authors have compared the efficiency of heat pumps using different heat sources, as well as with conventional heating systems. After reviewing various geothermal heat pumps, Self et al. [3] conducted a comparison of the efficiencies, costs, and CO_2 emissions of the following heating systems: geothermal heat pumps, air source heat pumps, electric baseboard heaters, and natural gas furnaces (mid- and high-efficiency). They determined that geothermal heat pumps are highly efficient systems that utilise significantly less energy for space heating than alternative heating systems. Their use is also economically advantageous in cases of low electricity prices and is accompanied by the weakest emissions when electricity is obtained from low-emitting sources. Luo et al. [4] evaluated the geothermal potential for three types of ground source heat pump system installations in the urban area of Wuhan City in China, namely surface water heat pump systems (SWHP), groundwater heat pump systems (GWHP), and ground coupled heat exchanger heat pump systems (GCHP). They also compared the efficiency of GCHPs with GWHPs. They found that GCHPs operate with a higher efficiency due to the more stable temperatures in the deeper underground than those of the shallow aquifers. Zhen et al. [5] presented the field measurement results of a groundwater source heat pump, which is part of the heating system at an airport on the Tibet Plateau. The analysis showed that the geothermal water heat pump (GWHP) achieved a coefficient of performance (*COP*) of around 5.0. This suggests high energy efficiency and cost-effectiveness compared to conventional heating systems. When compared to an air source heat pump (ASHP), the GWHP demonstrated not only a higher *COP* but also more consistent performance over time.

When it comes to water source heat pumps, groundwater heat pumps are most often included in the literature [6-9]. Fu et al. [10] analysed the system HP performance based on local meteorological data and building conditions along the Haihe River in Tianjin. Results showed that the heat pump's *COP* is closely related to the river's water temperature. The *COP* value during the heating season was 3.08. Papers in which surface water from rivers or lakes is addressed

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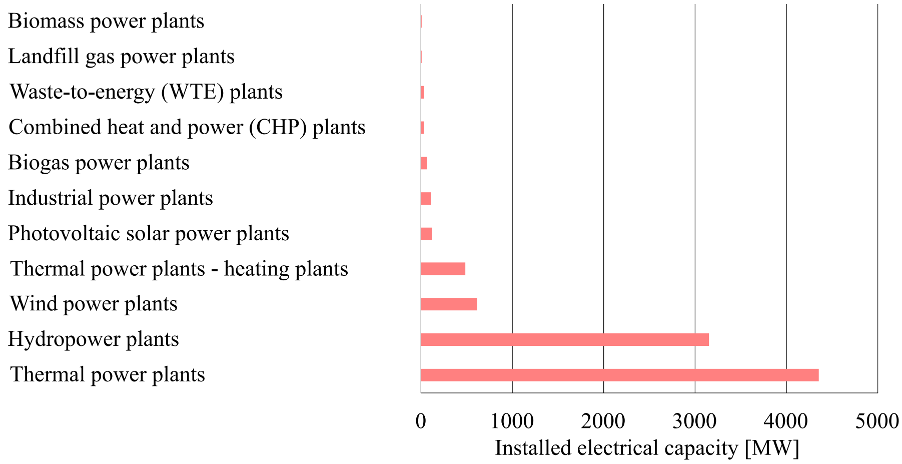

Fig. 1. **The structure of electricity generation in Serbia**

as the heat pump source in the South-East Europe region are not so common. SWHP is designed to be integrated into an extensive industrial energy hydroelectric power plant system. That would be a valuable opportunity for reducing fossil fuel dependency and operational costs, while increasing overall energy system efficiency. Hydropower plants (HPPs) in Serbia play a crucial role in electricity production and in balancing the power grid. Energy generated from such sources represents renewable energy, whose contribution to total production has a significant impact on CO2 emissions. The structure of installed electricity capacity of power plants in the Republic of Serbia in 2024, based on data from the annual energy report [11], is presented in Fig. 1.

