The Calculation of the Seasonal Performance Factor (SPF) of a Domestic Hot Water Heat Pump Integrated with a Mechanical Ventilation Installation with Heat Recovery for a Residential Premises in the EnerPHit Standard

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Abstract

The existing residential premises located in the attic in Poznań, owned by a private person, was qualified for deep energy modernization due to high energy consumption and related costs. The goal was achieved by thermal modernization of the premises to the EnerPHIT standard according to the Passive House Institute in Darmstadt. One of the most important elements of the energy modernization was the installation of mechanical ventilation with heat recovery, which was integrated with the installation of a heat pump for heating domestic hot water. In the summer, the domestic hot water heat pump it receives heat from the air blown into the object's volume, contributing to its cooling, this is the so-called discharge cooling - free of charge, created as a result of heating domestic hot water. In transitional periods and in winter, the domestic hot water heat pump extracts heat from the ventilation air discharged from the building. Exhaust air has a greater energy potential than outside air because it is warmer and more humid. The paper presents estimates of energy (savings of approximately 7,3 % of electrical energy consumed), economic (SPBT = 1.92 years), and environmental (7.8% reduction in CO2 emissions) benefits related to implementing this solution for the residential premises in question in Poland. The presented solution contributes to sustainable development goals because it minimizes energy consumption and reduces CO2 emissions, which is important. It also decreases running costs, while the investment itself is modest.

Keywords: *deep energy modernization, SPF, energy efficiency*

1. Introduction

The commitment undertaken by Poland as a European Union member state to achieve climate neutrality is one of the greatest civilizational challenges for Poland in its history, affecting almost all areas of our lives. To achieve the EU's climate neutrality goal as early as 2050, we need to take concrete actions spread over many years in advance. We have a generational opportunity to shape a low-emission future and accelerate economic development. [1-3]

One of the possibilities to achieve the set climate goals is the deep thermal modernization of existing buildings to the EnerPHIT standard. The EnerPHit standard was developed by the Passive House Institute as a tool for the sustainable modernization of existing residential buildings. The main goal of EnerPHit is to reduce energy consumption and ensure the comfort of residents by improving building insulation, ventilation and heating systems. [4-9]. The main criteria of the EnerPHit standard include, among others: reducing energy demand to 25 kWh/m2 per year and using highly efficient heating and ventilation systems. An important element of the standard is also ensuring an appropriate level of tightness of the building, which is crucial for minimizing heat loss and ensuring adequate indoor air quality. EnerPHit is crucial for reducing energy consumption due to the increasing threats related to climate change and the use of natural resources. Improving the energy efficiency of existing buildings is one of the most effective ways to reduce greenhouse gas emissions and reduce the need to use fossil fuels. Modernization to the EnerPHit standard brings many benefits, both for residents and the environment. Improving insulation helps reduce heating bills, which has a positive impact on the household budget. Additionally, improving thermal comfort and indoor air quality promotes the health and well-being of residents. [10-14]

The second option is the use of energy-efficient technical solutions and renewable energy sources. Energy-efficient installation solutions for buildings undergoing thermal modernization include many different technologies that aim to minimize energy consumption and improve the building's energy efficiency. One of the most popular solutions is the installation of a heat pump. A heat pump is a device that uses energy from the environment (air, water, soil) to heat or cool rooms and prepare hot domestic water. Another important solution is mechanical ventilation with heat recovery. It is a system that enables air exchange in the building while retaining the heat generated in the heating process. Thanks to this, mechanical ventilation with heat recovery allows maintaining appropriate air quality in rooms while limiting energy losses through ventilation. This is particularly important in buildings with a low tightness index, where natural air exchange is insufficient. All these technologies are important for reducing energy consumption in buildings. Energy consumption in buildings has a huge impact on carbon dioxide emissions into the atmosphere and climate change. Therefore, the introduction of energy-saving installation solutions is key to reducing greenhouse gas emissions and sustainable development. [15-23]

