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Energy efficiency of air-to-water heat pumps at different operating modes in residential heating systems - case study in Bosnia and Herzegovina

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Abstract— **This paper presents the possibilities of using air-water heat pumps for heating residential buildings. Description of the most important parts of the air-water heat pumps, as well as the basic guidelines for design and implementation, are shown in this paper. Practical example with heat pumps settings and measurements of capacity and Coefficient of Performance (COP) and Seasonal Coefficient of Performance (SCOP) are described in this paper. All research regarding air-to-water heat pumps of different operating modes was conducted at a real facility in Pazarić, location near Sarajevo, Bosnia and Herzegovina. In addition, the energy efficiency class was determined on the considered example of the heat pump. Based on these measurements, calculation and by comparison, important conclusions were obtained regarding the use of observed heat pump, control and maintenance of such systems in terms of increasing energy efficiency related to indoor comfort in the residential building.**

Keywords - Air-water heat pumps; Energy efficiency; Parameters setting; Energy efficiency; Improvement indoor comfort;

I. INTRODUCTION

Heat pumps, at the current stage of development, represent a highly efficient technology necessary for reducing overall energy consumption, improving energy efficiency and reducing greenhouse gas emissions. The main advantage of heat pumps is that they generate thermal power greater than the input energy, using various heat sources: outdoor air, groundwater, soil, industrial or household wastewater, etc. Due to the numerous negative impacts of fossil fuel combustion, there is an increasing focus on renewable energy sources. One of the most promising technologies that includes the use of renewable energy sources in heating systems are heat pumps. If heat pumps are additionally combined with solar photovoltaic systems, it is possible to approach zero energy consumption (nZEB). In order to mitigate the impacts caused by the energy crisis and climate change, the European Parliament has adopted several directives that aim to reduce greenhouse gas emissions by 90% by 2050 [1].

In addition, technological developments have enabled the use of natural working fluids such as: propane (R290), carbon dioxide (R744), isobutane (R600a), ammonia (R717) and the like. These natural working fluids have long been considered a long-term solution in the development of heat pump technologies. Their use has so far been limited by the level of development of individual heat pump components (mostly the level of development of compressors). These natural refrigerants have a low global warming potential (GWP) and ozone depletion potential (ODP). For example: R290 has a GWP of 20, and an ODP of 0, R600a has a GWP of 3 and an ODP of 0, while R744 has a GWP of 1 and an ODP of 0. For example, R410a (the working fluid that is still most widely used) has a GWP of 1975, while R32 has a GWP of 675 [2]. R32, with its relatively high GWP coefficient, represents a transitional solution to the above-mentioned or other natural refrigerants.

Another reason for the increasing use of heat pumps in households around the world is the possibility of generating electricity from their own sources in households around the world (solar photovoltaic systems for homes). Heat pumps can help to increase the own consumption of electricity (which is produced by solar photovoltaic panels) instead of exporting it to the grid at lower tariffs or storing it for later use. The main reason why it is better to use this excess electricity for heating the household is the relatively low feed-in tariffs for excess energy from home photovoltaic systems.

Although heat pumps have become the most commonly used heat source in new buildings, they currently only meet 5% of Europe’s heating needs in buildings [3]. In order to achieve the climate targets set by 2050, it is necessary to increase the use of heat pumps in buildings by a factor of 10. This is why many countries have started providing financial incentives for the installation of heat pumps. For example, the Chinese government, in order to reduce air pollution, implemented a "coal for electricity" campaign where it provided financial support and preferential electricity prices to users who replaced coal-fired boilers with air-to-water or air-to-air heat pumps [4].

Today, the heat pump market is expanding. This is due to the price of fossil fuels and legislation in the field of energy efficiency and renewable energy sources. Also, their easy integration into existing heating systems contributes to the increasing replacement of pellet, gas or oil boilers with heat pumps. All this has contributed to the heat pump market growing progressively year after year. Heat pumps that use air as a heat source are the most commonly used heat pumps.

This paper deals with air-water heat pumps and their energy efficiency in heating residential buildings. Low-power heat pumps (up to 20 kW) are discussed, as well as their possibilities and problems in operation.

II. METHODOLOGY

The methodology adopted for determining the SCOP and energy efficiency of air-to-water heat pumps with the use of the combined methods can be described by the following steps: review of the basic theoretical characteristics of air-to-water heat pumps, sizing of air-to-water heat pumps and their energy efficiency in different operating modes, review of energy efficiency classes of heat pumps, consideration of an example of the operation of an air-to-water heat pump in the heating system of a family house in Pazarić (Sarajevo), application of the combined methodology of reading the parameter values from the indoor unit of the heat pump and calculating the SCOP value, determination of the energy class of the observed heat pump, adjustment of the operating parameters of the heat pump in order to increase energy efficiency and basic conclusions and recommendations related to operating air-to-water heat pumps. Basically, the priority task related to heating a family house in Pazarić was to achieve adequate indoor comfort, which was not at a satisfactory level. By adjusting the operating modes of the observed heat pump, the seasonal efficiency of the heat pump, expressed through SCOP, and most importantly, indoor comfort, increased. Which was confirmed by the users of this system, later. This clearly leads to the final outcome of creating a general protocol for adjusting design and system parameters to increase the energy efficiency of air-to-water heat pumps. Combined methods were used for calculation and verification of results [5, 6, 7].

III. CLASSIFICATION OF HEAT PUMPS

A heat pump is a device that uses a left-handed cycle to raise energy from a lower temperature level to a higher temperature level. To do this, it is necessary to supply additional energy that is needed for compensation work, i.e. increasing the pressure of the refrigerant. Based on this additional energy, the following are most commonly used today:

- Compressor heat pumps, where the cooling fluid flows through the compressor, i.e. raising the pressure of the cooling fluid.
- Diffusion absorption heat pumps, where the pressure of the cooling fluid is raised through the supplied heat.

In our region, especially when it comes to low-power heat pumps used in individual residential buildings, compressor heat pumps are used. The operating principle of a compressor heat pump is based on 4 cycles: evaporation, compression, condensation and throttling. In the evaporator, the refrigerant evaporates by taking heat from the heat source. Therefore, refrigerants with a low evaporation point are used (they can take more heat from the heat source and can operate at lower temperatures of the heat source). This is followed by compression in the compressor. Together with the pressure, the temperature of the refrigerant increases and in the condenser this heat is transferred to the consumer (heating water, air or some other fluid). After that, throttling is performed to the pressure prevailing in the evaporator and the cycle is repeated. In order for the left-hand cycle in the heat pump to be realized, it is necessary to enable [8, 9]:

- A heat source that will transfer heat to the refrigerant in the evaporator.
- A heat sink to which the refrigerant transfers heat in the condenser.

Depending on the type of heat source and sink, the following are most commonly used on our market:

- Water-to-water heat pumps.
- Ground-to-water heat pumps.
- Air-to-air heat pumps.
- Air-to-water heat pumps.

In addition to these divisions, water-to-air, ground-to-air, and similar heat pumps are common in the world, but they are not represented in our region and are not included in this paper.

IV. AIR-TO-WATER HEAT PUMPS

Air-to-water heat pumps are most common in systems where there is already a hot water distribution system for the heating installation. In this system, the outside air serves as the heat source, and the water from the heating system serves as the heat sink. These heat pumps are taking up an increasing share of the European heat pump market [10]. The reason for this is that they can be easily integrated into existing hot water heating systems (radiator heating, fan convectors, panel heating) with relatively low investment costs.

Fig. 1 shows a schematic diagram of an air-to-water heat pump [11].