Approximately 35 % of Serbia's electrical capacity is generated by hydropower plants, with a total capacity of 3,150.7 MW, of which 3,018 MW comes from large HPP. On the other hand, the annual electricity production in HPP is 10.537 GWh [11]. Not only are hydropower plants large producers of electricity, but they are also significant consumers of electricity, which is used for various systems. Their electrical consumption covers systems for turbine regulation, generator cooling, block transformer cooling, drainage, heating and air conditioning, lighting, rectifier and inverter distribution, auxiliary systems of the unit, control and process equipment, and more. The percentage share of individual systems in the total consumption for the "Bajina Bašta" HPP is presented in Fig. 2.

These data were obtained based on tabular presentations provided in the literature available to the authors [12]. Based on the presented information, it can be observed that more than 70 % of the total electricity consumption in HPP is attributed to the heating and air conditioning systems.

It is worth noting that large HPPs in Serbia were constructed in the 1960s and later decades, with heating plants designed to use electric boilers as the heat source. This fact suggests the possibility of enhancing the energy efficiency of Serbia's entire energy system by replacing electric boilers in HPPs with more energy-efficient systems. Additionally, the presence of large water reservoirs at HPP locations provides an opportunity to utilise water source heat pumps (WSHP, SWHP) to meet heating energy needs. However, depending on the local climate, there is also the possibility of using air-source heat pumps (ASHPs). For this reason, in this study, river water and air temperatures were monitored over a one-year period for the specific

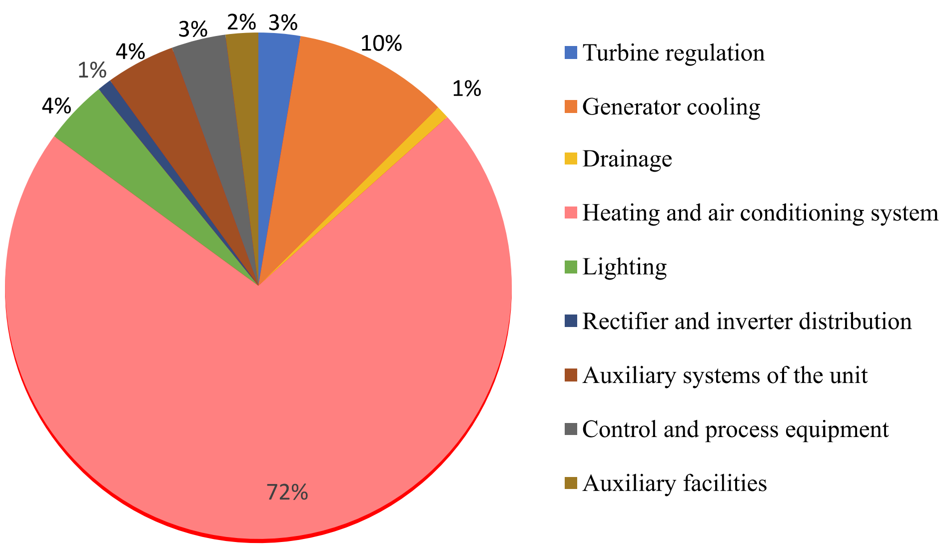

Fig. 2. **Structure of electricity consumption at the HPP Bajina Bašta**

location to obtain accurate input data for calculating the performance of a particular type of heat pump. The continuous development of low-global-warming-potential (GWP) refrigerants and efficient heat exchanger technologies has expanded the feasibility of heat pumps even in previously challenging industrial environments. As such, selecting the appropriate working fluid is critical to ensuring both technical and environmental performance of heat pump systems [13-15]. With this in mind, this paper selects the optimal working fluid for SWHP. In addition to thermodynamic characteristics, environmental impact and flammability were also considered. Although numerous studies have examined the performance of heat pumps in buildings and in geothermal applications [3–5,7–9], only a limited number of papers have addressed systems that utilise rivers or lakes as heat sources [10]. This indicates that surface-water-based heat pumps remain an underexplored research area compared to the well-documented geothermal systems. The present study combines in situ monitoring of river water and air temperatures with a thermodynamic model to compare WSHP and ASHP configurations and to identify the optimal working fluid for hydropower-based HVAC systems. The paper is structured as follows: Section 2 presents the methods with experimental setup and collected data and introduces the thermodynamic model and its assumptions, Section 3 discusses the results of working fluid selection and seasonal performance evaluation, and Section 4 presents the main conclusions. The significance of this research lies in demonstrating the potential of heat pump technology to substantially increase the energy efficiency of large-scale electricity production systems, thereby contributing to the improvement of energy efficiency and to decarbonisation strategies in electricity-generating facilities, fully aligned with long-term climate and energy transition goals [1,2].