Another way is to use energy-saving and ecological technologies in construction. The main motive for looking for energy-saving and ecological technologies in construction results from the need to reduce carbon dioxide (CO2) emissions into the atmosphere. The construction sector, along with the production of building materials, is the main factor that has a negative impact on the natural environment. It is important to limit the consumption of raw materials, including concrete, and modify them (physicochemical properties) in order to construct low-emission buildings at each of the three main stages of their life, i.e. the construction stage, the use stage and the demolition stage. [24-30]

There are many possibilities to achieve climate neutrality. Very often it is difficult to clearly indicate which option is the most advantageous and preferred for a specific application. In this respect, it may be helpful to use one of the many available multi-criteria methods. Multi-criteria decision support methods are extremely important in the context of thermal modernization of buildings for several reasons. First of all, the decision to carry out thermal modernization is always very expensive and difficult, so any support in the decision-making process is welcome. Multi-criteria methods allow you to take into account many different factors and criteria, which allows for a more comprehensive analysis and assessment of potential actions. Multi-criteria decision support methods can help in selecting the best thermal modernization solutions that will reduce energy consumption and improve the energy efficiency of the building. When making a decision regarding the thermal modernization of a building, it is important to take into account many factors, such as investment costs, energy savings, environmental impact, user comfort, and the value of the property. Multi-criteria methods allow for effective comparison of various thermal modernization scenarios in terms of all these factors, which allows the selection of the optimal solution. [31-35] It is also worth paying attention to machine learning methods. [36, 37].

2. The Hybrid Mechanical Ventilation System with Heat Recovery and a Heat Pump for Heating Domestic Hot Water

The article estimates the energy and economic benefits resulting from the integration of an air-water heat pump for the preparation of domestic hot water with a mechanical supply and exhaust ventilation system with heat recovery. In the summer, the domestic hot water heat pump it receives heat from the air blown into the object's volume, contributing to its cooling, this is the so-called discharge cooling - free of charge, created as a result of heating domestic hot water. In transitional periods and in winter, the domestic hot water heat pump extracts heat from the ventilation air discharged from the building. Exhaust air has a greater energy potential than outside air because it is warmer and more humid.

3. Building Description

The existing residential premises located in the attic in Poznań, owned by a private person, was qualified for deep energy modernization due to high energy consumption and related costs. The goal was achieved by thermal modernization of the premises to the EnerPHIT standard according to the Passive House Institute in Darmstadt. One of the most important elements of the energy modernization was the installation of mechanical ventilation with heat recovery, which was integrated with the installation of a heat pump for heating domestic hot water.

The residential premises under consideration are an apartment located in an existing tenement house, inhabited by 4 people. The entire building is located in climate zone II according to the Polish Standard PN-76/B-03420.

- total usefull floor area with adjustable temperature/total usable volume A_G = 58.8m^2/V_G = 165.23m^3
- energy demands for heating and ventilation 1 494.4 kWh/a
- specific energy demand for heating and ventilation 25.42 kWh/(m^2·a)
- designed demand of heat generation power for heating and ventilation $Q_{C.O.}$ = 1 107.6 W
- specific designed demand of heat generation power for heating and ventilation 18.84 W/m2
- designed demand of heat generation power for hot water production $Q_{C.W.U.}$ = 1 600 W
- airtightness of the building n50 = 0.91 h-1
- heat transfer coefficient of the external walls / of the roof Uw = 0.071 W/(m2·K) / Ur = 0.060 W/(m2·K)
- high insulated windows capable to gain solar energy in the heating season with external blinds, to protect from overheating in cooling season: U= 0.9 W/(m2K), Ug= 0.5 W/(m2K), gwin= 0.7, gsum= 0.35
- PER demand 48.79 kWh/(m^2·a)*
- renewable energy generation (with reference to projected building footprint) 59.73 kWh/(m^2·a)

** All energy uses in the building are included.*

The residential premises in question meet the EnerPHit Plus class. Figure 1 shows the demand and production chart of PER and the classification of the residential premises.