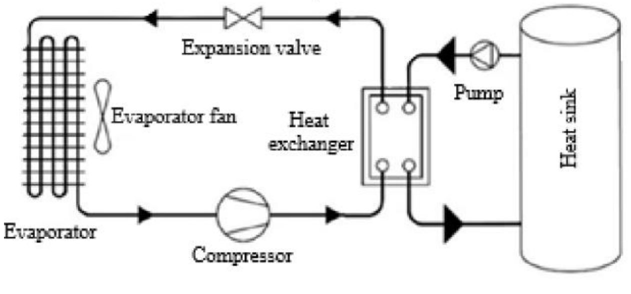


Figure 1. Schematic of an air-to-water heat pump [11]

In all heat pumps where air is used as a heat source (air-air and air-water), the thermal output and efficiency decrease in cold conditions, i.e. the energy efficiency (COP) of these heat pumps depends on the temperature and humidity of the outside air.

According to the construction, air-water heat pumps can be divided into:

- Single-stage heat pumps.
- Two-stage heat pumps.
- Cascade heat pumps.

In our area, and in general, with regard to lower-power heat pumps (for heating individual residential buildings), single-stage heat pumps are most commonly used [11].

V. SIZING OF AIR-TO-WATER HEAT PUMPS AND THEIR ENERGY EFFICIENCY IN RESIDENTIAL HEATING SYSTEMS

Due to the increase in energy prices, heat pumps are increasingly taking part in heating residential buildings. The overall benefits of using heat pumps are multiple: greater user comfort, fully automated operation and savings in operating costs. In order to achieve the above benefits, it is necessary that the complete thermotechnical system of the observed building is well designed and constructed, quality equipment is installed and regularly serviced throughout its service life. In addition to newly designed buildings, heat pumps are increasingly used as a replacement for conventional heat sources in existing thermotechnical systems. The observed residential heat pumps are made in two versions:

- Monoblock design of the heat pump, where the complete equipment is located in one (external) heat pump unit. The heat pump is connected directly to the existing or newly designed heating system in the building via a hot water pipe.
- Split version of the heat pump. In this version, the heat pump consists of two parts, an outdoor and an indoor unit. The outdoor unit houses the main components: compressor, evaporator, expansion valve, while the indoor unit houses the condenser with a regulator and associated equipment for connecting the heat pump to the hydraulic system. The outdoor and indoor units are connected by a pipeline through which the refrigerant flows.

The heat pump in hot water heating systems can be dimensioned to meet the heat demand on its own or to operate in combination with other heat sources. Based on this, the following heat pump operating modes can be distinguished [12]:

- Monovalent operating mode.
- Bivalent operating mode with the use of an additional heat source.
- Bivalent operating mode with an alternative heat source [12].

A. Monovalent operating mode

In monovalent operation mode, the heat pump is dimensioned to cover the heat needs of the building (including DHW preparation) throughout the entire heating season without the need for additional heat sources. In air-to-water heat pumps, the capacity decreases with decreasing outdoor temperature, while at the same time the heat losses of the designed building increase. Accordingly, in order for the heat pump to operate in monovalent operation mode (without additional heat sources), it is necessary to “oversize” the heat pump so that its capacity at the outdoor design temperature is greater than or equal to the heat needs of the building. In this way, the heat pump operates with reduced capacity for most of the heating season, while the maximum capacity is used only in design conditions. In monovalent operation mode, it is necessary to initially select a heat pump with higher power, so that it can meet the heat needs in design conditions.

B. Bivalent heat pump operating mode with the use of an additional heat source

In this operating mode, the heat pump is sized to cover the building's heat needs up to a certain outdoor temperature (bivalent point) determined by the designer. By lowering the outdoor temperature below the bivalent point, the heat pump gives a signal to the additional heat source to turn on and compensate for the lack of capacity. This additional heat source can be an electric heater, an electric boiler, a gas or fuel oil boiler, another heat pump, and the like. It is not suitable to use pellet and wood-burning boilers due to their slow response. All additional heat sources must be able to operate in the temperature mode of the heat pump. The inclusion of an additional heat source is controlled by the heat pump controller. This method of supplementing the heat pump capacity is most often used with air-to-water heat pumps. In the bivalent operating mode with supplementing the capacity with an additional heater, the designed heat pump has a lower capacity than if it had been selected in the monovalent operating mode.

Engineers from Midea Corporation conducted an analysis for a single-family house in Munich (Germany). The external design temperature was adopted from the literature and is -16 ºC. The minimum average monthly winter temperature was -6 ºC and this was chosen to be the bivalent point. The total losses at the external design temperature were 10 400 W, while at the selected bivalent temperature they were 7 500 W. The designed temperature regime of the heat pump was 35/30 ºC. A low-temperature underfloor heating system was used to heat the building.

Table 1 shows the selection of the heat pump for monovalent and bivalent operation with an additional electric heater that is part of the heat pump [13].

It is important to note that the selected heat pump in bivalent mode operates at nominal load, while the selected heat pump in monovalent mode operates, at the design temperature, at maximum load. Both heat pumps are in split design, consisting of an outdoor and indoor unit in which there is an additional electric heater with a power option of 3.6 or 9 kW. The previous table shows that if a heat pump is selected for monovalent mode, it is necessary to choose a significantly more powerful (and more expensive) unit that will operate at minimum load for most of the heating season. By correctly selecting the bivalent point, it is possible to adopt a smaller heat pump, which means lower investment costs, cheaper maintenance in the future, and the like more.

Fig. 2 shows diagrams illustrating the selection of a heat pump for monovalent and bivalent operation with an additional heat source for a specific case [12, 13].

TABLE I. SELECTION OF HEAT PUMP IN MONOVALENT AND BIVALENT OPERATING MODE

Operating mode	*Heat losses*	*Outside temperature*	*Unit type*	*Capacity at 35/30 °C*	*COP*
Monovalent	10 400 watts	-16 °C	MHA-V16W/D2N8-B	10 700 watts	2.17
Bivalent with supplementary el. heater	7 500 watts	-6 °C	MHA - V10W/D2N8-B	7 960 watts	2.4

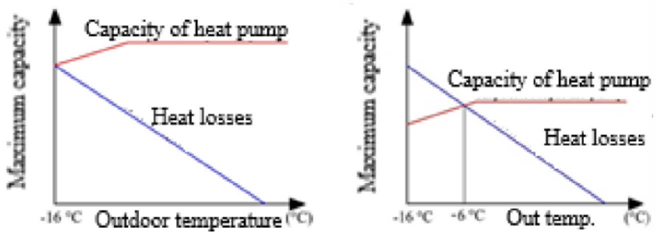


Figure 2. Monovalent operation mode, left and bivalent heat pump operation mode, right

C. *Bivalent mode of operation of the heat pump with an alternative heat source*

The bivalent operating mode of a heat pump with an alternative heat source is used so that, up to a certain value of the external temperature (bivalent point), only the heat pump covers the heat needs of the building. When the temperature drops below the selected value, the alternative heat source is switched on and the heat pump stops working. This operating mode is used in existing installations that are dimensioned for high temperature regimes (e.g. 80/60 °C) that the heat pump cannot achieve. This usually happens in existing installations with radiator heating where the heat pump (even with an additional heat source) cannot achieve the required parameters of hot water in the heating system. A gas boiler, fuel oil, biomass, etc. can be used as an alternative energy source. Fig. 3 shows a diagram of the monovalent and bivalent operating modes of a heat pump [13].