2 METHODS

2.1 Experimental Setup

The average water temperature of the Drina River was measured using a band water level meter (manufacturer: Seba Hydrometrie, type: KLL-T, Germany). This is a portable hand-held device for determining the current water level and the water temperature in water depths up to 500 m. The built-in temperature sensor accurately measures water temperature with a high resolution of 0.1 °C.

The outdoor air temperature measurements were recorded using the humidity temperature datalogger (manufacturer: ExTech Instruments, type: RHT20, China).

2.2 Experimental Results

The average temperature of the Drina River water and the air temperature are presented in Fig. 3. The temperature of the Drina River was measured daily at a depth of 2 meters below the surface throughout the entire year, including both heating and non-heating seasons. Such extended monitoring was conducted in anticipation of future analyses involving cooling applications using river water as the heat sink. Similarly, outdoor air temperature was measured three times per day (at 7 AM, 1 PM, and 7 PM) during the entire year to ensure representative climatic data for both heating and cooling season evaluations. The annual profiles of both river water and air temperatures are shown in Fig. 3.

Considering the facts that the heating season in Serbia starts on October 15th and ends on April 15th, that the temperature profile of the water from the Drina River and the air temperature (Fig. 3), that coefficient of performance of heat pump (*COP*) increases with the temperature of the heat source (water, air, ground, etc.). It can be concluded that the use of a water-to-water heat pump is thermodynamically more justified at the given location compared to an air-to-water heat pump [16]. However, there is a need to thermodynamically quantify the benefits of a water-to-water heat pump compared to an air-to-water heat pump. In support of this, it is essential to develop a thermodynamic model of heat pump behaviour, which will, among other things, enable the selection of the optimal working fluid under given conditions.

2.3 Parameters and the Thermodynamic Model of the Heat Pump

The hydropower Plant Bajina Bašta is located on the Drina River, near the town of Bajina Bašta in Serbia. The HPP has the installed capacity of 422 MW [17]. The heating system in HPP objects relies on two electric boilers, each with a capacity of 500 kW, for a total capacity of 1 MW. To increase the energy efficiency of the system, a heat pump with a total heating capacity of $\dot{Q}_H = 1$ MW will be analyzed. A water source heat pump (WSHP) was first analyzed, and then the same thermodynamic model was used for an air source heat pump (ASHP). For thermodynamic analyses of both types of heat pumps, WSHP and ASHP, temperatures of their heat source are presented in Fig. 4. It can be noticed that the minimum water temperature in the Drina River throughout the year is $t_{in} = 6$ °C. To avoid freezing river water, the maximum drop in temperature of the river water in the heat exchanger (evaporator) is $\Delta t_w = 5$ K. On the other hand, the heating system is designed to use supply water with a temperature $t_s = 45$ °C, while the return water temperature is $t_r = 40$ °C, that is, the water temperature rise at the heat exchanger (condenser) is $\Delta t_{hw} = 5$