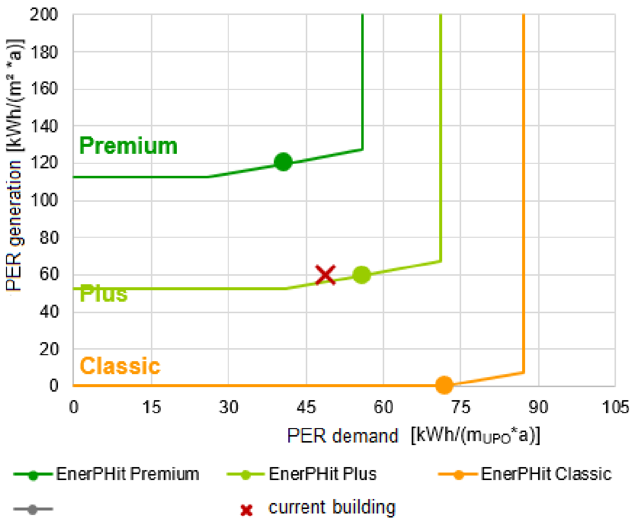

Fig. 1. The demand and production chart of PER and the classification of the residential premises.

4. HVAC System

The modernized residential premis are heated using electric underfloor heating. The minimum nominal efficiency of energy production for heating purposes using electricity is at least 99%. Each room has an electric heating system equipped with individual thermostats enabling temperature regulation. Preparation of hot water for the modernized residential premises will take place in one hot water tank. The domestic hot water tank with a capacity of 200 liters is a component of the Atlantic Explorer+ domestic hot water heat pump. The heat pump meets the requirements of the new energy efficiency standard. The tank has a night tariff function, anti-legionella function and a thick layer of polyurethane foam insulation.

Basic features of the domestic hot water system and other important assumptions:

- Hot water tank with a capacity of 200 liters,
- The heat pump can only operate in the temperature range -5 to +43°C,
- The water temperature adjustment range in the tank is from +50 to +62°C,
- The electrical power of the heat pump compressor is 525 W,
- The catalog COP coefficient is 3.2 for an air temperature of +7°C,
- The catalog COP coefficient is 3.8 for an air temperature of +15°C,
- The electrical power of the peak heater is 1800 W,
- No hot water circulation system (distribution system capacity less than 3 liters),
- In normal operation, the heater works to overheat domestic hot water and when the outside air temperature is below -5 degrees Celsius. This article does not take into account the amount of heat for DHW superheating,
- It was assumed that the domestic hot water stored in the tank would be heated to a temperature of 50°C,
- The heat pump's operating schedule takes into account that domestic hot water is heated from 12:00 until the entire tank is heated to a temperature of 50°C,
- The heating time of domestic hot water depends on the heating power of the heat pump, which is directly dependent on the temperature of the lower heat source.

Characteristics of heat power, energy consumption and effectiveness of energy processing (COP) for the preparation of domestic hot water are shown in Fig. 2.

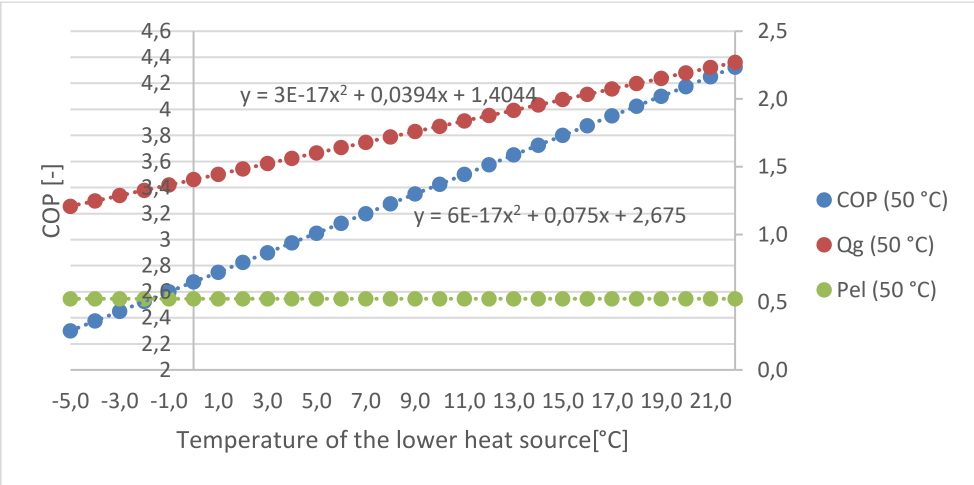

Fig. 2. Parameters of the heat pump in the relationship on the temperature of the low-heat reservoir.

