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Simulation and Performance Analysis of an Air-Source Heat Pump and Photovoltaic Panels Integrated with Service Building in Different Climate Zones of Poland

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Abstract: In recent years, due to the global energy crisis, the idea of a photovoltaic-assisted air-source heat pump (PV-ASHP) has become increasingly popular. This study provides a simulation in TRNSYS and the analysis of the use of a PV-ASHP system in a service building in different climate zones of Poland. For each of the six cities—Kolobrzeg, Poznan, Krakow, Warsaw, Mikolajki, and Suwalki, the effect of changing five system parameters (area, efficiency, type, and location of photovoltaic panels, and the use of a heat pump control strategy) on the amount of energy generated and consumed was determined. We also estimated the extent to which the photovoltaic panels could cover the energy requirements for the heat pump (HP) operation and the system could provide thermal comfort in the service room. Finally, a simplified analysis of the operating costs and capital expenditures was made. The results highlighted the issue of the incoherence of renewable energy sources and the need to store surplus energy under Polish climatic conditions. Abandoning the HP control strategy increased energy consumption by 36–62%, depending on the location and Variant, while the change in the place of the PV panels on the roof slope reduced energy generation by 16–22%. When applied to an ASHP in a service building, the use of PV panels to power it seems to be cost-effective.

Keywords: heat pump; photovoltaics; heating; cooling; energy demand; renewable energy; TRNSYS

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Citation: Ołtarzewska, A.; Krawczyk, D.A. Simulation and Performance Analysis of an Air-Source Heat Pump and Photovoltaic Panels Integrated with Service Building in Different Climate Zones of Poland. *Energies* **2024**, *17*, 1182. https://doi.org/10.3390/en17051182

Academic Editor: Frede Blaabjerg

Received: 2 February 2024
Revised: 23 February 2024
Accepted: 24 February 2024
Published: 1 March 2024

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1. Introduction

In recent years, due to the state of political and economic affairs in the world, there has been a significant increase in the interest in renewable energy sources and a desire to intensify and accelerate their implementation, especially in European Union (EU) member states. The current policy agenda is based on concerns about energy security and, in line with the latest targets proposed for 2030 under the "Fit for 55" package, includes (1) increasing the share of renewable energies in energy consumption to 42.5%, targeting up to 45%, (2) reducing the EU's primary and final energy consumption by 11.7% for 2030 compared to projections for 2020 (equivalent to 40.5% and 38%, respectively, compared to projections for 2007) [1]. Consequently, with the need to obtain more energy in a more environmentally friendly and efficient way, the concept of photovoltaic panel-powered heat pumps has become increasingly popular [2]. In 2021, 158 GW of photovoltaic energy was installed in the European Union, while air-source heat pumps achieved the largest share of the heat pump market, accounting for as much as 94% of all devices [3,4].

In view of the high energy, economic and environmental potential of combining different types of renewable energy sources [5,6], many hybrid solar-assisted heat pump installations have also been studied and analyzed in recent years [7], both for heating and cooling [8–10], as well as for domestic hot water preparation [11–13], in different types of buildings [2,14] located in different climatic and ambient conditions [15–19].

Wang et al. [20] conducted a systematic review of the leading solar-assisted air-source heat pump systems. The results showed that the PV-ASHP system has the best techno-economic performance, achieving on average the best coefficient of performance (COP) of about 3.75, at a moderate cost and payback time, compared to a COP of 2.90 and 3.03 for ST-ASHP (solar thermal-assisted air-source heat pump) and PV/T-ASHP (photovoltaic/solar thermal-assisted air-source heat pump), respectively. A review of solar-assisted heat pump systems using solar panels and PV and PV/T technologies in terms of performance was also performed by Zohri et al. [21].

Stamatellos et al. [22], using a detailed transient building and energy system model, investigated how the combination of a rooftop photovoltaic system and a heat pump can affect the economic profile of the entire energy system of a household located in Greece. They estimated that an installation of up to 4.8 kWp could be considered cost-effective for 20 years, and the optimal tilt of south-facing photovoltaic panels, which allow increased electricity production during the summer, is 30°.

Da et al. [23] developed and simulated a PV-ASHP model with thermal energy storage in TRNSYS (Transient System Simulation Tool) software. The results showed that the annual PV self-consumption and self-satisfaction rates, as well as COP, increased by 131.25%, 10.53%, and 9.56%, respectively, with a solar contribution to the system of 55.54% and a PV output of 82 W/m^2 of building area. TRNSYS was also used to simulate a solar-assisted air-source heat pump heating system in a rural house [24].

Using other simulation tools such as GeoT*SOL and PV*SOL Premium, Mârza et al. [25] evaluated energy efficiency improvements for a solar household. They assumed three solutions: thermal renovation of the building envelope, the addition of photovoltaic panels to generate electricity, and the use of heat pumps for heating. The results showed that the PV system covered 34% of household consumption when using ASHP and 36% when using GSHP (ground source heat pump), and operating costs decreased by 47% for the PV system with ASHP and 53% for the PV system with GSHP.

