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Operation of a hybrid heating system based on heat pumps using a photovoltaic installation

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Abstract

In Poland, heating systems using renewable energy sources have gained importance in construction projects, especially in newly designed buildings. This is mainly due to the Regulation of the Minister of Infrastructure, which sets technical conditions for buildings. As of December 31, 2020, the primary energy index for newly designed single-family buildings should not exceed 70 kWh/(m^2·year). This requires efficient energy sources in building design. Renewable energy installations have significantly lower primary energy utilization rates than fossil fuel systems, making them the preferred choice. In a facility in Batowice near Krakow, a hybrid energy system with ground-source and air-source heat pumps has been installed. These pumps are powered by electricity from a photovoltaic installation connected to the grid. The study aims to determine the optimal heat pump choice based on the facility's conditions and optimize electricity consumption from the photovoltaic installation. Both heat pumps showed similar efficiencies during the heating season from December 2022 to March 2023: the ground-source heat pump achieved an annual coefficient of performance of 2.69, and the air-source heat pump achieved a seasonal coefficient of performance of 2.63. Given the high non-renewable primary energy factor for grid electricity, the feasibility of replacing gas boilers with heat pumps requires careful evaluation. The results indicate that integrating a heat pump with a photovoltaic installation substantially reduces the primary energy utilization index, supporting climate protection and the advancement of renewable energy sources. However, heat pumps alone may not be sufficiently efficient without the support of a PV installation.

Keywords: Renewable energy sources; Heat pumps; Hybrid installations; Energy efficiency; Photovoltaic installations

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1. Introduction

Poland and other European Union (EU) countries have committed to preparing an energy scenario by 2050 that allows for sustainable and carbon-free energy production. Therefore, one of the critical objectives of EU energy policy is to improve the energy performance of the building stock. In achieving these objectives, heat pumps (HPs) can play an essential role in electrifying sources of heat generation and domestic hot water preparation. HPs are expected to bring the most significant environ-

Nomenclature

Abbreviations and Acronyms

AHP – air-source heat pump
COP – coefficient of performance
EP – primary energy
EU – European Union
GHP – ground-source heat pump
HP – heat pump
PEF – primary energy factor
PV – photovoltaic
RES – renewable energy sources
sCOP– seasonal (annual) coefficient of performance

mental benefits in energy markets where renewable energy, such as wind, has a considerable share. A noteworthy challenge associated with the electrification of heat is the transition of residential space heating from conventional fossil fuel-based technologies to electricity.

The primary challenge in utilizing heat pumps is the resultant primary energy utilization index. To ensure the ecological viability of replacing a fossil fuel-based heat source, it must be replaced with a device with a lower primary energy input. Given the high primary energy factor associated with grid electricity (Table 1), replacing a gas boiler with a heat pump powered by the electrical grid becomes environmentally beneficial only if the heat pump's average annual coefficient of performance (sCOP) exceeds 2.3. Otherwise, the carbon dioxide emissions from using a heat pump will surpass those from heating the building with natural gas.

Comprehensive field studies covering multiple heating seasons are required to determine the feasibility of implementing heat pumps in heating systems. It is also essential to ascertain whether the type of heat pump significantly impacts the expected outcomes. The unique characteristics of the studied facility allow for the empirical comparison of air-source and ground-source heat pumps operating under identical conditions within a single hybrid system. This study is particularly valuable because, in a standard facility, two different types of heat pumps are typically not installed within the same heating system. Furthermore, the photovoltaic (PV) installation in the building facilitates the evaluation of the potential for using solar energy to power heat pumps, substantially contributing to the reduction of the primary energy utilization index. In addition to comparing the performance of different heat pumps, this study aims to maximize the utilization of energy generated by the PV installation during its production phase.

Kim et al. [1] suggested a hybrid solar-geothermal carbon dioxide heat pump system for residential applications. By using a heat pump with CO_2 as the working medium, the temperature of the heating medium produced was significantly increased. Sridhar et al. [2] have developed a numerical algorithm that, based on intelligent measurement data, allows the selection of a hybrid heating system for a set of buildings, increased electrification of the heat sources, and improved flexibility. Yao et al. [3] analysed a residential heating system based on a heat pump with a borehole heat exchanger powered by electricity from PV-T panels. They demonstrated that the heat pump in the developed hybrid system can achieve a COP significantly above 7. Kazem et al. [4] showed that the combined use of PV-T installations to power heat pumps can reduce grid electricity consumption significantly. In addition, the waste heat from the PV-T systems enhances the heat pumps' efficiency. Long et al. [5] have proposed a combined system for heating the house and sup-plying domestic hot water. An air-source heat pump and a solar thermal collector were used to heat the residence and provide hot water. This solution enables significant energy savings [5]. Bezrodny et al. [6] proposed the use of heat pumps in air-conditioning systems. The authors showed that recirculating the exhaust air through the heat pump evaporator allows the preset room conditions to be maintained over a wider range of variations in ambient air parameters. In addition, lower specific energy consumption of the heat pump is achieved, improving its efficiency. Hanuszkiewicz-Drapała and Bury [7] conducted a thermodynamic analysis of a heat pump with a horizontal ground heat exchanger used to heat and cool a residential building. They investigated the impact of the heat supplied to the ground during the summer on the operation of the heating system and electricity consumption during the following heating season.