A photovoltaic installation generating electricity is located on the roof of the residential premises. A total of 22 photovoltaic panels were used with a specific power of 401 Wp. The total power of the photovoltaic installation is 8.8 kWp. The installation works with one inverter. On average, the installation generates 6,791.70 kWh/year of electricity per year. The generated electricity is consumed by the HVAC installation, hot water production installation, lighting and other living and social needs.

The residential premises are equipped with a supply and exhaust ventilation unit with high-efficiency heat recovery with a nominal capacity of 300 m3/h. A Zehnder air handling unit was used, type ComfoAir Q450, RIGHT version, with a maximum capacity of 450 m3/h. The unit has automatic control that allows operation in the range of 70%, 100% and 130% of its nominal capacity, turning the unit on/off and switching to summer mode, as well as time control. The ventilation unit has a heat recovery efficiency of approximately 89%. The air handling unit is equipped with a summer bypass. The temperature sensor integrated in the ventilation unit is responsible for the proper operation of the by-pass. The air handling unit has protection against freezing of the heat exchanger. The impulse pre-heater is always turned on if the temperature of the intake air is lower than 0 degrees Celsius and heats the ventilation air to 0 degrees C. The maximum electrical power of the pre-heater is 2.2 kW.

Basic features of the ventilation system and other important assumptions:

- The air-flow rate within the cooling season (from 1 May to 30 September) 300 m^3/h,
- The air-flow rate within the heating season (from 1 October to 30 April) 150 m^3/h,
- Heat recovery rate η_{HR}=89.0%,
- Specific electric power $P_{el,spec}$ = 0.26 Wh/m^3,
- The efficiency of the heat transfer in the electric heater 95%,
- The air-flow is constant in the day/night period,
- In the cooling season, when the external air temperature te > 16°C, the AHU works using the by-pass (without recuperation),
- In the heating season, when the external air temperature te < 0°C, the electric pre-heater turns on and heats the air drawn in to a temperature of 0°C,
- The calculations do not include additional ventilation of the building above the flow of 300 m3/h.

5. Integration of the domestic hot water preparation system and mechanical ventilation installation

In order to increase the energy efficiency of heating domestic hot water and in an attempt to avoid the need to use an electric heater built into the heat pump during periods when the outdoor air temperature is lower than -5°C, it was decided to integrate an air-water heat pump for the preparation of domestic hot water with a mechanical supply and exhaust ventilation system with heat recovery. This solution also has the ability to cool the supply air-flow during cooling season.

Basic features of the hybrid system and other important assumptions:

- When the heat pump is operating, the ventilation air flow is always 300m^3/h (also in winter),
- Additional electrical energy is required to pump a larger amount of ventilation air, to preheat it and to reheat it,
- In the summer, the heat pump will additionally cool the building - the calculations take this energy benefit into account and present it as an equivalent value that would need to be cooled in a classic installation,
- For the air conditioning installation, the average annual efficiency SEER = 3.5 was assumed.

The hybrid system operates in two operating modes depending on the building's cooling needs:

1) In the summer, the domestic hot water heat pump it receives heat from the air blown into the object's volume, contributing to its cooling, this is the so-called discharge cooling - free of charge, created as a result of heating domestic hot water. The principle of operation is shown in Figure 3.