In other studies, solar-assisted heat pumps have also been identified as an important future research direction due to their potential to improve the capacity factor and overall efficiency of power generation through cogeneration of heat and electricity [26], and they were even identified as one of the key solutions used to implement zero-energy buildings [27].

As renewable energy sources obtain energy mostly from the external environment, the main factor affecting their performance appears to be climate. Paying attention to this aspect, in Polish climatic conditions, several analyses of PV-HP system operation have been carried out so far [28,29]. The results have shown that due to the incoherence of the PV system, its use to power a heat pump operating only during the heating season is not the most favorable solution. The authors suggested that a better solution is to use PV technology year-round and for powering electrical appliances.

Pater [30] analyzed the results of the year-round operation of a grid-connected hybrid photovoltaic system with an air-source heat pump for the preparation of domestic hot water (DHW) in a residential building in Krakow, Poland in the context of the increasing self-consumption rate of energy. Simulations in TRNSYS showed that due to the increase in ambient temperature, the PV efficiency in the summer period was almost 2% lower compared to the winter period, while the average annual energy efficiency of the PV systems included in the simulations was 17.34%.

Niekurzak et al. [31] conducted an economic and environmental assessment of a system that combines a heat pump with photovoltaic panels. The results showed that the investment in the heat pump is profitable—the break-even point occurred in the 9th year of the analysis, while, with the additional use of the photovoltaic installation, the payback period was reduced to 7 years. In addition, the use of a hybrid system allowed a reduction in CO_2 emissions in the analyzed household by as much as 2893 kg/year. Also, Gulkowski [32], in his analysis of the energy efficiency of nine prosumer photovoltaic

installations located in southeastern Poland, estimated that the payback period of PV systems was less than 8 years, and the average cost of electricity was 0.14 €/kWh.

Pointing out the need for economic analyses for renewable energy solutions, Trela and Dubel [33] confirmed that government subsidies and incentives have a key impact on the development of the RES industry in Poland and showed that the highest profitability of all solutions considered was characterized by the financing scenario in force in 2021 for a heat pump and a photovoltaic installation with sufficient capacity to cover the demand in the last year of operation. The importance of economic instruments in the development of RES in Poland was also analyzed by Maruszewska et al. [34].

An economic and energy assessment of a heat pump system powered by photovoltaic panels in other countries was also carried out by Delač et al. [35] and Al-Falahat et al. [2]. The latter, using an experimental study of a photovoltaic system located on the roof of a hotel building in Jordan, estimated that the simple payback period of that system is about 1.94 years, with an annual net profit of approx. 185,850 JOD.

In recent years, photovoltaic-thermal (PV/T) collectors, which combine electricity and heat generation, thus increasing the overall efficiency of the system, have also become particularly popular [36–38], even in Polish climatic conditions [39,40].

Based on an experimental installation in a small office building, Bae et al. [41] showed that systems using photovoltaics and an air-source heat pump are a suitable alternative to PVT-GSHP systems, with about 9% higher efficiency and 44% lower initial cost.

It is worth noting that, as with most renewable energy sources, in addition to the numerous economic, ecological, and energy benefits, the main inconvenience and barrier to the use of PV-ASHP systems are the high investment costs and often, the additional costs associated with the need to adapt and thermo-modernize the building. Other important considerations are the unfavorable climatic conditions prevailing in Poland, i.e., seasonal inconsistencies between the availability of solar energy and the building's heat load [23], as well as the limited possibility of generating electricity when it is most needed (during the winter season).

The purpose of this study was to simulate and analyze the performance of an air-source heat pump and a photovoltaic panel system integrated into a service building located in different climate zones of Poland.

This study provides valuable information on the potential benefits and limitations of cooperation between photovoltaic panels and an air-source heat pump, both in terms of energy and economics. It combines a case study and theoretical analysis based on simulation to fill a gap in the lack of considerations of PV-ASHP system operation in service buildings under Polish climatic conditions. Compared to a previous study conducted on the same building and involving an analysis of the influence of selected factors on heating costs and pollutant emissions [42], this study focuses on simulating the implementation of a particular system and testing the impact of individual factors that may be relevant to its selection. It also gives a starting point for further research on the desirability of using renewable energy sources in non-residential buildings.

2. Materials and Methods

2.1. Building

The object under analysis is an existing vehicle diagnostic station (service building) made using traditional technology and located in the IV climate zone of Poland, in Bialystok. The total roof area is 148.3 m^2 (two slopes of 74.15 m^2). Detailed information on the building, as well as its plan, is presented in the previous study [42]. Figure 1 shows a photo of the building under real conditions.



Figure 1. Photo of the analyzed service building.

The building model (Figure 2) was created in SketchUp [43], implemented into TRNBuild [44] and then modified to reflect real-world conditions as closely as possible [45].