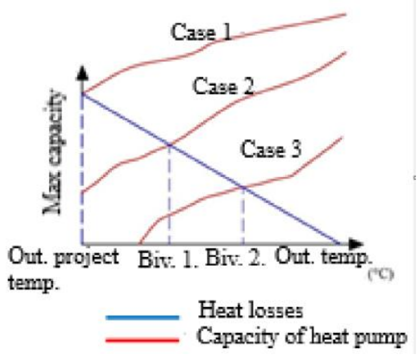
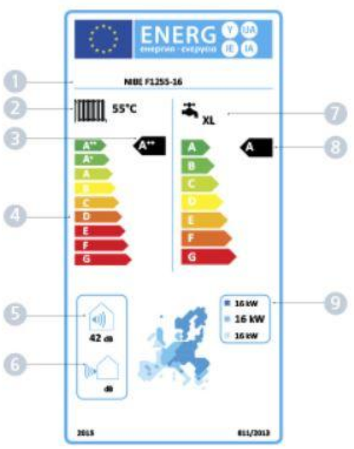


Figure 3. Diagram of monovalent and bivalent operating mode (Case 1 – monovalent operating mode, Case 2 – bivalent operating mode with additional source, Case 3 – bivalent operating mode with alternative heat source)

VI. ENERGY EFFICIENCY CLASSES OF HEAT PUMPS

Since September 2015, all heat pumps with an output of up to 70 kW must have a label that defines the energy class in terms of electricity consumption. According to the energy efficiency classes, all heat pumps are classified from G (the worst rating) to A+++ class (the best rating). The classification of heat pumps according to energy efficiency is made according to the EN 14825 standard. An illustration of such a label with explanations is given in Fig. 4. [10].



1 – manufacturer and model of the TP
2 – heating mode
3 – energy class in heating
4 – efficiency class scale
5 – noise level of the outdoor unit
6 – noise level of the indoor unit
7 – heating of domestic hot water
8 – energy class in heating of DHW
9 – Heating power in different climate zones

Figure 4. Label for defining the energy class of heat pumps

Energy efficiency classes are defined according to the seasonal value of the heat pump's coefficient of performance (sCOP) and are:

- A+++: sCOP > 5.1.
- A++: sCOP > 4.6.
- A+: sCOP > 4.
- A: sCOP > 3.4.
- B: sCOP > 3.1.
- C: sCOP > 2.8.
- D: sCOP < 2.5.

For the European area, there are 3 climate zones: cold, medium cold and warm climate zones [10]. The data on the energy labels refer to the specific climate zone where the product is sold. Climate zones are classified according to the average outdoor design temperatures, according to the EN 14825 standard. Thus, in the cold climate zone, the outdoor design temperature is up to tsp = - 22 ˚C, in the medium cold climate zone up to tsp = - 10 ˚C, and in the warm climate zone up to tsp = 2 ˚C.

In a study [10] entitled “Nordsyn study on air-to-water heat pumps in humid Nordic climate”, which was funded by the Nordic Council, the deviations of the heating capacities and coefficients of performance of heat pumps in real conditions from the declared values of the manufacturers were observed. The conclusion is that the energy labels of air-to-water heat pumps only show the energy efficiency class for medium-cold climate conditions, even though they are sold and installed in cold climate zones. Also, when they performed measurements of the heating capacities and coefficients of performance (COP) in the field, they concluded that they differed from the declared values. There are several possibilities why the actual measurements differed from the declared values:

- suboptimal operation of the heat pump (high temperatures of the heating water supply, heat losses in the heating system).
- poor adjustment of the heat pump operation regulator during service commissioning.
- standard factory tests are performed at lower humidity than real conditions.

The energy efficiency of air-to-water heat pumps in heating systems depends mostly on: the temperature and humidity of the outside air, the temperature regime of the hot water, and the load on the heat pump.

The outdoor air temperature has the greatest influence on the amount of heat that the refrigerant can take up in the evaporator. The more heat the refrigerant can take up in the evaporator, the greater the capacity of the heat pump. By reducing the amount of heat transferred to the evaporator, the compressor must compensate for the lost power, which results in higher electricity consumption and lower COP. The intensity of frost formation on the evaporator (which is the biggest problem of modern air-to-water heat pumps) directly depends on the humidity and temperature of the outdoor air. The problem of frost formation on the evaporator already occurs at temperatures below 5 ⁰C. Fig. 5 shows a diagram of the change in heat pump capacity and heating coefficient for different outdoor air parameters [14].

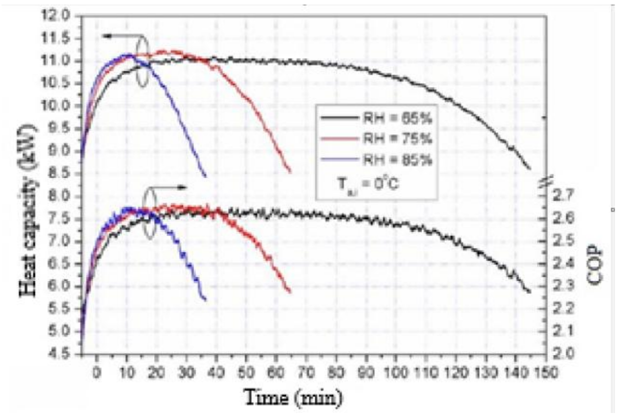


Figure 5. Change in heat pump capacity and COP due to frost formation on the evaporator

The general rule is that all heat pumps have higher heating coefficients (most often capacities) at low-temperature heating regimes. The lower the outlet water temperature, the higher the COP of the heat pump. In residential buildings, panel heating (floor, wall, ceiling), radiators or fan convectors are most often used as heat transfer devices. The selected temperature regime of the heating water depends on the selected heating elements. Table 2 shows the temperatures of the heating water that can be used in different hot water heating systems [15].

TABLE 2. MINIMUM HEATING WATER TEMPERATURES DEPENDING ON THE TYPE OF HEATING ELEMENT

Heating element type	***Minimum heating water temperature***
Plate and aluminum radiators	45 ˚C
Cast iron radiators	55 ˚C
Fan convectors	45 ˚C
Underfloor heating	30 – 35 ˚C

The minimum temperatures shown are for design conditions. Fig. 6 and 7 show the change in heat pump capacity and coefficient of performance (COP) as a function of heating water temperature and outdoor air temperature. The table is for the Swedish heat pump manufacturer “Nibe”, heat pump type F2120-20 [16].

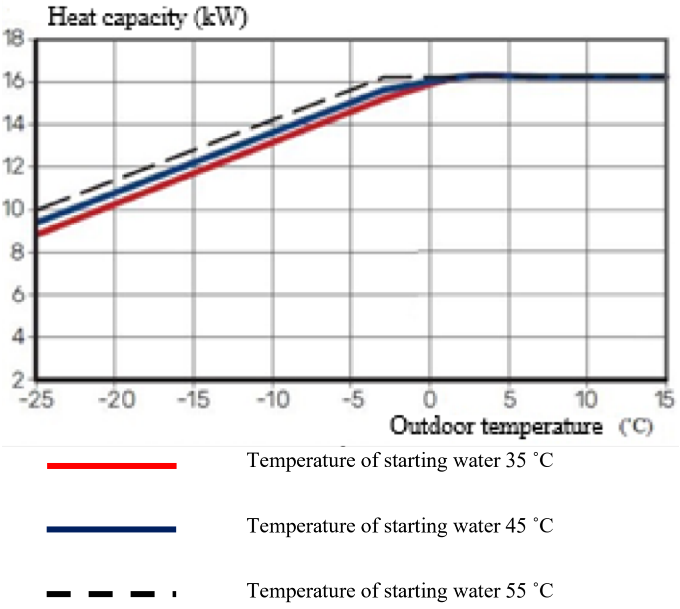


Figure 6. Capacity of the Nibe F2120-20 heat pump depending on the outdoor temperature and heating water temperature