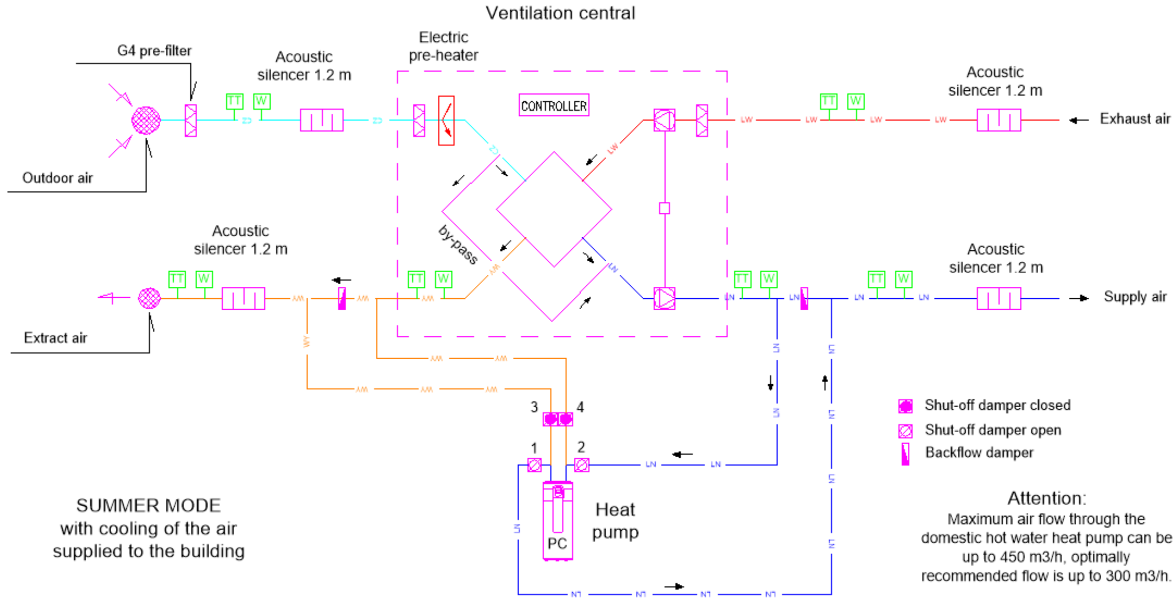

Fig. 3. SUMMER MODE - with cooling of the air supplied to the building.

When there is a demand for domestic hot water, the heat pump is activated, which extracts heat from the air stream supplied to the building. The air in summer has the same temperature and humidity as the outside air. The "by-pass" heat exchanger option is enabled in the air handling unit. In case of hot summers, the supply air can be passed through the recuperator first. The heat pump absorbs heat and cools the supply air by approximately 5-6K, which additionally cools the building. This is free cooling and partial dehumidification of fresh air. When the domestic hot water is heated to the required temperature, the heat pump turns off and the mechanical ventilation installation works as without integration.

2) In transitional periods and in winter, the domestic hot water heat pump extracts heat from the ventilation air discharged from the building. Exhaust air has a greater energy potential than outside air because it is warmer and more humid. The principle of operation is shown in Figure 4.

During the rest of the year, when there are no cooling needs, the hybrid installation operates in the second mode. In this mode, ventilation air is taken from the outside and, in the case of negative temperatures, preheated to 0°C using an electric air pre-heater. Then the air flows into a highly efficient heat exchanger (recuperator) with an efficiency of 89% and is heated to a temperature ranging from 17.8 to 20.0°C. On the supply side, the mechanical ventilation installation operates in standard mode. On the exhaust side, when there is a demand for domestic hot water, air is drawn by the heat pump from a place located behind the recuperator. In this place, during winter, the air always has a positive temperature and a very high relative humidity, which means that the air has a high energy potential. This air is taken into the heat pump, where energy is collected for the purpose of heating domestic hot water, and the air is then thrown out through the air exhauster outside the building. The air entering the heat pump therefore has a higher temperature and a much higher relative humidity. Due to the preliminary heating of the intake air, the temperature of the exhaust air will never be lower than 0°C. This means that the heat pump operates with much higher efficiency, especially in winter. In this case, the electric heater built into the heat pump will never turn on to heat domestic hot water, and thus the energy efficiency of the entire system is higher.

