Violeta MISEVIČIŪTĖ, Kęstutis ČIUPRINSKAS, Artur ROGOŽA

Vilnius Gediminas Technical University, Vilnius, Lithuania

Corresponding author: violeta.miseviciute@vilniustech.lt

Doi: 10.53412/jntes-2022-1-2

ANALYSIS OF WASTE HEAT RECOVERY IN A WATER TREATMENT PLANT AND THE USE OF THIS HEAT IN A COMMERCIAL BUILDING

Abstract: *Effective energy use plays a crucial role in the conservation of energy sources. The recovery of waste energy is one of the available energy saving potentials and can be the possibility of ensuring the energy needs of commercial buildings. To date, research on heat recovery from wastewater treatment has focused mainly on the heat potential of wastewater evaluation and technologies to apply this energy. This work examines the possibilities of wastewater heat recovery in the Vilnius wastewater treatment plant and assesses whether the thermal energy demand of the commercial building can be ensured by using the heat of the treated wastewater in a heat pump.*

Keywords: *renewable, wastewater treatment plant, heat pump, heat energy, commercial building, EnergyPro*

Introduction

About 40% of the heat produced in cities is discharged into the sewer along with the used water (Hepbasli et al., 2014). According to the EU directive 2018/2001 (EU, 2018), wastewater has been recognized as a renewable heat source (Nagpal et al., 2018). Depending on the purpose of water, the wastewater temperature ranges from 10°C to 40°C (Somogyi et al., 2018), so the wastewater entering the wastewater treatment plant has a significant energy potential, but it is treated and discharged to a natural receiver without further treatment. It is possible to recover heat from wastewater from domestic, industrial, and commercial objects applying technologies like heat exchangers and heat pumps; and reuse it to satisfy heating demands (Nagpal et al., 2018). The report (KPMG Baltics OÜ, 2021) emphasised that wastewater treatment plants, data centers, flue gas condensing and the development of low-temperature district heating areas have the greatest potential for low temperature waste heat if it is supplied from the return line of existing district heating networks. Among many options to improve energy self-sufficiency in sewage treatment plants, heat extraction using a heat pump holds great promise, since wastewater contains considerable amounts of thermal energy (Chae, Ren, 2016). The available heat from the wastewater treatment plant can be described as a low-quality heat and can be recovered through the use of heat pump technology (Đurđević et al., 2019). The purpose of this research is to analyse the possibilities of wastewater heat recovery in the Vilnius wastewater treatment plant and to assess whether the thermal energy demand of the commercial building can be ensured by using the heat of the treated wastewater in the heat pump.

Object

The largest wastewater treatment plant in Lithuania, the Vilnius wastewater treatment plant, chosen for research. All wastewater generated in the city of Vilnius is collected and delivered to this wastewater treatment plant, where it is cleaned mechanically and biologically. There are no residential areas near the plant, there are forests and the Neris river in the north and east directions around the wastewater treatment plant, and in the west and south it is bordered by the Paneriai forest. The closest heat consumer to the recovered heat supply object is the store building "DEPO", which is located about 2 km in the southeast direction from the object selected. The closest heat consumer to the object of recovered heat supply is the store building "DEPO" located about 2 km in the southeast direction. The heating area of this building is 19087 m^2 and the volume is 190105 m^3. This building has a heating area of 19087 m^2 and a volume of 190105 m^3. The class B energy efficiency building was built in 2018. The building is supplied with heat from the city district heating networks. The store has opening hours from 8 a.m. to 9 p.m. on weekdays, from 8 a.m. to 8 p.m. on Saturdays, and from 9 a.m. to 6 p.m. on Sundays.