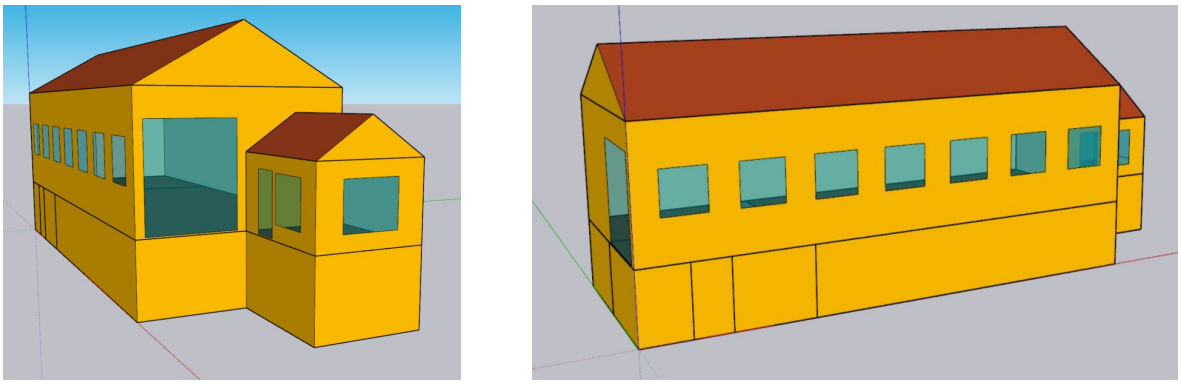


Figure 2. Model of the analyzed service building created in SketchUp.

2.2. Model Verification

The building consists of seven thermal zones, for which the design internal temperatures were adopted according to the real conditions:

- 24 °C in the bathroom
- 20 °C in the checkroom
- 18 °C in the waiting room with office, in the boiler room, and the service area
- 10 °C in the basement (underground floor) and in the attic

The upper temperature limit for maintaining thermal comfort during the summer was 26 °C in the whole building. These temperature levels were set by the simple thermostat and maintained by a heat pump.

The following table (Table 1) shows a comparison of other building data relevant to further energy analysis obtained in the simulation program and reality.

Table 1. Building data.

Data	TRNSYS	Real Data
"U" [1] of the roof	0.25 W/(m^2·K)	0.25 W/(m^2·K)
"U" [1] of the ground floor	0.45 W/(m^2·K)	0.45 W/(m^2·K)
"U" [1] of the external wall	0.30 W/(m^2·K)	0.30 W/(m^2·K)
"U" [1] of the internal wall	1.00 W/(m^2·K)	1.00 W/(m^2·K)
"U" [1] of the external door	1.27 W/(m^2·K)	1.30 W/(m^2·K)
"U" [1] of the glazing	1.27 W/(m^2·K)	1.30 W/(m^2·K)
Electricity consumption	–	5500 kWh
Total heating demand	5569 kWh	5600 kWh
Heating load of the service area	4506 kWh	–

Table 1. *Cont.*

Data	TRNSYS	Real Data
Cooling load of the service area	4546 kWh	–
Occupancy schedule	7^{00}–17^{00}	7^{00}–17^{00}

[1] "U"—heat transfer coefficient

Real data were collected from 2020 to 2022, but ultimately, we used the one-year period from July 2021 to July 2022 to verify the model for heating energy consumption and the two-year period from 2020 and 2021 to estimate average electricity consumption. Domestic hot water in the building was prepared using an electric instantaneous water heater. For the consideration of the cooling load, the calculations in TRNSYS additionally included heat gains from people, light, and equipment. More detailed data on heat and electricity consumption are presented in a previous study [42].

Due to the largest share of the design heating and cooling loads, as well as the highest daily occupancy in this area, it was assumed that the heat pump would operate for the service room, for which all calculations and simulations were performed.

For each of six cities—Kolobrzeg, Poznan, Krakow, Warsaw, Mikolajki, and Suwalki—representing five climate zones, the effect of changing five system parameters—(1) the area of photovoltaic panels, (2) the efficiency of photovoltaic panels, (3) the type of photovoltaic panels (covered and uncovered), (4) the location of photovoltaic panels, and (5) the use of a control strategy for the heat pump—on the amount of energy generated and consumed by the heat pump, the amount of energy generated by the photovoltaic panels, and the possibility of providing thermal comfort in the service room was studied, assuming a total of 36 Variants of the system.

We also carried out a simplified analysis of the operating costs and capital expenditures of the system.

Detailed characteristics of the climatic conditions, PV-ASHP system, and adopted Variants are provided in Sections 2.3–2.5

In order to determine the degree of maintenance of thermal comfort by the heat pump in the service room, based on real conditions, own observations and feelings, Polish requirements [46], as well as other studies [47,48], a temperature range of 18–26 °C was assumed as relative thermal comfort conditions.

Unit prices for electricity [49], as well as the euro exchange rate, were based on current data as of 10 December 2023 and included in Table 2. Then, taking into account these values, the efficiency of the heat pump, and the amount of energy (electricity) required to heat the building, the heating costs were calculated for all Variants.

Table 2. Data for operating cost calculations.

Electricity price (€) [1]	0.48
Euro exchange rate	4.34

[1] Price for businesses. All fixed and variable costs are included.