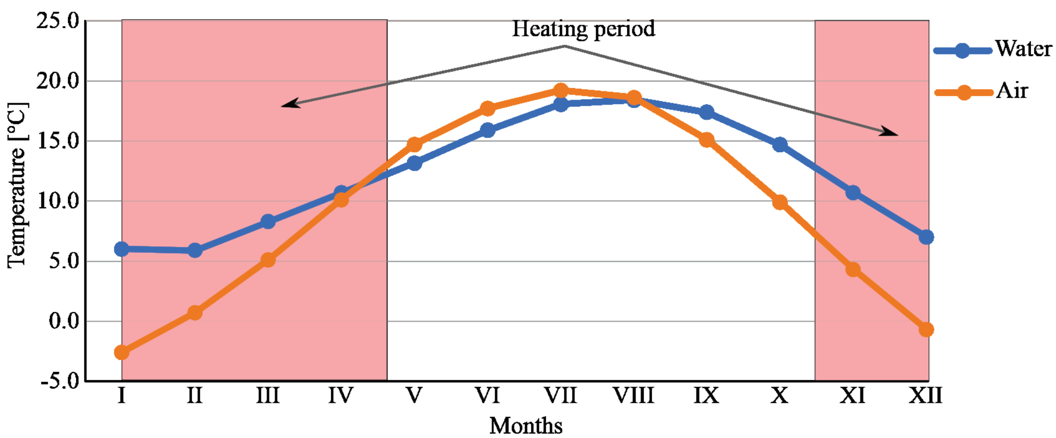

Fig. 3. Variation of the average temperature of the Drina River water and outdoor air throughout 2024

K. The minimum temperature difference between the temperatures of water and the working medium of the heat pump is $\Delta t = 5$ K. A schematic diagram of the heat pump system is presented in Fig. 4, while *T-S* diagram of the thermodynamic process is presented in Fig. 5, in which abbreviations are: *wm* working medium, *rw* river water, and *hw* heating water.

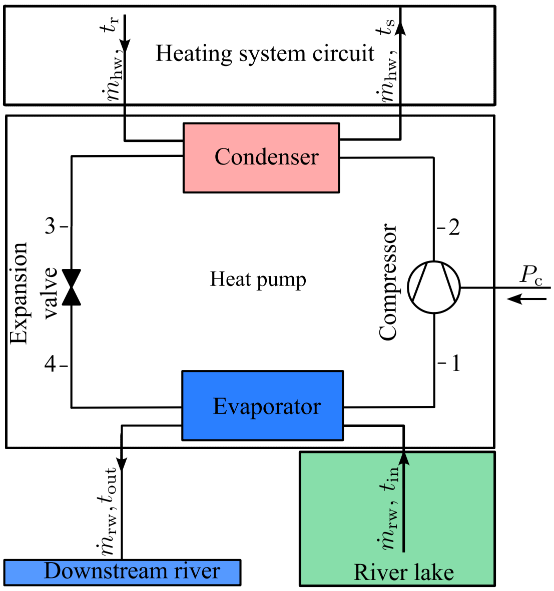

Fig. 4. WSHP coupled with the heating system

To simplify analysis in the article, the following assumptions were used:

- Heat transfer processes in all heat exchangers were isobaric.
- Heat transfer between the surroundings and the pipework was neglected.
- Pressure losses in all pipework were neglected.
- The heating power of the heat pump is $\dot{Q}_H = 1$ MW.
- The condensation temperature is $t_c = t_s + \Delta t = 45 + 5 = 50$ °C.
- Evaporation temperature is $t_e = t_{out} - \Delta t$.
- All calculations were carried out under stationary conditions, excluding variations in input parameters.
- The isentropic efficiency of the process in the compressor was calculated based on [18], that is

$$\eta_i = 0.85 - 0.0467 \frac{p_c}{p_e}, \tag{1}$$

- The working fluid enters the evaporator as saturated vapour.
- The working fluid exits the condenser as saturated liquid.
- Subcooling and superheating are not included in the model.

The evaporation and condensation pressures of the working fluid were determined as the saturation pressures corresponding to the calculated evaporation and condensation temperatures. For the WSHP configuration, the evaporation temperature was defined as the minimum river water temperature reduced by 5 K. For the ASHP configuration, the evaporation temperature was obtained by subtracting 5 K from the monthly average outdoor air temperature. In both configurations of heat pumps, the condensation temperature was set based on the heating system supply conditions, by adding 5 K to the required supply water temperature of the heating system. These temperatures were then used to calculate the corresponding saturation pressures using the CoolProp database of working fluids. A thermodynamic model was developed in MATLAB to compare various working fluids and heat pump types under identical conditions. The required input data were sourced from the CoolProp database [19], which provides open access to thermophysical properties.