Research methodology

The research is based on data received from reports prepared by JSC "Vilniaus vandenys" (JSC "Vilniaus vandenys", 2021) on the flow rate and temperature of treated wastewater at the Vilnius wastewater treatment plant and the calculated heat demand of the store. The heat potential of treated wastewater is determined by different temperature differences. In each case, heat pump duty cycle calculations are performed, the results of which are used in *EnergyPro* software (EMD International, 2022) compiled model. The created model is applied to check whether the heat pump will be able to cover the heat demand of the building, what will be its duration of operation, and the electricity consumption. The standard heat demand for heating of the "DEPO" building is calculated based on the building's energy efficiency certificate of the building issued on 02/28/2018. The determined heating energy demand of the building is 9.43 kWh/m^2/year. The heat demand for the preparation of hot water is determined according to the rules for the installation of hot water systems in buildings (Parliament of the Republic of Lithuania, 2017). The annual heat needs for the ventilation system are determined according to formula:

$$Q_{vent} = H_{ev} \cdot \Delta T \cdot t_{h.sez.} \cdot 10^{-3}, \text{ kWh/year} \quad (1)$$

where:

H_{ev} – ventilation specific heat loss, W/K;

ΔT – the difference between the average outdoor air temperature during the heating season and the indoor air temperature, K;

$t_{h.sez.}$ – store operating hours during the heating season, h.

When calculating the heat potential of the waste, the minimum hourly wastewater flow determined in the considered period was evaluated. The decrease in wastewater temperature in the heat pump was evaluated in three cases – if the temperature decreases by 2°C, 3°C and 4°C. Since wastewater is treated mechanically and biologically, its physical parameters (specific heat, enthalpy, density, etc.) are selected according to simplified formulas to calculate the thermophysical properties of water [6]. The thermal energy potential is calculated:

$$Q_{pot.} = \frac{Q_h \cdot \rho_n \cdot c_n \cdot \Delta T}{3.6} \cdot 10^{-6}, \text{ MW} \quad (2)$$

where:

$Q_{pot.}$ – heat energy potential of treated wastewater, MW;

Q_h – minimum or average hourly flow rate, m^3/h;

ρ_n – density of wastewater, kg/m^3;

c_n – specific heat of wastewater, kJ/(kg·K);

ΔT – difference in wastewater temperatures before and after the heat pump, K.

The working agent (refrigerant) of the analysed heat pump is R1234ze(E). This refrigerant is classified as a low global warming potential refrigerant, and its thermodynamic parameters are analogous to R134a (Rogoža et al., 2021). The refrigerant temperature in the condenser is 65°C, and in the evaporator −5°C are assumed in the calculations, and the heat pump cycle is plotted on the ph diagram of the refrigerant R1234ze(E). Figure 1 represents the principal scheme of the heat pump. The dotted line in the scheme indicates the boundaries of the thermodynamic system.

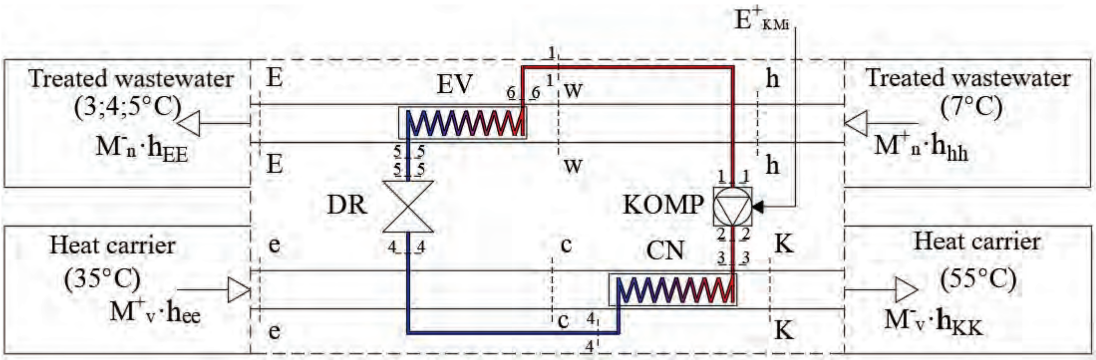

FIGURE 1. *Principal scheme of the heat pump. Abbreviations: EV – evaporator, KOMP – compressor, CN – condenser, DR – expansion valve, M_v – mass flow of water supplied to the building, M_n – mass flow of treated wastewater, h... – enthalpy at considered point*