2.3. Climatic Conditions

Simulations in all Variants were carried out for six cities, representing all (five) climate zones of Poland, according to the PN-EN 12831:2006 standard [50]:

- Kolobrzeg—located in climate zone I, where the design outdoor temperature is −16 °C and the average annual outdoor temperature is 7.7 °C.
- Poznan—located in climate zone II, where the design outdoor temperature is −18 °C and the average annual outdoor temperature is 7.9 °C.
- Krakow and Warsaw—located in climate zone III, where the design outdoor temperature is −20 °C and the average annual outdoor temperature is 7.6 °C.
- Mikolajki—located in climate zone IV, where the design outdoor temperature is −22 °C and the average annual outdoor temperature is 6.9 °C.

- Suwalki—located in climate zone IV, where the design outdoor temperature is −24 °C and the average annual outdoor temperature is 5.5 °C.

Due to the large territorial spread, as many as two locations with different geographic coordinates were considered for the third climate zone. The above temperatures (design and average annual) were used for heat load calculations and sizing of heating systems in Poland. In this paper, they are presented to characterize the analyzed climatic zones and show the differences between the data from the standard [50] and the weather data used by TRNSYS [51].

In TRNSYS, weather data for a typical meteorological year (TMY), taken from the Meteonorm database, were used for simulation [52]. A comparison of the parameters that characterize the climatic conditions of selected cities used by TRNSYS and have the greatest significance for the operation of the system is shown in Table 3.

Table 3. Climatic conditions of selected cities.

	Ambient Temperature [°C]			Total Horizontal Radiation [W/m^2]		Total Tiled Surface Radiation [W/m^2]	
Location	**Max.**	**Avg.**	**Min.**	**Max.**	**Avg.**	**Max.**	**Avg.**
Kolobrzeg	28.1	8.4	−12.3	921	121	1202	140
Poznan	30.9	8.3	−15.5	945	116	1135	134
Krakow	29.7	7.7	−16.6	920	119	1035	135
Warsaw	29.8	7.8	−16.6	989	114	1116	129
Mikolajki	28.7	7.0	−18.8	922	123	1189	145
Suwalki	29.5	6.1	−20.7	943	121	1149	145

The division of Poland's territory into climate zones according to [50] is presented in Figure 3.

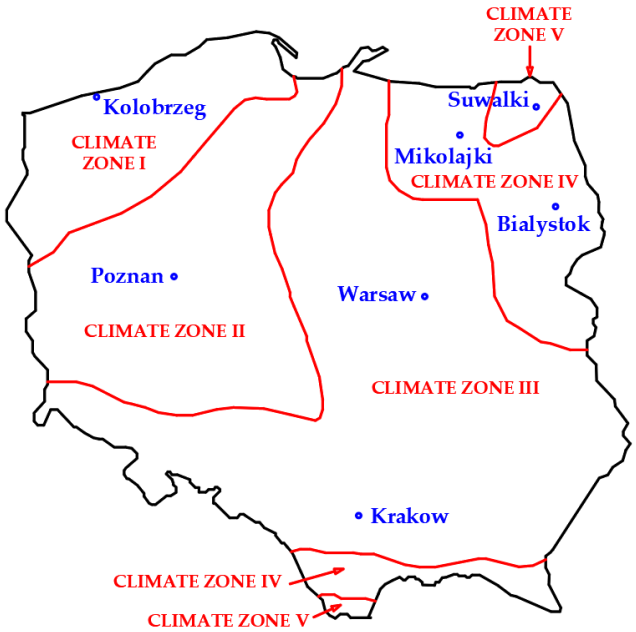


Figure 3. Territory division of Poland into climate zones (based on our previous study [50]).

2.4. TRNSYS Model

Simulations of PV-ASHP system operation in different Variants were carried out in the TRNSYS Simulation Studio v. 18 software [51], and the building parameters were modified using the TRNBuild plug-in [44]. Simulations were carried out with a time step of 0.125 h, but for the analysis, mainly hourly, monthly, and annual average results were considered.

The major components of the model include the following:

- Building (Type 56: Multi-Zone Building)
- Air-source heat pump (Type 119c: Air-Source Heat Pump with No Auxiliary)
- Photovoltaic panels (Type 562d: Simple PV Model, Covered with PV Efficiency from Correlations or Type 562h: Simple PV Model, Uncovered with PV Efficiency from Correlations)
- Thermostat (Type 166: Simple Room Thermostat)
- Weather (Type 15-6: Weather Data Processor for Meteonorm Files)
- Differential controllers (Type 165: ON/OFF Differential Controller)

While additional components are online plotters, printers, printegrators, periodic integrators, equations, etc. [53,54]. A model of the system is presented in Figure 4.