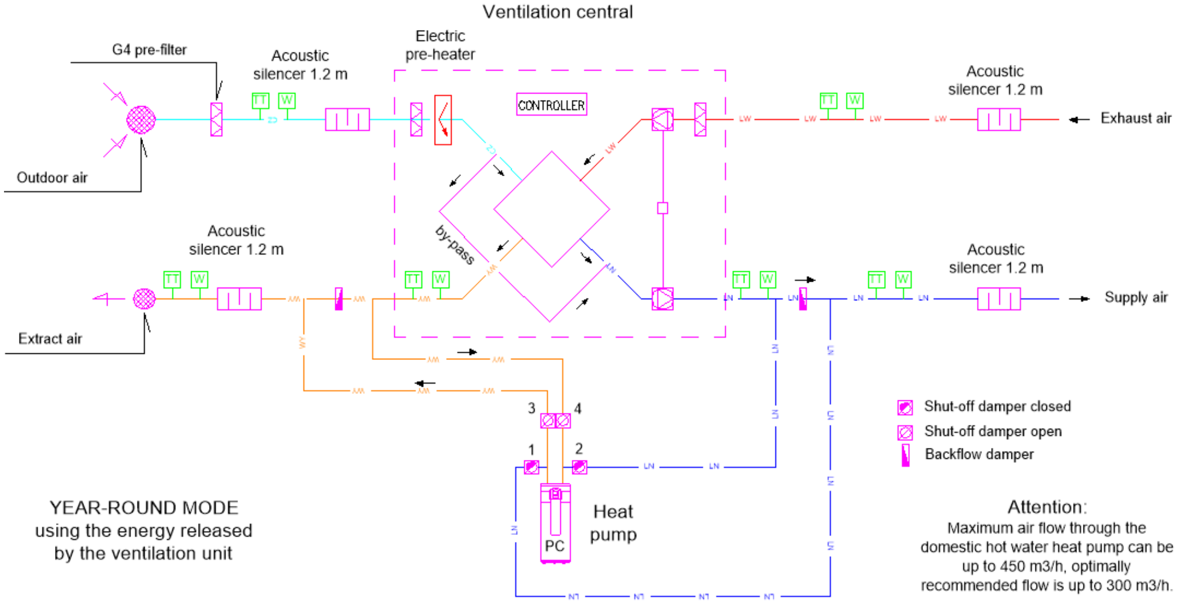

Fig. 4. YEAR-ROUND MODE - using the energy released by the ventilation unit.

6. Methodology and formulas used

In order to increase the energy efficiency of heating domestic hot water and in an attempt to avoid the need to use an electric heater built into the heat pump during periods when the outdoor air temperature is lower than -5°C, it was decided to integrate an air-water heat pump for the preparation of domestic hot water with a mechanical supply and exhaust ventilation system with heat recovery. This solution also has the ability to cool the supply air-flow during cooling season. The simplest way to determine the energy efficiency of a heat pump is to calculate the heat flow exchanged in the system. It can be calculated using the formula [37]:

$$\dot{Q} = \dot{m} \cdot \Delta h \ [\mathrm{kW}] \qquad 1)$$

where
- Q - is instantaneous power output to heat pump [kW]
- m - is the air mass flow rate flowing through the heat pump [kg/s]
- Δh is the difference in the specific enthalpy of the moist air between the inlet and outlet of the heat pump [kJ/kg]

The air mass flow rate can be determined by knowing its flow rate through the exchanger according to the formula [37]:

$$\dot{m} = \frac{\dot{V} \cdot \rho}{3600} [\mathrm{kg/s}] \qquad 2)$$

where
- V - is the volumetric flow rate of the air flowing through the heat pump [m^3/s]
- ρ - is the density of the air flowing through the heat pump [kg/m^3]

The specific enthalpy of humid air can be determined from the formula [37]:

$$h_1 = 1.005 \cdot t_1 + x_1 \cdot (1.86 \cdot t_1 + 2500.8) [\mathrm{kg/s}] \qquad 3)$$

where
- t_1 is humid air temperature [°C]
- x_1 is moisture content of the moist air [kg/kg]