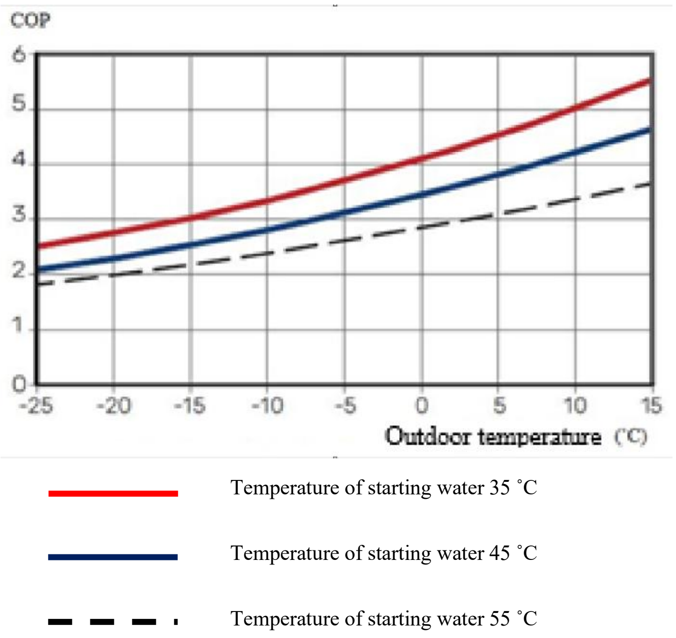


Figure 7. COP of the Nibe F2120-20 heat pump depending on the outdoor temperature and heating water temperature

When sizing a heat pump, it is necessary to follow the manufacturer's recommendations and to be guided by data on the coefficients of performance (COP) at different capacities of the same heat pump. For example, manufacturers in their data sheets most often provide capacities at maximum, nominal, average and minimum operating modes. Table 3 shows the capacity of an air-to-water heat pump, type PUHZ-SHW80VHA, manufactured by "Mitsubishi Electric", at the optimal operating mode (i.e. the operating mode at which the heat pump has the highest COP) [17].

TABLE 3. COP OF HEAT PUMPS PUHZ-SHW80VHA AT OPTIMAL CONDITIONS [17]

Outlet temperature of hot water [°C]		*35 °C*		*45 °C*		*55 °C*	
Outside temperature [°C]		Q [kW]	COP	Q [kW]	COP	Q [kW]	COP
	-7	7.18	3.2	7.33	2.46	7.4	1.97
PUHZ-SHW80VHA	2	7.54	3.68	7.35	3	7.21	2.33
		6.82	4.06	6.72	3.15	6.66	2.46
	7	7.15	4.82	6.03	3.7	5.79	2.9

If the mentioned heat pump were to be used under the conditions given in the table, it would work with the highest heating coefficient. If the heat pump were to be used at maximum power, its operating characteristics are shown in Table 4 [17].

TABLE 4. COP OF HEAT PUMPS PUHZ-SHW80VHA AT MAXIMUM LOAD [17]

Outlet temperature of hot water [°C]		*35 °C*		*45 °C*		*55 °C*	
Outside temperature [°C]		Q [kW]	COP	Q [kW]	COP	Q [kW]	COP
	-7	11.35	2.84	10.73	2.19	10.22	1.68
PUHZ-SHW80VHA	2	12.11	3.22	11.35	2.67	10.84	2.05
	7	12.36	4.34	11.55	3.42	10.8	2.75

Looking at Tables 3 and 4, it is clear that there are differences in the heat coefficients of the same heat pump, at the same conditions of outdoor temperature and water inlet temperature, but with different operating powers. For example, when operating at an outdoor design temperature of -7 °C, selecting the heat pump to operate at the optimal power level (Table 6) can result in a COP higher by 12-18% than if the heat pump were operating at maximum power.

All of these parameters are important to consider when sizing the heat pump. Just as it is not good for the heat pump to operate at maximum power, it is also not good for it to be oversized (larger investment, more expensive maintenance, compressor operating at minimum power, etc.). The designer must consider all of these parameters when selecting the heat pump.

In order to achieve the best possible performance of air-to-water heat pumps in real conditions, special attention should be paid to the design, construction and commissioning of the heat pump according to the basic guidelines:

- Dimension the system to operate with the lowest possible heating water temperature [18]:
- The heat pump capacity should be sufficient to cover the projected heat needs.
- Minimize heat losses in the system.
- During commissioning, set the additional electric heater to operate only in situations when its operation is necessary.
- Optimize the flow and heat output of the heating elements.
- Enable zone control and control of the water inlet temperature depending on the outdoor temperature.
- Enable correct installation of the heat pump so that the air flow around the outdoor unit is not blocked.

VII. CASE STUDY AND ANALYSIS OF THE OPERATION OF AN AIR-TO-WATER HEAT PUMP IN THE HEATING SYSTEM OF A FAMILY HOUSE IN PAZARIĆ (SARAJEVO)

The following example analyzes a heat pump used to heat a family house in Pazarić, Sarajevo. In addition to heating, the heat pump is also used to prepare domestic hot water (DHW). The building is two-story, with a total net area of approximately 160 m2. The basement of the building contains a garage with a storage room, a room, a living room and a toilet. The ground floor contains the main living room with a kitchen and dining room, two rooms and a bathroom. Total heat losses according to the existing project are approximately 15.2 kW at -18° C. Aluminum radiators, fan convectors and pipe registers in the bathrooms are used as heating elements. A two-pipe system with distribution cabinets in the garage where the heat pump is also located is designed. The entire building is divided into two branches: Branch 1 - heating of the living room on the ground floor and Branch 2 - radiator heating of other rooms. The circulation pumps of Branch 1 and 2 are controlled via digital programmable thermostats via the reference room, while the temperature in all rooms is regulated locally using thermal heads on the radiators. The heat pump and radiators are selected at a temperature regime of 50/45 ˚C for a bivalent outdoor temperature of t = -10 ˚C. In the case of lower outdoor temperatures, the user of the building uses other sources of heating the building (solid fuel - wood). Heat losses and the selection of radiators are not the subject of this paper. The text below only deals with the analysis of the heat pump installation. As a heat source for heating in the winter period and the preparation of DHW in both winter and summer periods, a heat pump in a "split" version was installed, type "Mitsubishi Zubadan PUHZ-SHW112YAA + ERST20C-VM2C", a product of the company "Mitsubishi Electric", with the following characteristics, Table 5.

TABLE 5. CHARACTERISTICS OF THE OBSERVED HEAT PUMP FOR HEATING A FAMILY HOUSE [17]

Outdoor heat pump unit - Mitsubishi Zubadan PUHZ-SHW112YAA:	
- Nominal heat capacity at (tsp = 7 ˚C), 50/45 ˚C:	11.2 kW, COP = 3.01
- Nominal heat capacity at (tsp = 2 ˚C), 50/45 ˚C:	10.8 kW, COP = 2.25
- Nominal capacity at bivalent point (tsp = -10 ˚C), 50/45 ˚C:	10.8 kW, COP = 2.01
- number of compressors:	1
- compressor type:	hermetic scroll compressor
- evaporator defrosting method:	defrosting by adding hot gas from the compressor outlet
- number of fans:	1
- refrigerant:	R410A, m = 4.6 kg
- operating voltage V/Ph/Hz:	400/3/50 Hz
- maximum electrical power of the outdoor unit:	5.5 kW
- outdoor unit dimensions (WxHxD):	1050x1020x330 mm
- outdoor unit weight:	128 kg
Internal heat pump unit – Cylinder ERST20C-VM2C:	
- operating voltage V/Ph/Hz:	1 x 230 V
- power of the additional electric heater in the indoor unit:	2 kW
- volume of the DHW tank in the indoor unit:	200 l
- dimensions of the indoor unit (WxHxD):	595x1600x680 mm
- net weight of the indoor unit:	110 kg

The outdoor and indoor units are connected by insulated copper pipes through which the refrigerant (R410a) flows. The indoor unit includes an expansion vessel, a safety valve, a dirt trap and a primary circulation pump. Also, the indoor unit is located in a domestic hot water tank, made of stainless steel, with a capacity of 200 liters. When the hot water temperature sensor, installed in the domestic hot water boiler, reads a temperature drop of 10 °C, below the set value, the heat pump redirects its full power to heating the DHW tank. Once the set temperature is reached, the heat pump continues to send hot water to the heating system.

For protection against legionella, the indoor unit of the heat pump is set to heat the water in the boiler to 65 °C once a week, at night.