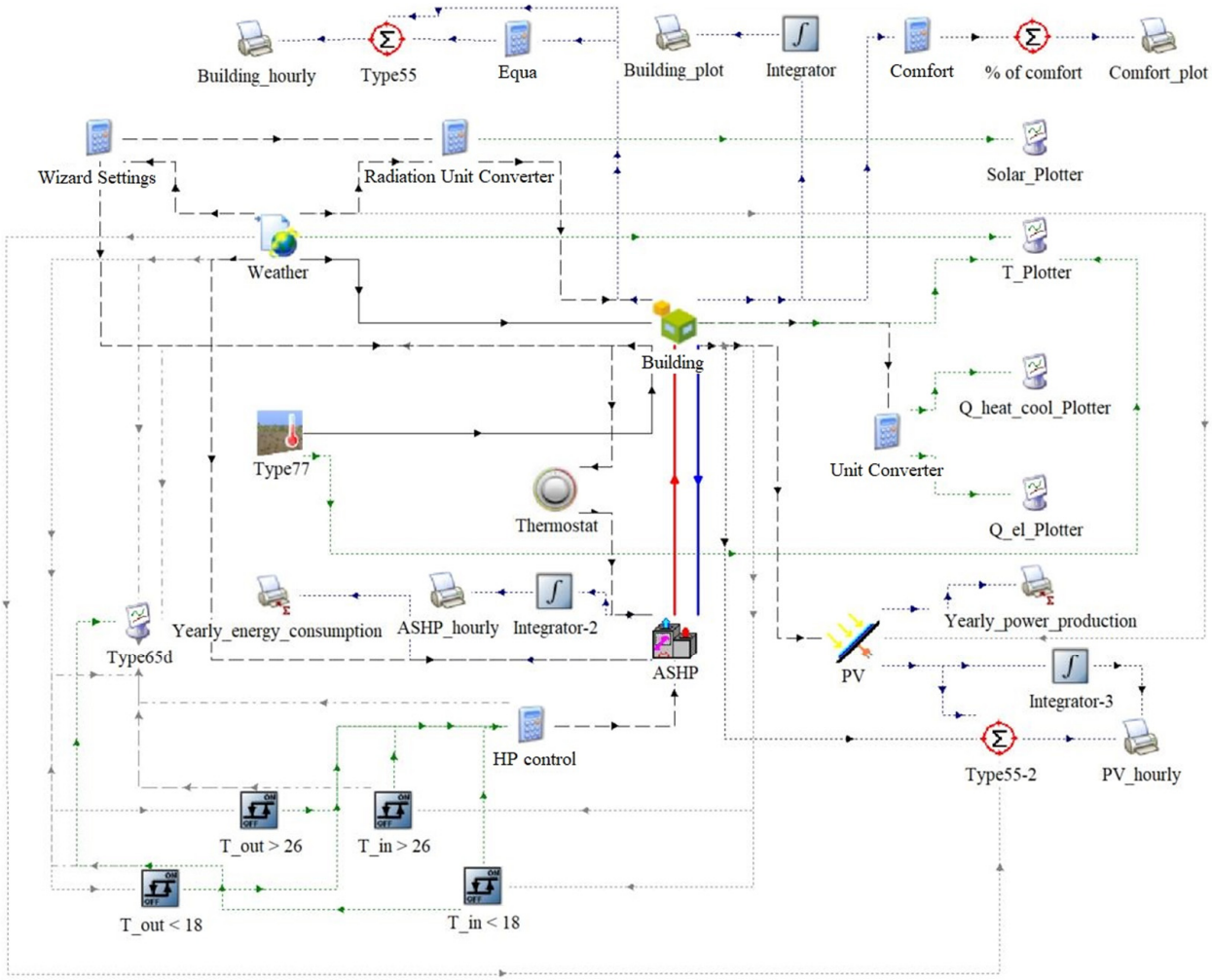


Figure 4. TRNSYS model of the PV-ASHP system.

For this analysis, an air-source heat pump was adopted, with a nominal air flow rate of 300 L/s, without auxiliary. The nominal capacity of the heat pump was selected by taking into account the maximum heating and cooling loads of the service area, which were about 5.4 and 6.2 kW, respectively.

Detailed data on heating and cooling performance depending on the flow rate and temperature of outdoor and indoor air were implemented into the heat pump as external files.

Variants 1–5 also used a control strategy that affects the position of the heat pump's outside air damper, depending on the outdoor and indoor air temperatures. The control strategy involved the following:

- Closing the outside air damper in the heat pump when the temperature of both outside and inside air is higher than 24 °C or lower than 18 °C.

- Opening the outside air damper in the heat pump when the outside air temperature is greater than or equal to 18 °C and the inside air temperature is less than 18 °C and when the outside air temperature is less than or equal to 24 °C and the inside air temperature is greater than 24 °C.

The Type562 used to model photovoltaic panels includes four modes for calculating panel efficiency, depending on the available data. This analysis uses mode two, in which the overall efficiency is calculated based on Equation (1):

$$\eta = \left(1 + \eta_{T,coef}\left(T_{PV} - T_{ref}\right)\right)\left(1 + \eta_{I,\,coef}\left(I_T - I_{T,ref}\right)\right)\eta_{ref} \quad (1)$$

where $\eta_{T,coef}$ and $\eta_{I,coef}$ are coefficients that describe the change in photovoltaic array efficiency as a function of cell temperature or incident solar radiation, T_{PV} is the PV cell temperature, T_{ref} is cell temperature in the conditions under which the reference PV efficiency was measured, I_T is the total amount of solar radiation incident on the PV collector surface, $I_{T,ref}$ is the total amount of solar radiation incident on the PV collector surface in the conditions under which the reference PV efficiency was measured, and η_{ref} is the overall efficiency of the photovoltaic array under reference conditions [55].