Heat pumps for residential heating powered by electricity from renewable sources reduce greenhouse gas emissions and dependence on imported fossil fuels [8]. Heat pumps combined with heat storage are well suited to providing short-term flexibility, shifting loads to periods of low prices and high renewable electricity supply. Harnessing the flexibility of heat pumps, a more balanced local energy system can be created [9,10]. Hybrid installations using renewable energy sources are an increasingly common solution. In his article on hybrid installations, Pater argues that it is possible to easily significantly increase the share of renewable energy sources in the production of energy for heating purposes [11], and in the next study, he analyses a hybrid based on a heat pump combined with a photovoltaic installation to supply the building with hot water [12].

The performance of photovoltaic panels is strongly dependent on external conditions such as sunshine, temperature, air pollution, cloud cover or precipitation. Although photovoltaic panels operate most efficiently in full sunlight, different atmospheric conditions still allow their use over a wide geographical and climatic range. Katoch et al. in [13] analysed the influence of the dust gathering on the photovoltaic panel on its performance and average output power and short circuit current. Kuczyński and Borowska [14] investigated the exergy efficiency of photovoltaic installations as a critical parameter to determine the maximum amount of electricity that could be produced under certain conditions. Kadhim and Al-Ghezi [15] made a comprehensive review of cooling systems that allow for increased efficiency, energy production and service life of photovoltaic modules.

The intermittent electricity production in photovoltaic panels requires such installations to be equipped with energy storage systems. Deka and Szlęk [16] investigated the different methods of storage of excess energy from renewable sources as one of the ways to reduce reliance on fossil fuels for residential heating and cooling. Excess energy can be stored in systems using phase change materials (PCM) and later used to produce cold in adsorption chillers or to support refrigerant preparation in heating systems. Karwacki et al. [17] conducted a study to identify the best phase-change material for thermal energy storage in domestic installations. Cieśliński et al. [18] carried out experimental viscosity determinations of phase-change materials, which were used to develop accurate correlation formulas for determining the viscosity of PCMs.

The conducted research aims to evaluate the feasibility of implementing hybrid systems based on renewable energy sources for powering buildings under Polish conditions. The primary objective of the study was to compare the performance of ground-source and air-source heat pumps and to investigate the potential for optimizing their integration with photovoltaic installations.

2. Legal requirements for buildings

In the context of the regulations in force in Poland, one of the most essential indicators, important for investors and building designers, is the facility's unit demand for non-renewable primary energy. The latest amendment has maintained the limitation introduced since December 31, 2020, on the primary energy (EP) index for heating, ventilation and domestic hot water preparation at 70 kWh/(m²·year) for single-family houses and 75 kWh/(m²·year) for collective residential buildings.

Public buildings, excluding healthcare facilities, have a demand limit of 45 kWh/(m²·year) [19]. These restrictions compel investors and designers to seek energy-efficient construction solutions and utilize energy sources with low primary energy utilization rates. Table 1, included in the Regulation of the Minister of Development and Technology [20], presents the values of primary energy utilization rates for various energy sources.

3. Hybrid installation

A hybrid power supply system based on multiple energy sources has been implemented in the building being considered, located in Batowice near Krakow in Poland. The primary heat sources for the heating system are two heat pumps (Table 2):

- a ground-source heat pump (GHP) with a capacity of 10.9 kW (B0/W35),
- an air-source heat pump (AHP) with a capacity of 12 kW (A7/W35).

A fireplace with a water jacket also serves as an auxiliary heat source, and a gas-condensing boiler is installed as a peak heat source.

The heating system incorporates a central heating buffer tank with a capacity of 1500 litres. Furthermore, the hot water provision includes a separate domestic hot water tank with a capacity of 800 litres. During the summer months, a solar collector installation is utilized to prepare domestic hot water. Moreover, besides being connected to the power grid, electricity generated by a 9.6 kW PV installation is also utilized. The installation layout is presented in Fig. 1. In order to conduct a comparative analysis of two different types of heat pumps, a ground and air heat pump was installed in one building, as part of one heating system. Table 2 contains a comparative summary of the most important parameters of both devices. Please remember that both heat pumps differ in their specific operation depending on the prevailing external conditions. The outside air temperature is of little importance for a ground heat pump. The air heat pump is very sensitive to weather conditions because it uses outside air as the lower heat source. From the user's point of view, it is very important to determine which source will be a more justified choice, both in terms of energy and finances. Comparing the behaviour of both devices under identical operating conditions is the best way to determine when and which device will work better.

Table 1. The effort of non-renewable primary energy factors (PEF) for the production and delivery of the energy carrier for technical systems [20].