In order to separate the hydraulic circuits of the heat pump and the rest of the installation, as well as to provide a sufficient amount of water for the smooth operation of the heat pump, a hydraulic diverter was constructed, with a volume of V = 200 liters.

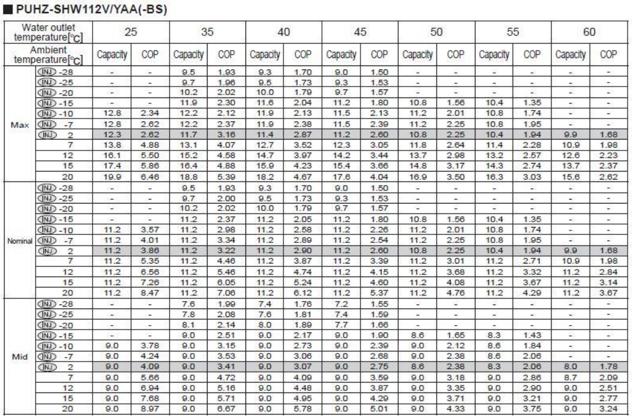
Two branches depart from the hydraulic switch into the building:

- Branch 1 – heating of the living room on the ground floor.
- Branch 2 – radiator heating of other rooms.

Expansion of the water is enabled via an additional closed expansion vessel.

It is important to note that the pipe network is uninsulated and that it is led to all heating elements through the floor screed.

Fig. 8 shows the characteristics of the selected heat pump at different operating modes [17].



■ PUHZ-SHW112V/YAA(-BS)

Water outlet temperature[°C]		25		35		40		45		50		55		60	
Ambient temperature[°C]		Capacity	COP	Capacity	COP	Capacity	COP	Capacity	COP	Capacity	COP	Capacity	COP	Capacity	COP
Max	INJ -28	-	-	9.5	1.93	9.3	1.70	9.0	1.50	-	-	-	-	-	-
	INJ -25	-	-	9.7	1.96	9.5	1.73	9.3	1.53	-	-	-	-	-	-
	INJ -20	-	-	10.2	2.02	10.0	1.79	9.7	1.57	-	-	-	-	-	-
	INJ -15	-	-	11.9	2.30	11.6	2.04	11.2	1.80	10.8	1.56	10.4	1.35	-	-
	INJ -10	12.8	2.34	12.2	2.12	11.9	2.13	11.5	2.13	11.2	2.01	10.8	1.74	-	-
	INJ -7	12.8	2.62	12.2	2.37	11.9	2.38	11.5	2.39	11.2	2.25	10.8	1.95	-	-
	INJ 2	12.3	2.62	11.7	3.16	11.4	2.87	11.2	2.60	10.8	2.25	10.4	1.94	9.9	1.68
	7	13.8	4.88	13.1	4.07	12.7	3.52	12.3	3.05	11.8	2.64	11.4	2.28	10.9	1.98
	12	16.1	5.50	15.2	4.58	14.7	3.97	14.2	3.44	13.7	2.98	13.2	2.57	12.6	2.23
	15	17.4	5.86	16.4	4.88	15.9	4.23	15.4	3.66	14.8	3.17	14.3	2.74	13.7	2.37
	20	19.9	6.46	18.8	5.39	18.2	4.67	17.6	4.04	16.9	3.50	16.3	3.03	15.6	2.62
Nominal	INJ -28	-	-	9.5	1.93	9.3	1.70	9.0	1.50	-	-	-	-	-	-
	INJ -25	-	-	9.7	2.00	9.5	1.73	9.3	1.53	-	-	-	-	-	-
	INJ -20	-	-	10.2	2.02	10.0	1.79	9.7	1.57	-	-	-	-	-	-
	INJ -15	-	-	11.2	2.37	11.2	2.05	11.2	1.80	10.8	1.56	10.4	1.35	-	-
	INJ -10	11.2	3.57	11.2	2.98	11.2	2.58	11.2	2.26	11.2	2.01	10.8	1.74	-	-
	INJ -7	11.2	4.01	11.2	3.34	11.2	2.89	11.2	2.54	11.2	2.25	10.8	1.95	-	-
	INJ 2	11.2	3.86	11.2	3.22	11.2	2.90	11.2	2.60	10.8	2.25	10.4	1.94	9.9	1.68
	7	11.2	5.35	11.2	4.46	11.2	3.87	11.2	3.39	11.2	3.01	11.2	2.71	10.9	1.98
	12	11.2	6.56	11.2	5.46	11.2	4.74	11.2	4.15	11.2	3.68	11.2	3.32	11.2	2.84
	15	11.2	7.26	11.2	6.05	11.2	5.24	11.2	4.60	11.2	4.08	11.2	3.67	11.2	3.14
	20	11.2	8.47	11.2	7.06	11.2	6.12	11.2	5.37	11.2	4.76	11.2	4.29	11.2	3.67
Mid	INJ -28	-	-	7.6	1.99	7.4	1.76	7.2	1.55	-	-	-	-	-	-
	INJ -25	-	-	7.8	2.08	7.6	1.81	7.4	1.59	-	-	-	-	-	-
	INJ -20	-	-	8.1	2.14	8.0	1.89	7.7	1.66	-	-	-	-	-	-
	INJ -15	-	-	9.0	2.51	9.0	2.17	9.0	1.90	8.6	1.65	8.3	1.43	-	-
	INJ -10	9.0	3.78	9.0	3.15	9.0	2.73	9.0	2.39	9.0	2.12	8.6	1.84	-	-
	INJ -7	9.0	4.24	9.0	3.53	9.0	3.06	9.0	2.68	9.0	2.38	8.6	2.06	-	-
	INJ 2	9.0	4.09	9.0	3.41	9.0	3.07	9.0	2.75	8.6	2.38	8.3	2.06	8.0	1.78
	7	9.0	5.66	9.0	4.72	9.0	4.09	9.0	3.59	9.0	3.18	9.0	2.86	8.7	2.09
	12	9.0	6.94	9.0	5.16	9.0	4.48	9.0	3.87	9.0	3.35	9.0	2.90	9.0	2.51
	15	9.0	7.68	9.0	5.71	9.0	4.95	9.0	4.29	9.0	3.71	9.0	3.21	9.0	2.77
	20	9.0	8.97	9.0	6.67	9.0	5.78	9.0	5.01	9.0	4.33	9.0	3.75	9.0	3.24

Figure 8. Characteristics of the heat pump Mitsubishi Zubadan PUHZ-SHW112YAA [17]

For the above case, an analysis of the energy efficiency of the installed heat pump was performed for 2021. The temperature regime of the heat pump during the observed year in design conditions was 50/45 ºC.

For the purposes of this work, data was taken from the internal unit of the heat pump, based on which the device's operating parameters can be read: the amount of heat energy delivered for a year, the amount of electricity consumed, as well as other parameters of the heat pump's operation. The readings were taken from the internal unit for 2021 (when the house was most used). This data was used to calculate the seasonal heating coefficient.

Table 6 shows the electricity consumption for the entire family house in Pazarić for the entire year 2021, which was taken from the electricity distributor's bill.