The heat flow in the evaporator is calculated according to formula:

$$Q_g = M_{R1234} \cdot (h_6 - h_5),\ \text{kW} \tag{3}$$

where:

M_{R1234} – refrigerant mass flow rate, kg/s;

h_6 – refrigerant enthalpy after the evaporator, kJ/kg;

h_5 – refrigerant enthalpy before the evaporator, kJ/kg.

The power required for the heat pump compressor is calculated according to formula:

$$E_{KMi} = M_{R1234} \cdot e_{KMi},\ \text{kW} \tag{4}$$

where:

M_{R1234} – refrigerant mass flow rate, kg/s;

e_{KMi} – compressor specific internal work, kJ/kg.

The coefficient of performance (COP) of the heat pump can be calculated according to formula:

$$COP = \frac{Q_k}{E_{KMi}} \tag{5}$$

where:

Q_k – condenser heat flow, kW;

E_{KMi} – compressor power, kW.

The *EnergyPRO* program (EMD International, 2022) was applied to create a model of the system considered. The model consists of a heat pump, the parameters of which are calculated according to formulas (3)-(5); the heat pump is supposed to be supplied with electricity from the power grid. The heat pump supplies the building with the heat for heating, ventilation, and hot water needed.

Results

The building's heat supply was simulated for the period from September 22, 2020 until September 21, 2021. The change in temperature and discharge of treated wastewater and outdoor air during the period considered is presented in Figures 2a and 2b.

a)

b)