No.	Method of Energy Supply	Type of Energy Carrier	PEF
1	Local energy production in the building	Heating oil	1.10
2		Natural gas	
3		Liquid gas	
4		Coal	
5		Lignite	
6		Solar energy	0.00
7		Wind energy	
8		Geothermal energy	
9		Biomass	0.20
10		Biogas	0.50
11	Network heating from co-generation	Coal or gas	0.80
12		Biomass, biogas	0.15
13	Network heating from a heating plant	Coal	1.30
14		Gas or heating oil	1.20
15	System power grid	Electricity	2.50

4. Research problem analysis and interpretation of measurement results

According to Table 1, in the case of an energy production system in a building, the amount of final energy for heating should be multiplied for non-renewable sources by the indicator PEF = 1.1. In practice, to meet the requirements of the regulation, we must reduce the use of usable energy in the facility to the level appropriate for low-energy buildings. The use of grid electricity carries an even greater burden on the environment, as illustrated by the PEF index value 2.5 (until April 28, 2023, this index was 3.0). Replacing heat sources using non-renewable energy (natural gas, coal, etc.) with heat pumps will be justified only if the total (weighted) coefficient PEF resulting from using renewable energy and electricity supplying the heat pump compressor is lower than 1.1. As we can see, this will be closely related to the achievable seasonal efficiency of the device used. Therefore, to obtain satisfactory results, a seasonal efficiency ra-

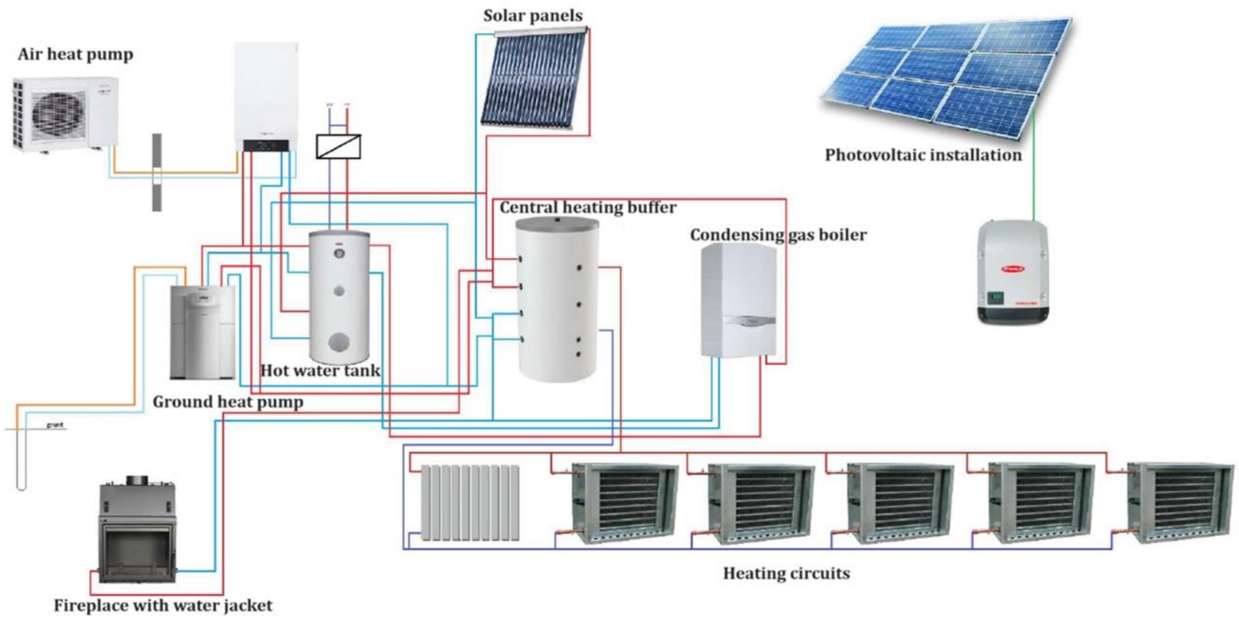

Fig. 1. Diagram of a hybrid installation powering the building in Batowice.

Table 2. Technical data of heat pumps.

Parameter	Air heat pump	Ground heat pump
HP type	Vitocal 151.A10	VWS 104/3
Refrigerant type	R290	R407C
Heating power	12 kW (A7/W35) 9.7 kW (A-7/W35) 9.37 kW (A7/W55)	10.9 kW (B0/W35) 9.7 kW (B0/W55)
Electrical power consumption	2.46 kW (A7/W35) 3.23 kW (A-7/W35) 2.6 kW (A7/W55)	2.2 kW (B0/W35) 3.2 kW (B0/W55)
COP	5.0 (A7/W35) 3.0 (A-7/W35) 3.7 (A7/W55)	4.9 (B0/W35) 3.0 (B0/W55)

tio of the heat pump should be obtained at a level higher than 2.3 (before changing the index, it was necessary to get a seasonal efficiency sCOP above 2.73). Otherwise, using a heat pump powered by network electricity will generate higher primary energy consumption than an installation with a gas or coal boiler. Figure 2 shows the average monthly COP values for the tested heat pumps from November 2022 to the end of 2023. The efficiency factor of both devices is so high that from an ecological point of view, with PEF = 2.5 for electricity from the grid, their use is profitable. This is a fundamental issue, especially when air heat pump, because the device is characterized by high vari-