TABLE 6. ELECTRICITY CONSUMPTION FOR THE OBSERVED FACILITY FOR 2021

Month	*Higher tariff [kWh]*	*Lower tariff [kWh]*	*Total [kWh]*	*The total value of the electricity bill [BAM]*
January	1353	803	2156	371.6
February	858	495	1353	231.2
March	979	671	1650	274.7
April	748	517	1265	211.8
May	341	209	550	97.1
June	88	110	198	35.7
July	110	110	220	33.9
August	22	44	66	21.0
September	231	176	407	71.4
October	657.8	469.7	1127.5	188.5
November	860.2	641.3	1501.5	247.5
December	833.8	621.5	1455.3	240.0
Total	7081.8	4867.5	11949.3	2024.4

The previous table shows the total electricity consumption of the entire facility (heat pump + other consumers in the house). It can be seen that about 80% of the electricity consumed is used to operate the heat pump that heats the facility and prepares DHW. It should be noted that DHW preparation via the heat pump is used in the summer period only in cases where a large number of people are staying in the facility, and that the kitchen is not connected to the central DHW distribution. According to the data read from the indoor unit of the observed heat pump, in 2021, a total of 25 783 kWh of heat energy was delivered from this heat pump, of which 868 kWh was delivered for heating domestic hot water and 24 915 kWh was delivered for heating the facility. The total electricity consumption (heat pump + electric heater in the indoor unit) was 9 819 kWh, of which 397 kWh of electricity was consumed during the operation of the heat pump in the domestic hot water preparation mode, and 9 421 kWh of electricity was consumed during the operation of the heat pump in the heating mode. The total price of electricity used to operate the heat pump for 2021 was around 1600 BAM. Taking into account the price of electricity in 2025, the heat pump's consumption would be around 2300 BAM.

Using the following formulations, based on the previous data, the total seasonal SCOP in different operating modes can be calculated Eq. (1-3):

- Total seasonal COP of the heat pump:

$$sCOP_{tot} = \frac{Q_H}{W} = \frac{25783}{9819} \approx 2.6 \tag{1}$$

- Seasonal COP of the heat pump in heating mode:

$$sCOP_h = \frac{Q_H}{W} = \frac{24915}{9421} \approx 2.64 \tag{2}$$

- Seasonal COP of the heat pump in DHW preparation mode:

$$sCOP_{DHW} = \frac{Q_H}{W} = \frac{868}{397} \approx 2.2 \tag{3}$$

According to the obtained sCOP values, the mentioned heat pump falls between D and C energy efficiency classes (2.5 < sCOP < 2.8). Based on the manufacturer's technical specifications for the installed Zubadan PUHZ-SHW112YAA unit, the nominal COP at 7 °C outdoor air drops from 4.46 (at 35 °C supply) to 3.01 (at 50 °C supply), showcasing a 32.5% reduction in immediate efficiency at page 7. On a seasonal scale, the calculated heating efficiency (sCOPh = 2.64) under the current 50/45 °C radiator regime highlights a seasonal efficiency degradation of approximately 34% compared to the potential (sCOP > 4) achievable with low-temperature underfloor systems (30–35 °C) under identical climatic conditions (pp. 5, 8).

If, instead of a heat pump, electricity, a pellet, gas or brown coal boiler were used for the specified amount of heat (25,783 kWh), the energy consumption would be as shown in Table 7. The efficiency coefficients of the boilers were taken from the manufacturer's catalogue [19, 20]. The actual efficiency coefficients in real conditions may be significantly lower.

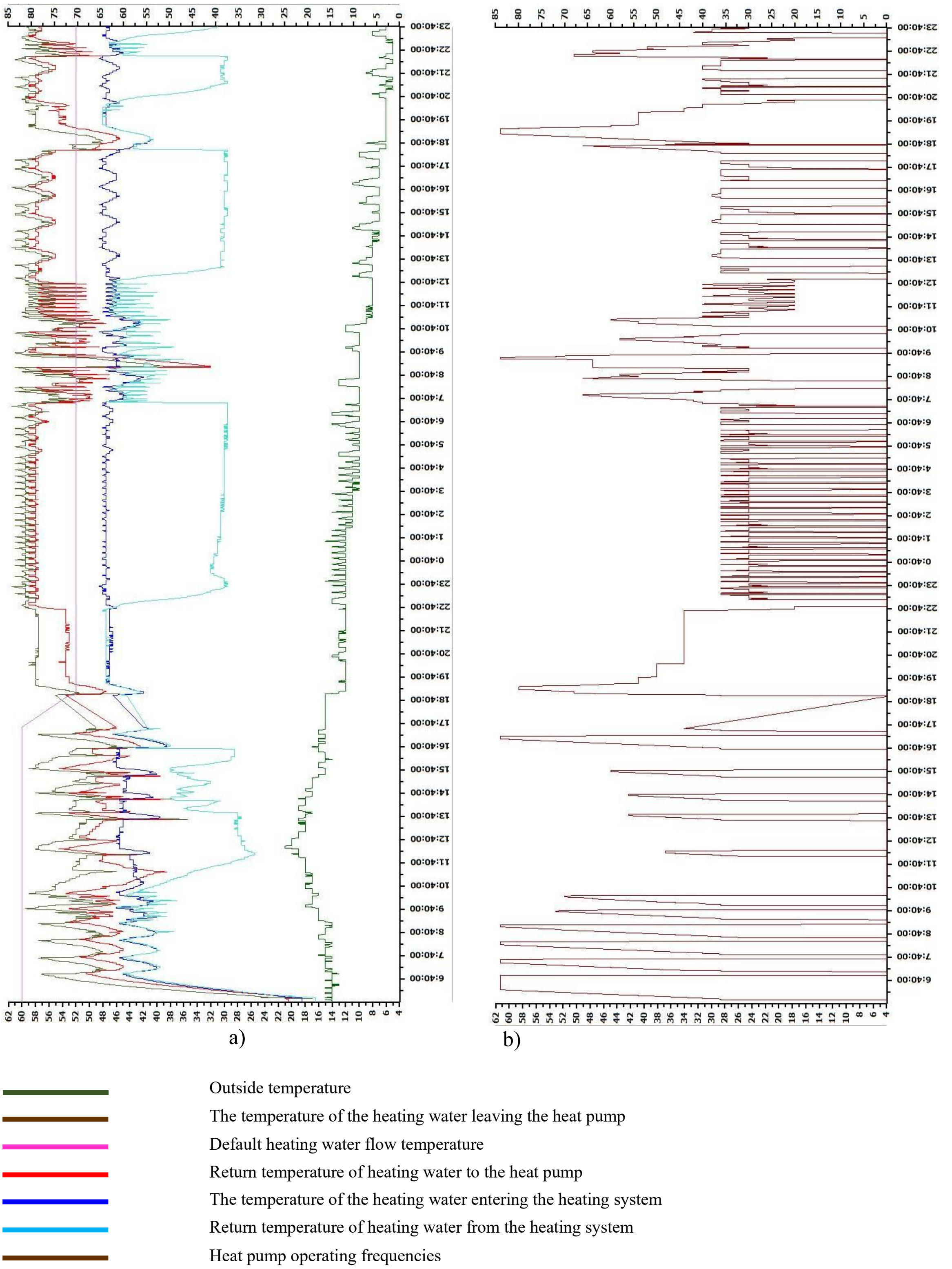
TABLE 7. COMPARISON OF HEAT PUMPS WITH OTHER POTENTIAL HEAT SOURCES

Heat source	*Annual fuel/energy consumption*	*The price for the required amount of fuel*	*Price difference compared to a heat pump for 2021*
Heat pump	25,783 kWh/year	1,600 BAM/year in 2021. 2,300 BAM/year in 2025.	-
Pellet boiler Hd = 16,000 kJ/kg 560 BAM/ton η ≈ 0.9	6,500 kg/year	3 640 BAM/year	+ 2,040 BAM/year
Coal boiler Hd = 18,000 kJ/kg 180 BAM/ton η ≈ 0.7	7,400 kg/year	1333 BAM/year	- 267 BAM/year
Gas condensing boiler Hd = 35 700 kJ/m2 1.46 BAM/m3 η ≈ 0.98	2 650 m3/year	3 800 BAM/year	+ 2 200 BAM/year

Analyzing the results obtained in the previous table, it can be seen that the annual energy costs, if a gas or pellet condensing boiler were used, according to current prices, more than double the electricity costs for operating a heat pump. A heat pump has an advantage over pellet and gas heating even if the price of electricity increases in 2025. Only coal heating has a lower annual cost. Due to its high environmental impact, coal heating is not an alternative when heating individual residential buildings due to the high amount of pollution.