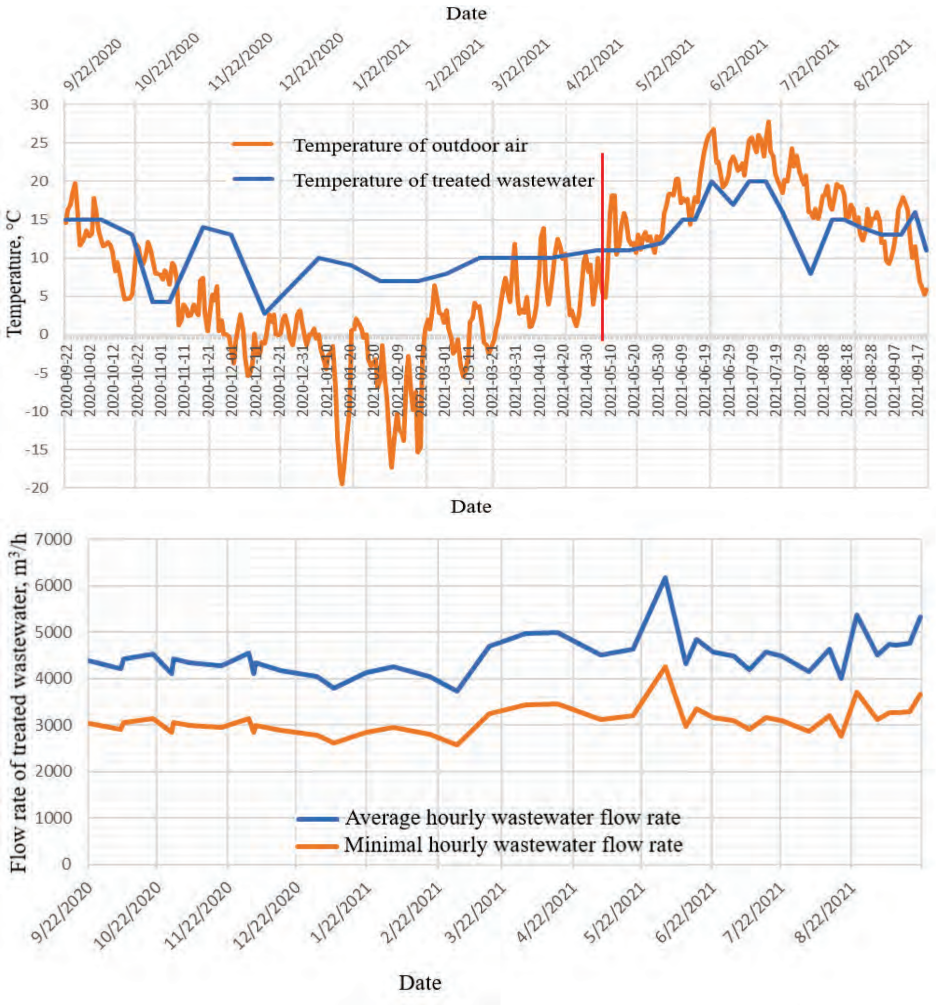

FIGURE 2. *Dependence of treated wastewater and outdoor air temperature (a) and hourly flow rates of treated wastewater (b)*

Figure 2 shows that the temperature of the treated wastewater varied from ~3°C to ~20°C during the period considered. The graph (Fig. 2a) shows that the effluent temperature is slightly dependent on the temperature of outdoor air, but it does not drop below 7°C. As can be seen in Figure 2b, depending on the daily flow rate, the average and minimum hourly flow rate of treated wastewater also fluctuates. The latter maintains around 3000 m^3/h during the period considered. The lowest flow rate of treated wastewater was determined on 2 March and was 2577 m^3/h.

Based on these data, the thermal potential of wastewater treated in the Vilnius wastewater treatment plant has been determined, with different temperature differences and minimum and average flow rates. Figure 3 presents these results.

It can be seen in Figure 3 that as the difference in wastewater temperatures before and after the heat recovery process increases, the thermal potential of the wastewater increases proportionally. At a minimum hourly wastewater flow of ~2577 m^3/h and ΔT = 2°C, the thermal potential is equal to 21.63 MW, and doubling the temperature difference doubles the theoretical thermal potential to 43.27 MW.

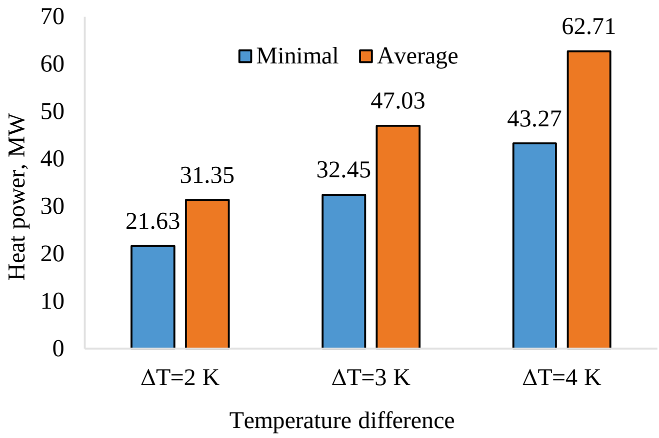

***FIGURE 3.** Dependence of treated wastewater heat potential on temperature difference of wastewater in the heat pump*

The annual heat needs of the "DEPO" store have been determined:

- for the heating of the premises – 180 MWh/ year;
- for ventilation system – 386 MWh/ year;
- for hot water preparation – 34 MWh/year.

The heating capacity of the building determined applied the *EnergyPro* program and is equal to ~400 kW. Based on the available data, the heat pump parameters were calculated, which could supply the building with heat energy. The technical parameters of this heat pump are presented in Table 1.