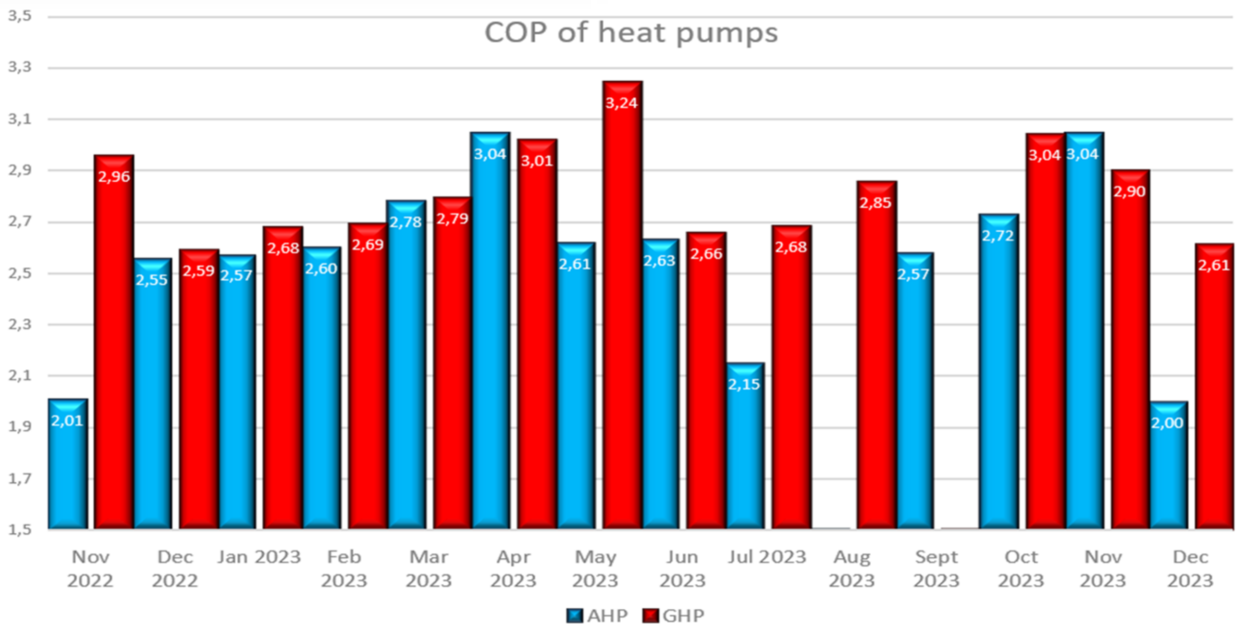

Fig. 2. Average monthly COP values of ground-source and air-source heat pumps installed in the analysed facility.
AHP – air-source heat pump, GHP – ground-source heat pump.