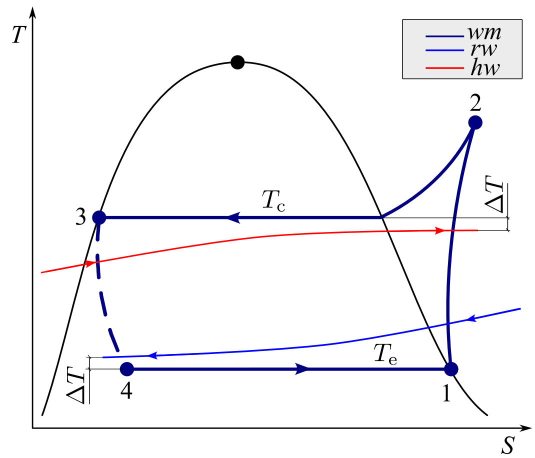

Fig. 5. T–S diagram of the process in the heat pump

3 RESULTS AND DISCUSSION

3.1 Selecting a Working Fluid

Recent studies have emphasised the importance of low-GWP refrigerants in industrial applications, striking a balance between energy efficiency, safety, and environmental performance [18,20]. In this article, thermodynamic analyses were performed for the following working fluids: R-410A, R-407C, R-134a, R-32, and R-1270. All these fluids are selected in such a way that their ODP factor is zero, meaning they do not contribute to ozone layer destruction [21].

Thermodynamic calculations based on the heat pump model, as well as the primary data of the considered working fluids, are presented in Table 1. The values refer to the most demanding operating condition for WSHP, that is, the case when the river water temperature reaches its annual minimum of 6 °C.

By analyzing the performance calculation results of the heat pump, it can be concluded that the two best working fluids, in terms of energy efficiency, are R-1270 and R-32. However, regarding flammability (Table 2) [22], R-32 is moderately flammable, whereas R-1270 is highly flammable (explosive) and should be excluded for safety reasons. Therefore, R-32 has been selected as the optimal working fluid. The lowest calculated *COP* value was obtained when the water temperature was at its minimum (*COP* = 3.27), which occurred in January, when the river water temperature was 6 °C. For this case, the compressor power was 305.78 kW, and the mass flow rate of working fluid (R-32) was 3.2 kgs^{-1}.

With the known heating power $\dot{Q}_H$ and the known specific enthalpy values for states 2 and 3, the mass flow rate of the working fluid through the heat pump installation was determined for each of the working fluids. The values obtained for the mass flow rate of the working fluid are also presented in Table 1. The lowest mass flow rate also implies the smallest pipe diameters in the heat pump installation. For the previously determined value of the working fluid mass flow rate, it is possible to determine the power supplied to the evaporator of the heat pump. This heat rate, under the previously given assumptions, is equal to the heat flow extracted from the river water, so it is possible to determine the mass flow rate of the river water used as the heat source. Since the water is taken in through free intake, a pressure of 3 bar is assumed. Based on the calculation results presented in Table 1, the type of working fluid used in the heat

Table 1. Results of the thermodynamic calculations

		Properties	1	2	3	4	$\dot{m}_f$ [kg/s]	COP	P_c [kW]	$\dot{m}_{rw}$ [kg/s]
R-410A	GWP	p [kPa]	701.1	3062.99	3062.99	701.1	5.06	3.13	319.91	32.32
	2088	T [K]	269.2	363.4	323.2	269.2				
	ODP	h [kJkg^{-1}]	420.12	483.38	285.65	285.65				
	0	s [kJkg^{-1}K^{-1}]	1.82	1.88	1.28	1.32				
R-407C	GWP	p [kPa]	399.6	1987.62	1987.62	399.6	4.96	3.18	314.95	32.56
	1774	T [K]	296.2	359.2	323.2	296.2				
	ODP	h [kJkg^{-1}]	407.41	470.96	269.2	269.2				
	0	s [kJkg^{-1}K^{-1}]	1.78	1.85	1.23	1.26				
R-134a	GWP	p [kPa]	252.68	1317.91	1317.92	252.68	5.51	3.2	312.88	32.66
	1430	T [K]	269.2	348.8	323.2	269.2				
	ODP	h [kJkg^{-1}]	396.25	453	271.62	271.62				
	0	s [kJkg^{-1}K^{-1}]	1.73	1.80	1.24	1.27				
R-32	GWP	p [kPa]	713.88	3141.23	3141.23	713.88	3.20	3.27	305.78	32.99
	675	T [K]	269.2	391.1	323.5	269.2				
	ODP	h [kJkg^{-1}]	514.49	610.07	297.49	297.49				
	0	s [kJkg^{-1}K^{-1}]	2.17	2.26	1.32	1.36				
R-1270	GWP	p [kPa]	517.38	2053.81	2053.81	517.38	2.93	3.35	298.42	33.34
	2	T [K]	269.2	350.7	323.2	269.2				
	ODP	h [kJkg^{-1}]	573.84	675.73	334.29	334.29				
	0	s [kJkg^{-1}K^{-1}]	2.39	2.49	1.44	1.50				