***TABLE 1.** Required technical parameters of the heat pump*

Heat flow in the condenser, kW	Heat flow in the evaporator, kW	Power required for the compressor, kW	Refrigerant flow rate, kg/s	Flow rate of treated wastewater, kg/s	Heat carrier (water) flow rate, kg/s	COP
400.00	259.89	140.11	2.93	15.46	4.79	2.85

The calculated thermal capacity of the heat pump is 400 kW; the power required for the compressor is 140.11 kW. The COP of the heat pump in this case is equal to 2.85. These parameters have been inputted into the heat pump table of the model created in the *EnergyPro* program, and it is checked whether such a heat pump will really provide the heat needs of the building. The determined minimum required flow rate of treated wastewater is equal to 55.66 m^3/h. The minimum hourly wastewater flow determined by measurements is 2577 m^3/h, and it exceeds the minimum demand 46 times.

EnergyPRO program compiled the annual schedule of heat production and consumption of the building, and Figure 4 presents the schedule of heat demand and production for the month of peak heat consumption.

As can be seen in Figure 4, the highest heat consumption in January is in the middle of the month and reaches ~400 kW, the total heat demand in January is ~116 MWh. The need for heat varies depending on the temperature of the outdoor air, the operating mode of the heating and ventilation systems, and the consumption of hot water. Figure 4 also shows that the entire heat demand is covered by the calculated heat pump, whose monthly performance data for all years are presented in Figure 5.