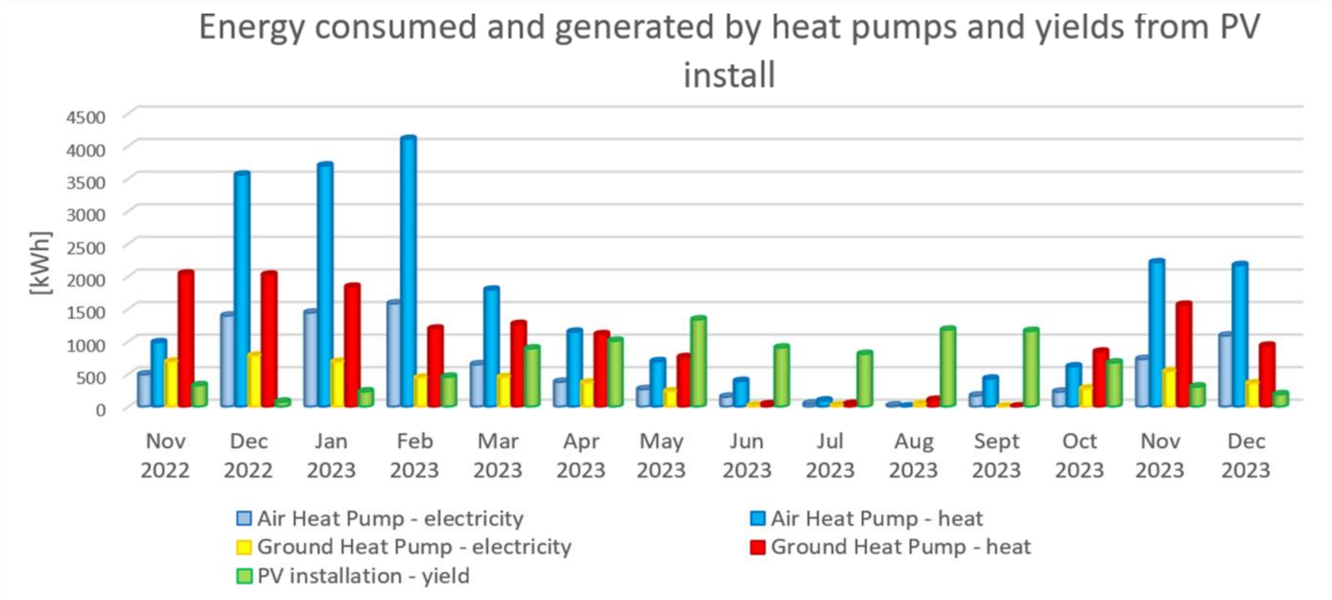

Fig. 3. Balance of energy consumed and produced by heat pumps and electricity production by the photovoltaic installation.

ability of operating efficiency with changes in outdoor air parameters. Installing a photovoltaic installation to power a heat pump comes in handy here. The PEF coefficient for solar installations is 0.0 [20], meaning that energy from a PV installation does not result in primary energy use. Another question when planning to install a photovoltaic system concerns the level of electricity used to power the heat pump compressor. We cannot ensure 100% use of energy from PV installations, and we will take part of the electricity for our pump from the network, so we will not eliminate the share of primary energy in the overall energy balance of the building. In the future, this may be possible when satisfactory efficiency of storing electricity is achieved. Still, with current technological limitations, we must assume that part of the electricity for our heat pump will come from non-renewable sources.

Two heat pumps were installed in the tested facility: a 10.9 kW ground source heat pump operating with R407C refrigerant and a 12 kW air source heat pump using R290 refrigerant. Additionally, a 9.6 kW photovoltaic installation was installed to meet the building's electricity demand partially. The photovoltaic system is connected to the power grid and operates under a prosumer net-metering system. Under this system, any surplus electricity generated by the photovoltaic installation not consumed by the building is transmitted into the grid. The prosumer will receive 80% compensation for the supplied energy for the following year. Since April 2022, a new billing system called net billing has been implemented, involving financial settlement for surplus energy. The prosumer sells surplus energy to the grid and receives a monetary credit, allowing them to purchase grid energy at a specified rate. Additionally, the prosumer is responsible for transmission fees for delivered and consumed energy.

To estimate the amount of primary energy used to operate the heat pump in the configuration with a photovoltaic installation, it is necessary to consider the methodology for calculating the share of renewable energy in the electricity used. First, we must determine how to divide energy use between the building's heat pump and other electrical devices. We have two options here: qualifying all renewable energy as consumed for the operation of the heat pump, especially in residential buildings, where the energy for lighting the building is not included in the balance of primary energy use in the building or dividing the consumption as a percentage between all electricity receivers in the considered object. The most rational and fair solution is measuring devices so that it is possible to indicate directly which source powered the heat pump in real-time during its operation. However, the solution is expensive and impractical from the point of view of an ordinary user, for whom the distribution of energy produced is irrelevant because it does not affect the economic aspect of using energy from a PV installation. A comparison of electricity consumption and production of heating energy by an air and ground heat pump and energy production by a photovoltaic installation in individual months is shown in Fig. 3.

It should be noted that the greatest energy demand for heat pump operation occurs in periods when production from PV installations is the lowest. Prosumer settlement of micro-installations enables annual balancing of energy delivered and consumed, which is a beneficial solution for the user. In turn, the use of the generated electricity for one’s own needs and the amounts of electricity fed into the network and consumed are shown in Fig. 4.

It can be said that using heat pumps enables an increase in the consumption of energy generated by the PV installation for internal needs. During months when heat pumps are used for heating, the self-consumption of electricity from the PV system significantly exceeds the amount of energy exported to the grid. The subsequent step involves determining the methodology for categorizing the electricity fed into the grid and the energy consumed in a 1:0.8 balance when employing net metering settlement [21]. In such scenarios, the grid is considered a storage facility for the generated energy, with an assumed annual efficiency of 80%. It can be presumed that the PEF index for the energy received from the grid in the balance is also 0.0, indicating renewable energy inclusion in the primary energy balance of the grid's current. Hence, adopting a PEF value of 0.0 solely for the energy sourced from the PV installation and used for internal needs at the production point appears reasonable. However, for the remaining electricity derived from the grid, whether within or outside the balance, a PEF coefficient of 2.5 should be employed following the reduction from 3.0.

Another problem we face here is using electricity from PV installations for our needs. Depending on the daily electricity use profile, an average household can use approximately 20–30% [22] of the energy produced for its own needs. The remaining part of the production from the photovoltaic installation is fed into the power grid. Therefore, the next challenge is to develop methods for maximising electricity consumption from the photovoltaic installation at the generation site, necessarily without increasing the energy needs of the building. The data analysis covered the period from November 2022 to the end of 2023 and allowed for a preliminary assessment of the cooperation of the photovoltaic installation with the building. Figures 4, 5 and 6 present the results of the research.