pump does not significantly affect the mass flow rate of the river water.

Table 2. Flammability of the considered working fluids

Refrigerant	Flammability Class
R-410A	1 (Non-flammable)
R-407C	1 (Non-flammable)
R-134a	1 (Non-flammable)
R-32	2L (Mildly flammable)
R-1270 (Propylene)	3 (Highly flammable)

3.2 Monthly and Seasonal Coefficient of Performance (*SCOP*)

The *SCOP* analysis presented in this section relies on the use of R-32 as the working fluid, which was previously identified as the most suitable option in terms of energy efficiency, environmental impact, and safety. To complement the instantaneous *COP* analysis, a *SCOP* evaluation was conducted to capture the seasonal efficiency of the WSHP and ASHP systems. Unlike the *COP*, which was calculated monthly, the *SCOP* considers the varying number of heating days in each month, that is, the number of heating degree days. Considering seasonal fluctuations in source temperature is essential for accurately assessing the real-world performance of heat pumps. Using the established thermodynamic model and data on the average monthly water temperature of the Drina River, the coefficient of performance can be determined on a monthly level by Eq. (2).

$$COP = \frac{\dot{Q}_H}{P_c}, \tag{2}$$

By calculating the coefficient of performance (*COP*) for each month, it is possible to assess the system's efficiency throughout the heating season. These values are then used to determine the seasonal coefficient of performance (*SCOP*), which provides a comprehensive evaluation of the heat pump's overall performance over an extended period. Using the same mathematical model of the heat pump, but under the assumption that an air-source heat pump (ASHP) is used with outdoor air temperatures from Fig. 3, the *COP* values and, consequently, the *SCOP* can also be calculated.

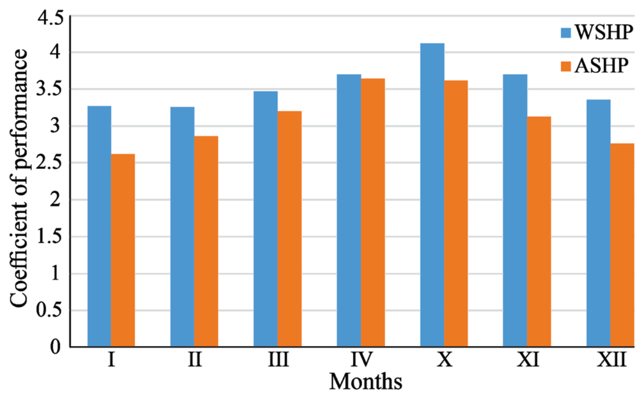

Fig. 6. Monthly *COP* values for WSHP and ASHP (based on R-32)

Throughout the entire heating season, the WSHP exhibits better performance than the ASHP (Fig. 6). As shown in Fig. 6, the lowest *COP* value for the WSHP system was obtained in January (*COP* = 3.27), while for the ASHP system, the lowest monthly *COP* was also calculated for January, amounting to 2.62.