The amount of energy derived to the heat pump can be determined from the formula [37]:

$$Q = \dot{Q} * \Delta t \ [\mathrm{Wh}] \qquad 4)$$

where
- Δt—time [h]

Using the above relationships and knowing the quantitative (flow) and qualitative (temperature and relative humidity) parameters of the air flowing through the heat pump, it is possible to determine the amount of energy taken from the exhaust air during the winter and the amount of energy taken from the supply air during the summer using the heat pump. Knowing the amount of guiding electrical energy inserted additionally to force the air through the installations, pre-heating of the intake air, secondary heating of the supplied air and, above all, the amount of electricity input to the heat pump, it is possible to determine the energy efficiency for the whole year and compare it with the classic solution. Simulations were prepared using meteorological data of the

Poznan City taken from ministerial resources, which are considering typical meteorological years and statistical climatic data compiled on the basis of the standard EN-ISO 15927:4. They take into account the dry and wet bulb temperature variations, relative humidity, moisture content and radiation intensity for different orientations and the angle of incidence for every hour of the year. These data can be used in designing and providing the basis for the performance of any analyses connected with the full-year operation of the device. To calculate the heat demand for preparing hot water, the actual profile of hot water consumption by users was adopted. To calculate the cooling demand daily usage profile of devices and daily attendance profile of residents were made. Knowing the unit prices of electricity for an alternative way of supplying heating and cooling to the extracted outside air, it is possible to calculate the operating cost savings and thus the economic efficiency and payback time of the hybrid solution. Similarly, environmental performance can be determined.

7. Results and Discussion

The calculations were carried out for the city of Poznań and are presented in Table 1. The calculations were made in MS Excel with the use of proprietary code. The hourly interval was taken into account in the calculations. The results of the simulation based on 30 years of publicly available climate data indicate that combining a mechanical ventilation installation with a heat pump for the purpose of preparing hot water contributed to a significant increase in its energy efficiency. For the summer period, the average annual heat pump efficiency index increased from SCOPsu=3.56 to SCOPsu=4.29, which is 20.4% higher. For the winter period, the average annual efficiency index of the heat pump with an electric heater increased from the value of SCOPre = 2.25 to the value of SCOPre = 3.18, which is a value as much as 41.1% higher. Such a large change is caused by the lack of need to activate the peak electric heater in the case of a hybrid solution. The total average annual efficiency of domestic hot water preparation (heat pump with electric peak heater) increased from SCOP = 2.66 to 3.56, which is a value as much as 33.89% higher. The advantage of the hybrid solution is the fact that in the summer it supplies the building with discharged cold, which is free of charge. The amount of equivalent electricity for heat collection in the summer for the traditional solution, taking into account the efficiency of the air conditioning installation, is 97.61 kWh/year. However, the hybrid solution results in higher electricity consumption for the purpose of pumping air in the non-summer period from the value of 310.39 kWh/year to the value of 358.72, which is caused by the need to increase the flow of the mechanical ventilation installation to ensure a minimum flow of ventilation air constituting a lower heat source for heat pump. For the same reason, the hybrid solution also increases the amount of electricity for preheating the air drawn from 326.73 kWh/year to 377.59 kWh/year and to reheat a larger amount of air, where electricity consumption increases from 457.62 kWh/year to 548.67 kWh/year.

The total annual electricity consumption of the mechanical supply and exhaust ventilation system with heat recovery and the domestic hot water heating installation decreases from 2,395.74 kWh/year to 2,221.73 kWh/year, which is equal to the difference of 174.01 kWh/year and represents a reduction in consumption. final energy by 7.26%.

Tab. 1. Energy analysis.