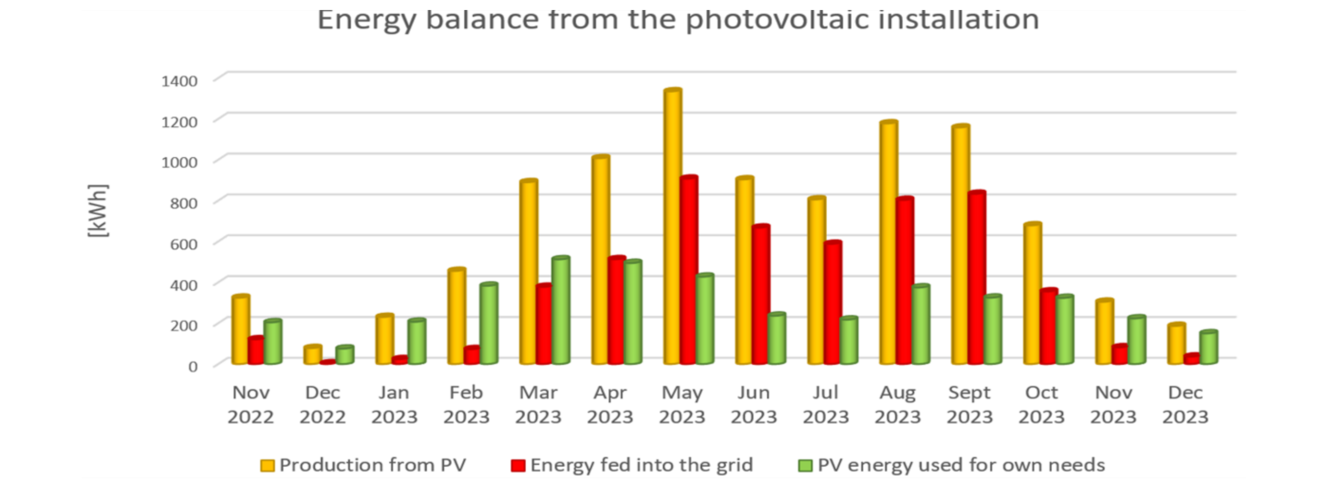

Fig. 4. Balance of electricity produced in a photovoltaic installation.

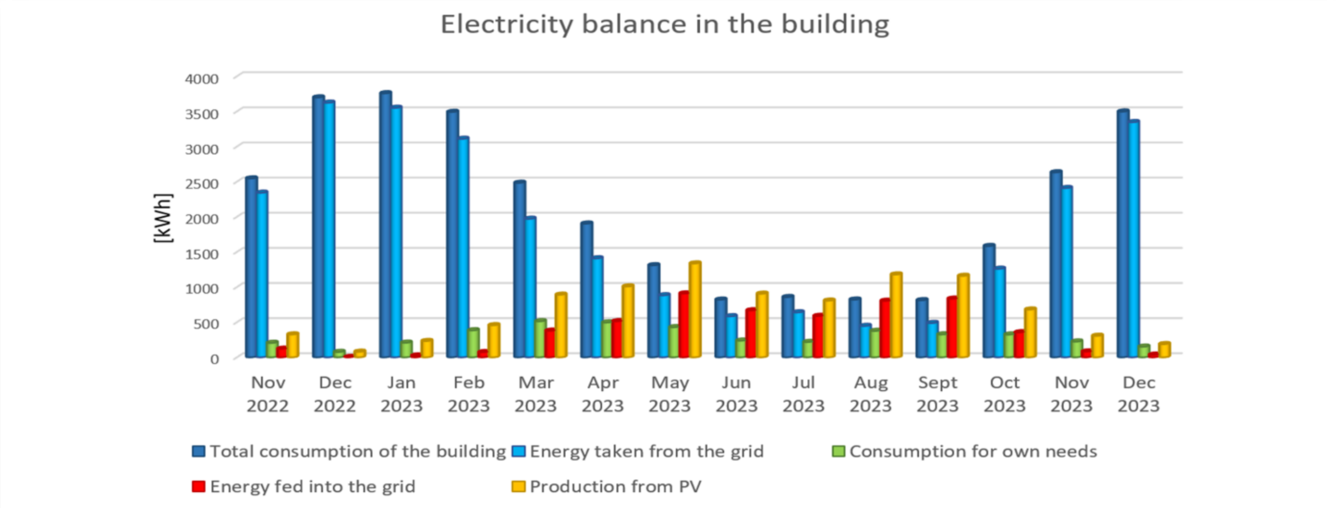

Fig. 5. Energy balance in the facility. Distribution of electricity consumed by the building and produced by the photovoltaic installation.