Monthly calculated *COP* values for both WSHP and ASHP were used to calculate the *SCOP* according to Eq. (3).

$$SCOP = \frac{\Sigma(COP \text{ x number of heating days in the month})}{\text{total heating days}}, \tag{3}$$

where the number of heating days in the month, as well as the total heating days during 2024, are presented in Table 3. Results of the calculations of *SCOP* for WSHP and ASHP are presented in Fig. 7.

Table 3. Number of heating days per month

Month	Jan	Feb	Mar	Apr	Oct	Nov	Dec	Total
Heating days	31	28	31	15	17	30	31	183

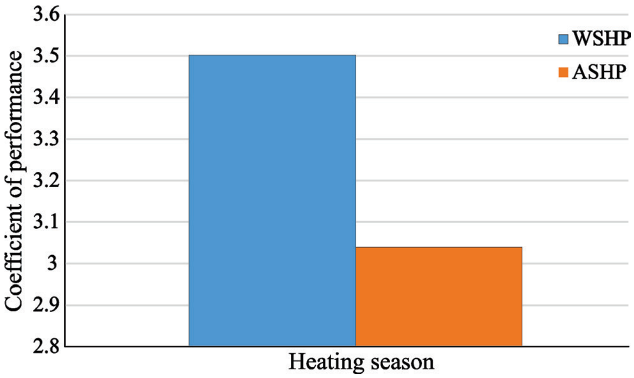

Fig. 7. The comparison of *COP* for WSHP and ASHP for the heating season

Since the *SCOP* of the WSHP was 15.3 % higher than that of the ASHP (Fig. 7), it consequently results in lower CO_2 emissions, as higher efficiency directly reduces electricity consumption and, therefore, environmental impact.

4 CONCLUSIONS

The conducted thermodynamic analysis confirms the significant potential of integrating heat pump systems into the HVAC infrastructure of hydropower plants as an effective way to improve energy efficiency and reduce internal electricity consumption. A comparison between water source heat pumps (WSHP) and air source heat pumps (ASHP) under realistic climatic conditions at the Bajina Bašta hydropower plant demonstrates a clear performance advantage of the WSHP configuration. The lowest monthly value of *COP* for the WSHP was 3.27, which occurred in January when the water temperature of the Drina River reached its minimum of 6 °C. During the same period, the *COP* for ASHP was significantly lower (2.62). The *SCOP* for the WSHP, calculated based on the actual heating season duration and river temperature profiles, reached 3.5, while the corresponding *SCOP* for ASHP was 3.04. These results confirm that the WSHP configuration achieves approximately 15.3 % higher seasonal efficiency than its air-based counterpart, with *SCOP* providing a more informative metric than *COP* alone for assessing long-term operational effectiveness.

Additionally, the selection of the working fluid plays a crucial role in determining the overall system performance and safety. Among the five refrigerants studied (R-410A, R-407C, R-134a, R-32, and R-1270), R-32 demonstrated the best balance of energy efficiency, fire safety, and environmental friendliness. While R-1270 exhibited slightly higher *COP* values, its high flammability renders it unsuitable for safe industrial applications. The analysis also revealed that the type of refrigerant has a negligible influence on the mass flow rate of river water, thereby simplifying the hydraulic design of the system.

In addition to the quantitative findings, the originality of this work lies in addressing the underexplored potential of applying heat pump technology in electricity-generating infrastructures. By coupling in situ temperature measurements with a thermodynamic model, the study provides a replicable methodological framework for evaluating HVAC modernisation in large hydropower plants. This contributes to mechanical engineering by offering new insights into sustainable energy system design, while supporting long-term strategies of energy efficiency improvement and decarbonisation in the power sector.

Future work should focus on dynamic operational modelling and complete techno-economic analysis under real climate conditions. Additionally, the inclusion of volumetric heating capacity (VHC) as a performance metric, together with the techno-economic analysis, will provide a more comprehensive insight into the optimal choice of working fluid for this and similar applications.