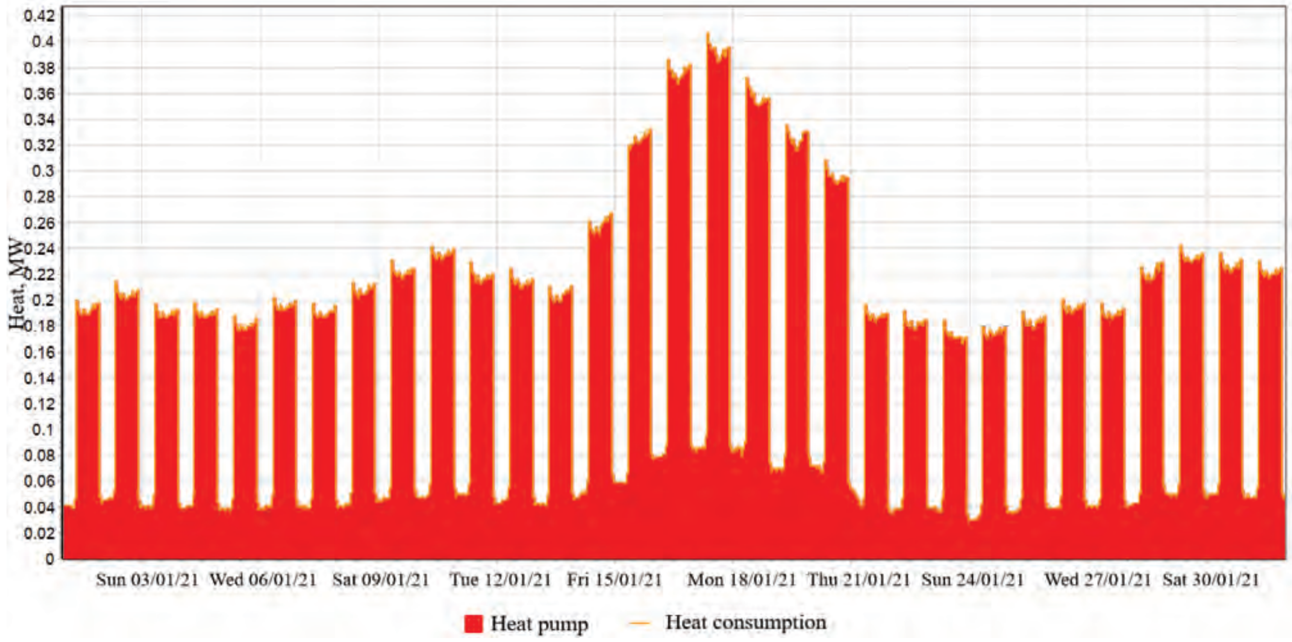

FIGURE 4. *Heat needs and production in January*

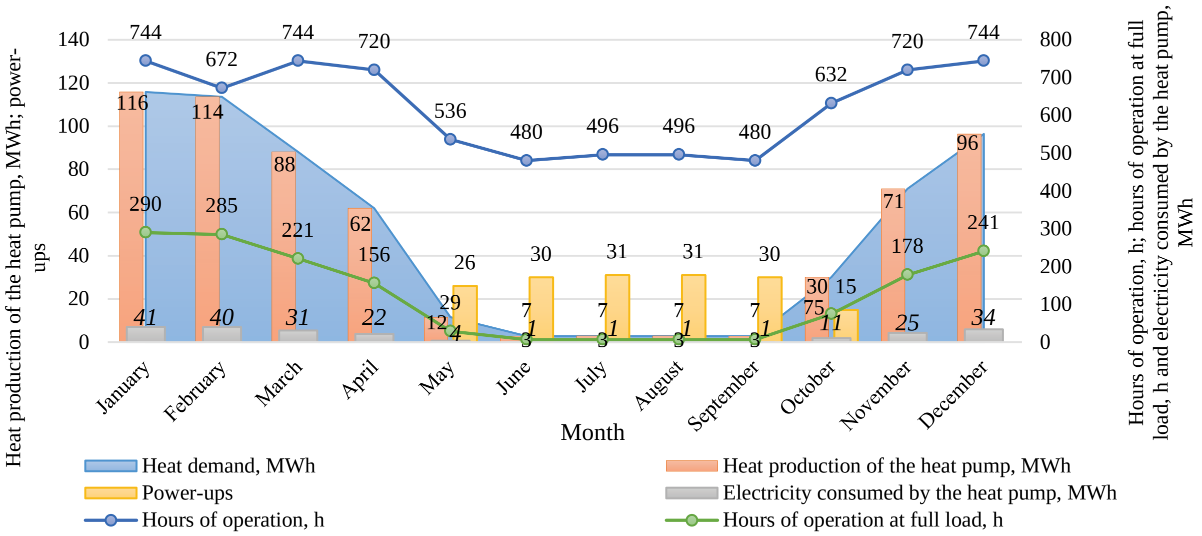

FIGURE 5. *Monthly energy transformation*

As can be seen in Figure 5, the total annual heat demand of the building is equal to ~600 MWh, the monthly maximum demand is observed in January and is equal to 115.8 MWh. The lowest heat needs are during the summer season, when the heat is used only for hot water preparation, this need is equal to ~3 MWh. In summary, the total amount of electricity consumed by the heat pump is 210.4 MWh. A zero number of heat pump start-ups indicates that the heat pump is operating at a constant, partial, or full load during the heating season. In total, the heat pump operates for 7464 hours per year, and it operates at approximately 20% of full load, this time, that is, 1503 hours.

Conclusions

1. In the period from 22 September 2020 to 21 September 2021, the temperature of treated wastewater in the Vilnius city wastewater treatment plant was 7-20°C, and the minimum hourly flow rate of treated wastewater was equal to 2577 m^3/h. The theoretical heat potential of treated wastewater is equal to 43.27 MW.

2. The COP of the heat pump, which uses treated wastewater as a heat source to supply heat to the investigated building, was determined to be 2.85.
3. After applying the *EnergyPro* modelling tool, it was determined that a heat pump with a thermal power of 400 kW would fully supply/provide the building with heat energy, i.e., the heat pump would produce 600 MWh of heat and consume 210 MWh of electricity per year.

This research did not receive any specific grants from funding agencies in the public, commercial, or non-profit sectors.

Acknowledgments

This article was prepared based on the data of Darjuš Bogdan's master's thesis.
The authors of the article are grateful for the provided material and cooperation.

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