The analyses were conducted in the context of electricity consumption by the tested facility, energy production in the photovoltaic installation, the possibility of covering the building's demand with the energy produced by the PV installation and the use of energy from photovoltaics for own needs at the time of its production. The analysis used data from the measurement system installed in the facility and on the platform provided by the power company (Figs. 7 and 8).

During the summer months, when PV installation production is at its peak, approximately 30% [22] of the energy generated is consumed for internal needs. This aligns with the typical annual energy consumption profiles of households. Additionally, as illustrated in Fig. 5, it can be observed that only during the peak production period does the PV installation generate more energy than what is required by the building.

Conversely, the utilization of energy produced directly at the generation site to meet the facility's internal needs averages approximately 20% (refer to Fig. 6).

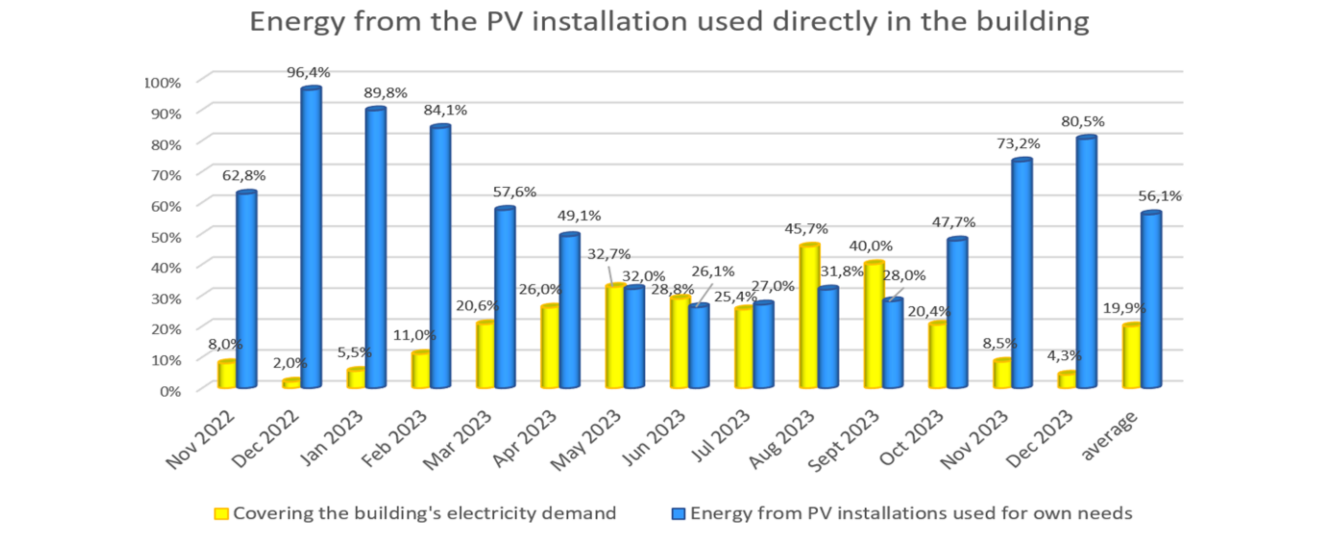

Fig. 6. Percentage of energy from the PV installation used for own needs in meeting the energy needs of the building and in the production of energy from photovoltaics.

The amount of energy generated by the photovoltaic installation is measured within the building, and information regarding the energy fed into the grid and the energy drawn from the power grid can be accessed by the customer through the platform provided by the power company (Fig. 7). Using the obtained data, it is possible to calculate the energy consumed by the prosumer for their own needs and the total energy used by the building.

Moreover, the platform provides information regarding virtual energy storage. The system converts the energy fed into the grid into equivalent units that can be credited to the prosumer's account. This enables the user to access information on the energy they can receive at no cost from the grid in the upcoming billing period (Fig. 8).

The conducted research aims to assess the more appropriate choice between a ground heat pump and an air heat pump, particularly in Polish climatic conditions. Additionally, the research endeavours to identify strategies to optimize the efficient utilization of electricity generated by photovoltaic systems to meet the energy demands of the building.

A preliminary analysis of measurement data showed that the operating parameters of both heat pumps are comparable during the heating season when the building consumes the most energy. A heat pump with a ground collector, due to the greater stability of the lower source, will have a slightly higher COP (Fig. 2 – red bars on the chart). Still, the cost of its installation will be much higher, which makes the economic viability of this project questionable. In turn, despite the expectation that in the summer, an air heat pump operating on a higher heat source parameter would have a higher COP, it turned out that this assumption was wrong. The ground heat pump, despite the lower temperature of the ground source, achieved higher operating efficiency than the air pump in the summer months. An additional experiment was conducted in August and September to investigate this dependency. Throughout August 2023, the heating of domestic hot water was supported only by a ground heat pump, while in September, an air unit was used for this purpose. The results confirmed previous observations. Despite the atmospheric air temperature being higher than the temperature of the brine feeding the ground heat pump, the efficiency of the air HP was lower than that of the ground one. The first thing that comes to mind is that an air heat pump, despite better operating parameters related to higher external air temperature, consumes more electricity due to constant readiness for operation. Heating the compressor crankcase, which is performed by an air heat pump, is not necessary in the case of a ground heat pump, which is especially noticeable during periods when heat pumps only work to heat domestic hot water, which is why they are turned on sporadically. When the compressor works more often during the heating season, this problem does not occur because there are only a few downtime periods for heating devices.