Nomenclature

COP	coefficient of performance, [–]
h	specific enthalpy, [kJkg-1]
n_i	isentropic efficiency of compression process, [–]
P_c	power of compressor, [kW]
p	pressure, [kPa]
p_c	condensation pressure of the heat pump working medium, [kPa]
p_e	evaporation pressure of the heat pump working medium, [kPa]
S	entropy, [JK^{-1}]
s	specific entropy, [kJkg^{-1}K^{-1}]
$SCOP$	seasonal coefficient of performance, [–]
T	temperature, [K]
T_c	condensation temperature of the heat pump working medium, [K]
T_e	evaporation temperature of the heat pump working medium, [K]
t_c	condensation temperature of the heat pump working medium, [°C]
t_e	evaporation temperature of the heat pump working medium, [°C]
t_{in}	river water temperature at the inlet of the heat pump, [°C]
t_{out}	river water temperature at the outlet of the heat pump, [°C]
t_r	return water temperature from the heating system, [°C]
t_s	supply water temperature to the heating system, [°C]
Δt	temperature difference between working medium and river/heating water, [°C]
ΔT_{hw}	temperature rise of heating water in the heat pump condenser, [K]
ΔT_w	temperature drop of river water in the heat pump evaporator, [K]
$\dot{m}_f$	mass flow rate of the heat pump working medium, [kgs^{-1}]
$\dot{m}_{hw}$	mass flow rate of heating water, [kgs^{-1}]
$\dot{m}_{rw}$	mass flow rate of river water, [kgs^{-1}]
$\dot{Q}_H$	heat pump heating capacity, [kW]

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Termodinamična ocena in izbor delovnega fluida za toplotno črpalko, integrirano v HVAC-sistem hidroelektrarne: študija primera iz Srbije

Povzetek *V članku je predstavljena termodinamična analiza dveh tipov toplotnih črpalk, integriranih v sistem ogrevanja, prezračevanja in klimatizacije (HVAC) hidroelektrarne Bajina Bašta v Srbiji. Cilj raziskave je zamenjati obstoječe električne kotle z energetsko učinkovitejšimi rešitvami z izkoriščanjem obnovljivih virov toplote. Opravljena je bila primerjalna ocena vodne toplotne črpalke (WSHP) in zračne toplotne črpalke (ASHP) z uporabo po meri razvitih MATLAB modelov, ki temeljijo na podatkih knjižnice CoolProp o delovnih fluidih. Analizo so podprli realni podatki, pridobljeni z in-situ meritvami temperatur zraka in vode na izbrani lokaciji, kar je omogočilo natančne vhodne parametre simulacij. Uporabljenih je bilo pet hladiv (R-410A, R-407C, R-134a, R-32 in R-1270), pri čemer je bil kot optimalno hladivo izbran R-32 zaradi visoke učinkovitosti, zmerne gorljivosti in nizkega vpliva na okolje. Najnižje grelno število (COP) za WSHP je znašalo 3,27 v januarju, medtem ko je sezonsko grelno število (SCOP) doseglo 3,36, kar je približno 15,5 % več kot pri ASHP (SCOP = 2,91). Raziskava potrjuje, da so WSHP-sistemi ob upoštevanju celotnega ogrevalnega obdobja tehnično in okoljsko superiorni v primerjavi z ASHP v analiziranih lokacijah. Predlagana konfiguracija, ki temelji na dejanskih meritvah in dobljenih rezultatih, lahko pomembno izboljša energetsko učinkovitost ter zmanjša notranjo porabo električne energije v hidroelektrarnah, s čimer podpira razogljičenje velikih obnovljivih energetskih objektov. Medtem ko so se prejšnje raziskave večinoma osredotočale na izboljšanje energetske učinkovitosti stavb, ta študija izpostavlja pomemben, a premalo raziskan potencial izboljšanja učinkovitosti v sektorju proizvodnje električne energije v Srbiji. Posebej obravnava hidroelektrarne v Srbiji, kjer so sistemi ogrevanja in klimatizacije, zgrajeni v šestdesetih letih, še vedno izrazito energetsko neučinkoviti. S kvantifikacijo koristi integracije WSHP in ASHP sistemov raziskava ponuja smer za pomembno povečanje energetske učinkovitosti hidroenergetskih objektov.*

Ključne besede *hidroelektrarna, toplotna črpalka, energetska učinkovitost, COP, SCOP*