This paper does not consider a more detailed comparison of the different heat sources shown in Table 7 from the perspective of total investment. It is clear that a heat pump, along with a condensing gas boiler, provides the greatest comfort and automated operation. Pellet and coal boilers require frequent cleaning, storage of energy, etc. The disadvantage of a heat pump compared to other heat sources is a somewhat more expensive investment and more expensive spare parts. In recent years, due to the crisis in gas and energy prices, more and more households are opting for a heat pump. The reason for this, to some extent, is the relatively low price of electricity compared to European Union countries.

Analyzing the calculated sCOP of the heat pump, for the observed object, it is not good enough, if we take into account that, according to the manufacturer's specification, at lower outlet water temperatures, it can be sCOP > 4 (energy efficiency class A+). In order to be able to analyze the obtained sCOP of the heat pump, it is necessary to look at the diagrams shown in the following Fig. 9 and 10. The diagrams were read from the indoor unit of the heat pump via Mitsubishi software. The readings were taken for the days: 4. - 5.11. and 18. - 19.11. for the year 2021.



a) b)

Figure 9. Heat pump operation diagram for the period: 4.11-5.11. 2021. a) temperature readings, b) heat pump compressor operating frequency

Fig. 9 shows the operation of the observed heat pump in two modes:

- For the period from 05:40 to 17:40, the heat pump operated according to the set water temperature in the hot water accumulator (hydraulic switch). The set water temperature was 50 ºC. The heat pump was switched off when the water temperature reached 55 ºC and switched on again when the water temperature dropped to 45 ºC. This resulted in significant variations in the temperature of the heating water entering the system (between 45 and 40 ºC), which affected the comfort of the end user.

- For the period from 17:40 to 23:40, the heat pump operated according to the set temperature of the heating water entering the system. This resulted in the heat pump operating constantly, with lower operating frequencies (lower compressor load, lower unit noise and lower electricity consumption). The heating water flow temperature was higher than in the first case and varied less, which contributed to greater user comfort and better heat transfer from the radiators.

Fig. 10 shows the continuation of the heat pump operation with regulation according to a constant flow water temperature. The heat pump operation diagram corresponds to the operation diagram from the period 17:40 – 23:40 from Fig. 9. The heat pump compressor operates at higher frequencies only at the beginning of the heat pump operation (the period of water heating in the system) and then operates at lower frequencies and with lower load. It is important to note that both diagrams (Fig. 9 and 10) were taken from the heat pump after a 24-hour test. That is, the heat pump was turned on and turned off after 24 hours and the diagrams shown were taken. During these 24 hours, the first heating of the building and maintenance of the designed temperature (20 ºC) were carried out. From the above diagrams shown in Fig. 9 and 10, some of the reasons for the reduced sCOP compared to the manufacturer's declared value can be concluded:

- The heat pump operates at the maximum water temperature possible at the current outdoor temperature;

- The difference between the temperature regime of the heat pump and the heating system is significant.

For example, for the temperature reading at 19:30 (Fig. 10), the heat pump operated at a temperature regime of 57.5 / 52.5 ºC. At that time, the flow and return temperatures of the heating water to the system were 47 and 44.5 ºC. Accordingly, it can be concluded that the heat pump operates at a higher temperature regime than is currently required. Ideally, this temperature difference should be as small as possible, so that the heat pump can operate at lower temperatures and achieve higher COP and sCOP.

In order to reduce this effect, it would be necessary to ensure better mixing of the water in the hydraulic switch (hot water accumulator). This can be achieved by:

- Ensuring better mixing of heating water in the hydraulic switch (by increasing the flow of hot water on the heat pump side, using adequate hydraulic switches intended for heat pumps, etc.);

- The heating system should be uninterrupted in operation;

- Implementation of weather-compensated control: The heat pump control unit must be configured to transition from a fixed supply temperature strategy to an outdoor temperature-driven heating curve (p. 11). This modification directly reduces the temperature difference between the heat pump generation and system distribution loops, optimizing compressor operational frequencies and boosting seasonal performance indices (p. 11);

- Enable flow regulation and complete insulation of the pipe network in order to minimize losses.

In this way, an increase in both the COP and sCOP values is simultaneously achieved, while improving the internal comfort in the building, which was the priority goal of this work. The complete hydraulic configuration and component layout of the analyzed residential heating system are illustrated in Fig. 11. The schematic clearly labels and presents all critical components for a better understanding of the problem.

Different combinations of photovoltaic thermal hybrid solar collector (PVT) and multi-source heat pump for space heating and hot water production (DHW) are increasingly expressed. All these combinations lead to an overall increase in efficiency [21]. This leads to nearly zero-energy buildings, i.e. nZEB (nearly zero-energy building). Such a building has a very low energy consumption, which is obtained to a significant extent from renewable energy sources, including that which is produced on the building itself or very close to it. Recently, increasing importance has been given to the development of studies that deal with a comprehensive methodology based on data for the assessment and optimization of the operational performance of residential air-to-water heat pumps with the use of real-time monitoring of the operation of the heat pump in combination with IoT and machine learning [22].

In this paper, the calculation results obtained in the paper related to air-to-water heat pumps with the calculation on the DEP platform (part for heat pump) [6, 23], were compared. Significant matches were achieved and the mutual validity of the results was confirmed. The basic assumption when using heat pumps starts from the fact that the building was previously renovated and thermally insulated, with the windows and doors having been replaced.