Since only a theoretical model was used for simulation, and the impact of coefficients $\eta_{T,coef}$ and $\eta_{I,coef}$ was not investigated in this study, for the purposes of analysis, it was assumed that $\eta_{T,coef} = -0.005\ \frac{1}{^\circ\mathrm{C}}$ and $\eta_{I,coef} = 0.000025\ \frac{\mathrm{h \cdot m^2}}{\mathrm{kJ}}$, i.e., the default values for Type 562 in this PV efficiency mode were maintained.

2.5. Variants

The Variants assumed heating and cooling with an air-to-air heat pump controlled using a thermostat and possibly a control strategy. For electricity production, covered or uncovered photovoltaic panels with an average efficiency of 20% or 15% were used and installed on a southeast- or northwest-facing roof with a slope angle of 30°. The assumed area of photovoltaic panels was 30 m^2 or 20 m^2.

Variant 1 was set up to test the effect of changing the area of photovoltaic panels on the amount of energy they generate in different climate zones of Poland.

Variant 2 was set up to test the effect of changing the efficiency of photovoltaic panels on the amount of energy they generate in different climate zones of Poland.

Variant 3 was considered the baseline.

Variant 4 was set up to test the effect of changing the location of photovoltaic panels (from a southeast- to a northwest-facing slope of the roof) on the amount of energy they generate in different climate zones of Poland.

Variant 5 was set up to test the effect of changing the type (covered and uncovered) of photovoltaic panels on the amount of energy they generate in different climate zones of Poland. In the case of covered photovoltaic panels, an additional glass cover (on the outside) was used for their construction. Covered and uncovered panels can also be called glazed and unglazed panels, respectively.

Variant 6 was set up to test the effect of the control strategy on the operation of the system in different climate zones of Poland.

Investigating the influence of the studied parameters on the amount of energy generated by photovoltaic panels will allow the assessment of their relevance in the selection of the system in Polish climatic conditions.

A summary of the settings adopted in each Variant is shown in Table 4.

Table 4. Characteristics of the analyzed Variants.

	Control Strategy	PV Type	Location	Area	Efficiency
Variant 1	Yes	Covered	Direction: southeast, Angle: 30°	20 m^2	20%
Variant 2	Yes	Covered	Direction: southeast, Angle: 30°	30 m^2	15%
Variant 3	Yes	Covered	Direction: southeast, Angle: 30°	30 m^2	20%
Variant 4	Yes	Covered	Direction: northwest, Angle: 30°	30 m^2	20%
Variant 5	Yes	Uncovered	Direction: southeast, Angle: 30°	30 m^2	20%
Variant 6	No	Covered	Direction: southeast, Angle: 30°	30 m^2	20%

3. Results and Discussion

3.1. Loads

The results of the heating and cooling load during the year, considering the representative Variant of climate zone IV (in which the analyzed building is located under real conditions) and only the service room (where the heat pump is to be installed), are shown in Figure 5.

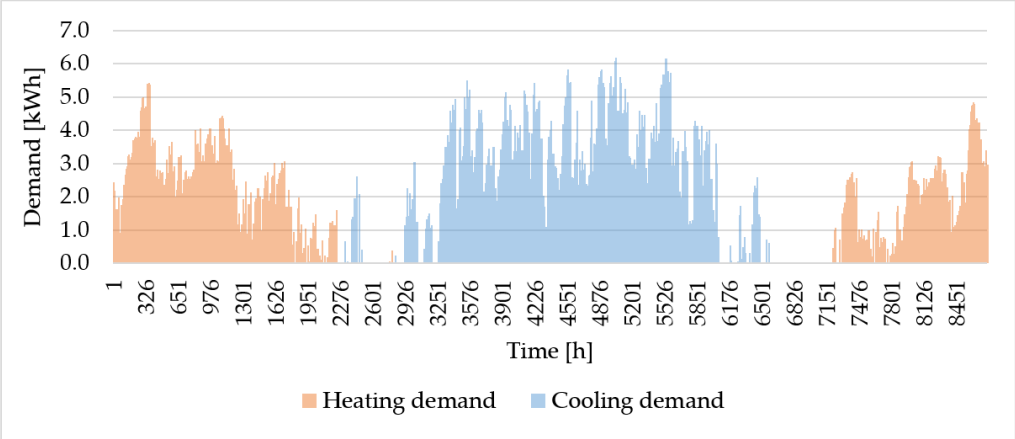


Figure 5. Annual distribution of heating and cooling load for the service room.

The annual distribution of the heating and cooling load for the service room has a shape that is fairly typical for Polish climatic conditions. The highest heating loads occur from November to March, while the highest cooling loads occur during summer. The relatively low values of the heating load with high values of the cooling load are due to the large amount of electrical equipment, lighting, and frequent operation of car engines, which are associated with additional heat gains.