	Traditional solution	**Hybrid solution**	
The amount of electricity needed to pump air in the summer	286.42	286.42	kWh/a
The amount of electricity needed to pump air in the remaining period	198.43	240.55	kWh/a
The amount of heat for preheating the intake air	310.39	358.72	kWh/a
The amount of electricity for the pre-heating of the intake air	326.73	377.59	kWh/a
Amount of heat for reheating the supply air	453.05	543.19	kWh/a
The amount of electricity for the reheating of the supply air	457.62	548.67	kWh/a
Amount of heat for DHW purposes in summer	1 147.50	1 147.50	kWh/a
The amount of heat for DHW purposes in the remaining period	1 590.00	1 590.00	kWh/a
The amount of electricity for the heat pump in the summer	322.44	267.79	kWh/a
The amount of electricity for the heat pump in the remaining period	490.86	500.70	kWh/a
The amount of electricity for the purposes of the electric heater for DHW purposes	215.63	0.00	kWh/a
The amount of heat received by the heat pump in the summer	0.00	341.64	kWh/a
The amount of equivalent electricity for heat collection in the summer	97.61	0.00	kWh/a
Total annual electricity consumption	2 395.74	2 221.73	kWh/a
Difference in electricity consumption	174.01		kWh/a
	7.26		%
Average seasonal efficiency of the heat pump in summer (SCOPsu)	3.56	4.29	-
Average seasonal efficiency of the heat pump with an electric heater in the remaining period (SCOPre)	2.25	3.18	-
Average annual efficiency of a heat pump with an electric heater (SCOP)	2.66	3.56	-

To determine the total economic and environmental benefits of using the designed hybrid system instead of the traditional system it was decided to perform an economic and environmental analysis. The results of the analysis are shown in Table 2. Assumptions for economic and environmental analysis:

- Average seasonal efficiency of chill production (for the non-integrated system), SEER = 3.5,
- Electricity unit price, PEL = 0.30 euro/kWh,
- Total difference in investment costs, I_0=100 euros,
- CO_2 emission factor (National Centre for Emissions Management), e_{CO2} = 685 kg/MWh.

Tab. 2. Economic and ecological analysis.

	Traditional solution	Hybrid solution	
Variable system operating costs	718.72	666.52	euro/a
Difference in annual system operating costs	52.20		euro
Total difference in investment costs	100.00		euro
Simple payback time	1.92		years
CO_2 emissions to the environment	1 641.08	1 521.89	kg CO_2/a
Reduction of CO_2 emissions to the environment	119.20		kg CO_2/a

The difference in the investment costs of the hybrid solution consists only in the expansion of the duct system in the mechanical ventilation system and the installation of air dampers and return dampers. However, this investment results in lower investment costs due to the lack of penetrations through the external wall. Hence the difference in investment costs is only 100 euro. The difference in average annual operating costs is 52.20 euro per year. The simple payback time is only 1.92 years. The use of a hybrid solution contributes to reducing carbon dioxide consumption by 119.20 kg CO_2/year, which is a reduction of 7.8%.

8. Conclusion

Based on the simulations performed, it was shown that the proposed technical solution has great application potential through additional use of the amount of energy contained in the ventilation air. The installation of mechanical ventilation with heat recovery is a better lower heat source for the heat pump for the preparation of domestic hot water than outdoor air. The presented solutions can be used in the design new buildings (not only residential) with almost zero energy consumption, as well as those with a positive energy balance, and especially for deep energy modernization of existing residential buildings. The use of a hybrid solution for using ventilation air as a lower heat source for heating domestic hot water in a heat pump should always be preceded by a thorough analysis. This analysis should primarily take into account the amount of ventilation air in the mechanical ventilation system and the consumption of domestic hot water during the day. The analysis should include the full-year operation of the system.

Savings of approximately 7,3% per year of electrical energy consumed can be expected compared to a traditional system. Simple payback time for investments is less than two years. The presented solution contributes to sustainable development goals because it minimizes energy consumption and reduces CO2 emissions, which is important. It also decreases running costs, while the investment itself is modest.

I am planning to validate the calculations based on collected measurement data in the near future. Figurer 3 i 4 shows the applied technological system with an indication of the measuring equipment. Incomplete data have been collected since 1 January 2021.

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