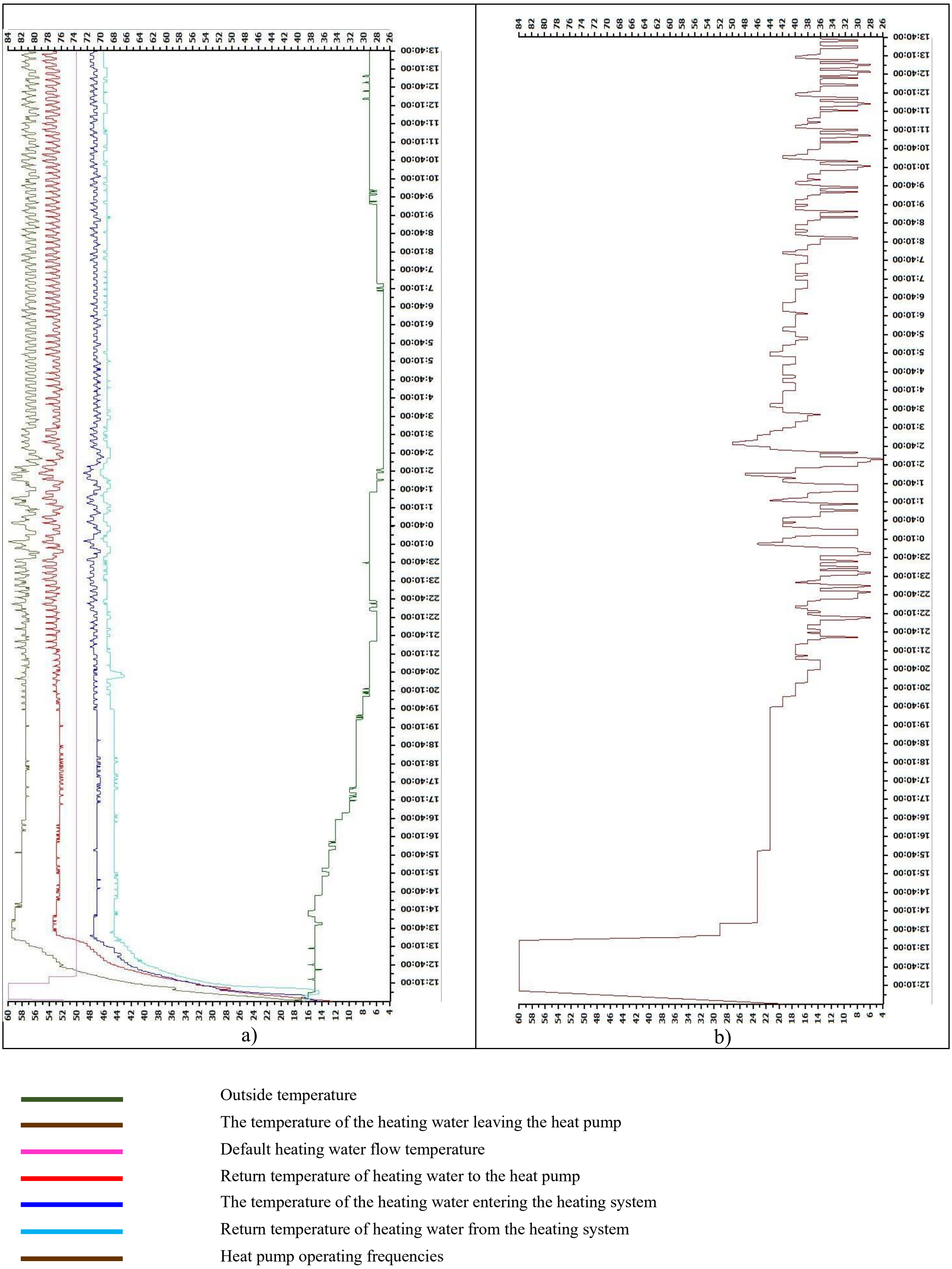


Figure 10. Heat pump operation diagram for the period: 18.11.-19.11. 2021. a) temperature readings, b) heat pump compressor operating frequency

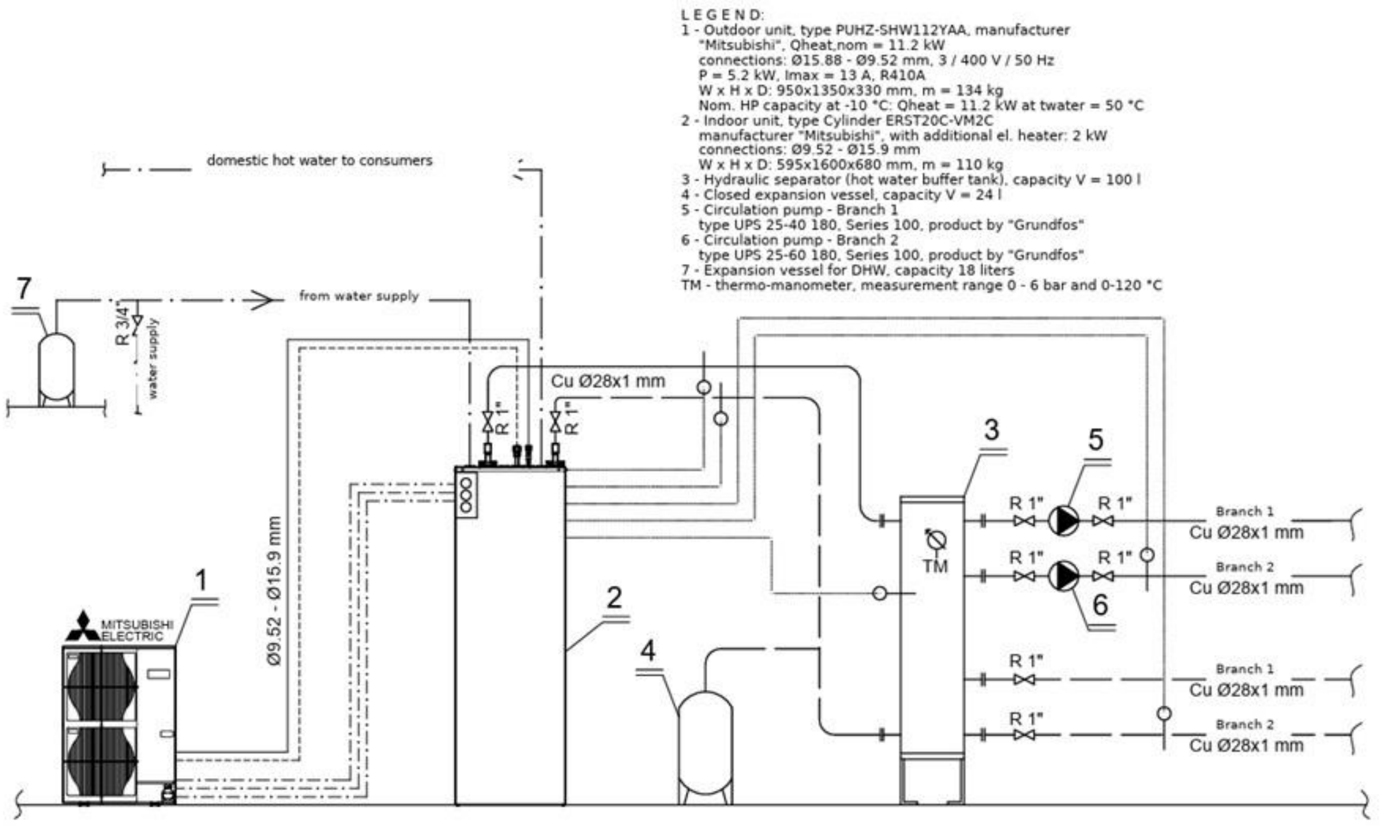


Figure 11. Heat pump operation diagram for the period: 18.11.-19.11. 2021. a) temperature readings, b) heat pump compressor operating frequency

VIII. CONCLUSION AND RECOMMENDATIONS

Air-to-water heat pumps have proven to be a stable source of energy for heating, even in cold climates. In addition to heating, most heat pumps can also be used for cooling, which was not taken into account in writing this paper. With the increase in energy prices, living standards, and people's needs for comfort, heat pumps are becoming a common choice as the main (and sometimes the only) source of heat for heating individual residential, as well as larger commercial and industrial buildings. More and more district heating plants in European countries are using large heat pumps to cover their heat needs up to a certain bivalent temperature. The expansion of heat pump sales in Bosnia and Herzegovina is also encouraged by the fact that there are a few manufacturers of air-to-water heat pumps in BiH.

Developed European countries such as Sweden, Norway, Denmark, and Switzerland are leading the way in the use of heat pumps. Most European countries financially encourage the use of heat pumps in order to enable the implementation of energy policies.

The installation of heat pumps is far from being without its drawbacks, which are reflected in a slightly higher initial investment, more expensive spare parts, and the like. Air-to-water heat pumps achieve significant savings in operation compared to conventional heating systems, while the installation cost is lower than that of ground-to-water and water-to-water heat pumps. The advantage of all heat pumps with water as a heat sink is that they can be easily integrated into existing central heating systems.

In addition, the development of technology has enabled the use of natural refrigerants such as: propane (R290), carbon dioxide (R744), isobutane (R600a), etc. These natural refrigerants have long been considered a long-term solution in the development of heat pump technologies.

If heat pumps are additionally combined with solar photovoltaic systems, it is possible to approach zero energy consumption (nZEB)

This paper presents the possibilities of using air-to-water heat pumps in heating residential buildings. This paper covers low-power heat pumps (up to 23 kW), the classification of this type of heat pumps, as well as descriptions of the most important parts of an air-to-water heat pump. Basic guidelines for designing air-to-water heat pumps are given, so that the system can operate with the greatest possible energy efficiency. The paper presents a practical example with a constructed air-to-water heat pump, its sCOP for the observed year, and heat pump operation diagrams are given. Based on the established protocol for adjusting the operating modes of the heat pump, results have been achieved in increasing the SCOP factor and internal comfort in the building.

The directions of further research will be focused on the development of a laboratory and a universal protocol for measuring and determining both the heating coefficient and the cooling coefficient of heat pumps in accordance with the geolocality of the heat pump application and the climatic environment in which the observed heat pump operates.

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