3.2. Energy Consumption

The results of energy consumption of the air-source heat pump in all climate zones of Poland, taking into account the different Variants, are shown in Figure 6.

Depending on the Variant and the city analyzed, the energy consumption of the heat pump ranged from 3701 kWh to 8082 kWh, which can be considered a wide range. The results were the same for individual cities in Variants 1–5 and significantly higher (36–62%) in Variant 6, in which the control strategy was abandoned.

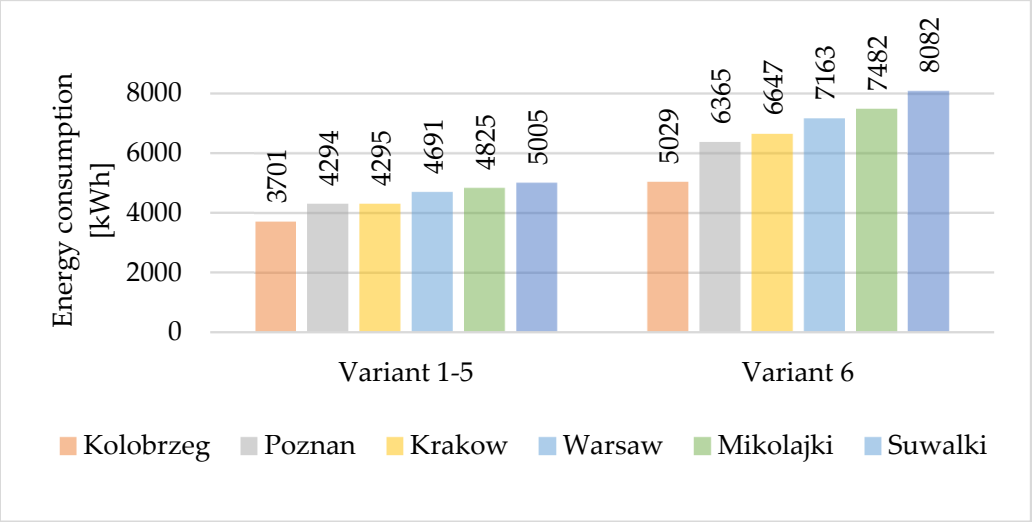


Figure 6. Results of energy consumption of the heat pump.

Regardless of the Variant analyzed, the lowest energy consumption required for the operation of the heat pump was obtained in Kolobrzeg, located in climate zone I, while the highest was obtained in Suwalki, located in climate zone V.

3.3. Energy Generation

The results of energy generation by the photovoltaic panels in all climate zones of Poland, taking into account the different Variants, are shown in Figure 7.

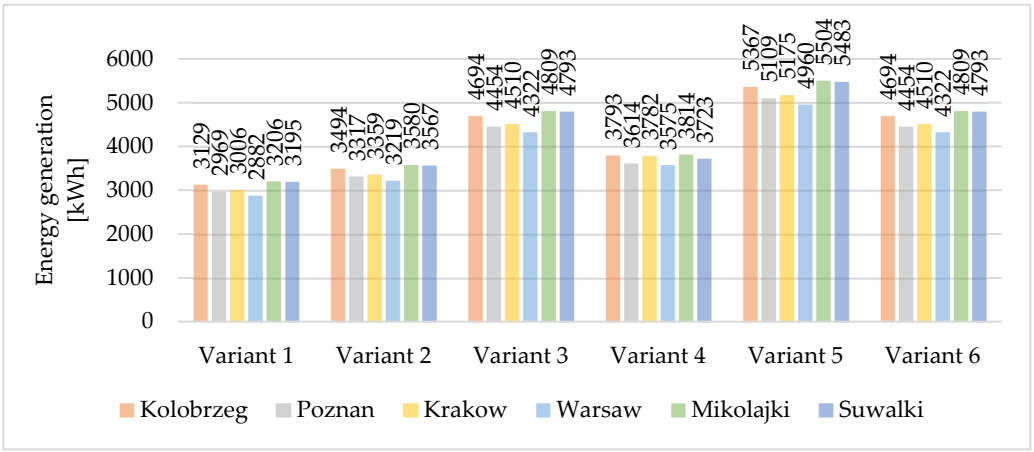


Figure 7. Results of energy generation by the photovoltaic panels.

Depending on the Variant and the city analyzed, the energy generation by photovoltaic panels ranged from 2882 kWh to 5504 kWh. The lowest energy generation was obtained in Variant 1 in Warsaw, while the highest was obtained in Variant 5 in Mikolajki.

Regardless of the climate zone, the highest values were reached in Variant 5, where uncovered panels, placed on the southeast-facing slope of the roof, with an area of 30 m^2 and an efficiency of 20%, were adopted, while the lowest was achieved in Variant 1, where covered panels, placed on the southeast-facing roof slope, with an area of 20 m^2 and an efficiency of 20%, were assumed.