In subsequent heating periods, modifications to the system are planned, consisting of adapting the hybrid operation to the building's changing energy demand. The analysis of the collected measurement data is intended to help develop solutions that will help designers efficiently select power supply installations for a building with a specific energy class. It should significantly improve cooperation between the architectural industry and designers of sanitary installations supplying buildings with low energy demand.

The heating system in the tested facility is equipped with a central heating buffer with a capacity of 1500 l and a domestic hot water tank with a capacity of 800 l. Both tanks are located in the heated space of the building. Owing to these installation elements, energy can be accumulated, and its use can be postponed in time. Therefore, the first idea that comes to mind is the production of heat during the day, when the air temperature is higher, which is of great importance for increasing the efficiency of the air heat pump. During the day, we also obtain energy from the photovoltaic installation to use the electricity produced directly to power the heat pump. The energy collected in this way, which was generated in the most favourable conditions during the day, can later be used when our needs related to space heating and domestic hot water are the highest. However, this will involve additional costs associated with raising the temperature in the buffer tank. This will help increase the heat capacity of the system but will force the heat pumps to work with less optimal parameters of the upper source. Analyzing measurement data collected last year and in subsequent heating seasons will allow for estimating actual savings related to these measures re-

Fig. 7. Visualization from the TAURON e-counter platform. Balance of electricity consumed and energy from the PV installation fed into the power grid [23].

Fig. 8. Visualization from the TAURON e-counter platform. Balance of electricity consumed and energy from the PV installation fed into the power grid - considering the settlement balance [23].

garding energy and economy. The calculations will require considering two variants of settlement of the photovoltaic installation with the power company. They may be considered for a maximum period of 15 years because the prosumer settlement ceases to be valid later. After the period for which the prosumer contract has been concluded, it becomes even more important to use as much energy from photovoltaics as possible for your own needs, so optimizing the operation of the building's power supply system is one of the key elements of the user's savings planning.

This research can contribute to optimising energy utilization in buildings, thereby enhancing energy efficiency in the construction sector. Moreover, by improving the correlation between the operation of heat pumps and the usage of energy generated in photovoltaic installations, the research aims to enhance the stability of the collaboration between photovoltaic systems and the power grid. This research holds significant importance, not only for economic purposes but also for climate protection, particularly in terms of enhancing the efficiency of harnessing renewable energy to mitigate the greenhouse effect.

5. Conclusions

The conducted research aims to determine the actual operating parameters of two types of heat pumps installed under identical conditions, which constitutes a unique approach to the subject. The hybrid system installed in the analyzed building allows for very flexible changes in the operating parameters of both devices. Additionally, the building's power supply system enables the study of the cooperation between the heat pumps and the photovoltaic installation. Research conducted over two heating seasons allowed for drawing conclusions that may significantly influence the approach of investors, designers and installers towards the use of RES in construction.

Summarizing the initial research, it should be noted that in the current climatic conditions in Poland, the operation of an air-source heat pump does not significantly differ from the performance of a ground-source heat pump. The efficiency indicators of both devices during the heating season differ slightly and are respectively: for the GHP 2.69; for the AHP 2.63. Considering the investment costs AHP are currently becoming a real alternative to the much more expensive GHP.

It was also noted that the cooperation of an AHP with solar collectors, in the summer, does not have a positive effect on the efficiency of the heat pump. Despite the higher temperatures of the lower source than in the heating season, the efficiency of the device decreases instead of increasing. In July, when the AHP was operating only for the domestic hot water buffer, its sCOP was only 2.16, which was the lowest value recorded during the unit's operation. The main reason for this situation is the long downtime of the heat pump in readiness for operation, which causes the consumption of electricity, despite the lack of need for the device to operate.

In turn, the cooperation of the heat pump with the photovoltaic installation can contribute to increasing the ecological efficiency of the use of the building's power supply system. In the period December 2022 – February 2023, the use of energy from PV for own needs exceeded 80%, and over the entire year amounted to 55.7%, significantly exceeding the assumed self-consumption, which in an average household is about 30%. Maximizing the use of energy generated by the PV installation for one's own needs will also contribute to increasing the economic efficiency of the project. The lack of prosumer settlement will reduce energy losses in the case of net-metering and eliminate additional energy purchase costs in the case of net-billing.

The research planned for the upcoming years aims to address these questions and alleviate any uncertainties regarding the viability of utilizing renewable energy in construction. This research is anticipated to provide valuable insights and clarification in this regard.

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