Depending on the city, changing the location of photovoltaic panels from the southeast to the northwest slope of the roof (Variant 4 vs. Variant 3) resulted in a 16–22% reduction in the amount of energy generated, while changing the type of panels from covered to uncovered (Variant 5 vs. Variant 3) resulted in a 14–15% increase. Moreover, in all climate

zones, choosing panels with 5% lower efficiency (Variant 2 vs. Variant 3) resulted in a 26% decrease in the amount of energy generated, while installing 10 m^2 less area of the panels (Variant 1 vs. Variant 3) resulted in a 33% decrease.

It is worth noting that both the energy consumption of the heat pump and the energy generation by photovoltaic panels differ for Warsaw and Krakow, located in the same climatic zone. Despite the same design outdoor temperature and average annual outdoor temperature [50], simulations based on meteorological data for the whole year [52] led to different results.

3.4. Thermal Comfort

The results of the degree of maintenance of thermal comfort by the heat pump, assuming boundary temperatures of 18–26 °C, are shown in Figure 8, while the results for a temperature range of 17.5–26.5 °C are shown in Figure 9.

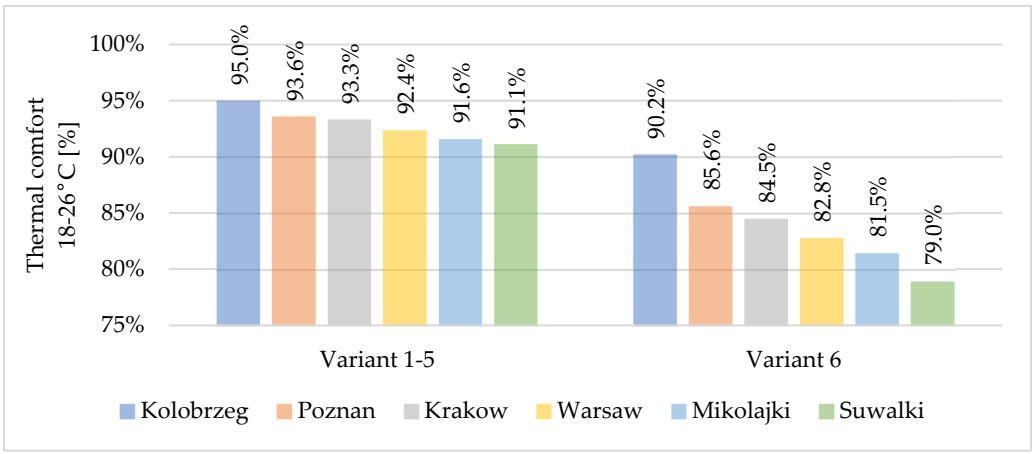


Figure 8. Results of the degree of maintenance of thermal comfort (18–26 °C).

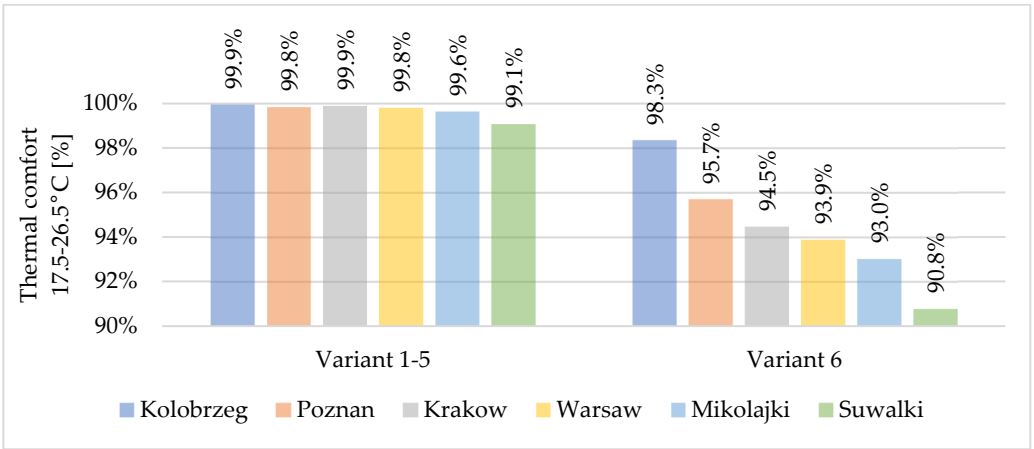


Figure 9. Results of the degree of maintenance of thermal comfort (17.5–26.5 °C).

Considering temperature boundaries of 18–26 °C, the analyzed PV-ASHP system is capable of providing thermal comfort in the service room 79% to 95% of the year, depending on the Variant and the city analyzed.

As with energy consumption, the results were the same for each city in Variants 1–5 and less favorable (5–15%) in Variant 6, in which the control strategy was abandoned.

In turn, considering slightly wider temperature boundaries, i.e., 17.5–26.5 °C, differing by a value often not perceptible to humans, the PV-ASHP system is capable of providing thermal comfort in a service room as much as 90.8% to 99.9% of the year, which can be considered a very satisfying result.

3.5. Degree of Coverage of Electricity Demand

The results of the degree of coverage of the heat pump's electricity demand by photovoltaic panels for the whole year are presented in Table 5.

Table 5. Degree of coverage of electricity demand by photovoltaic panels.

Location	Climate Zone	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5	Variant 6
Kolobrzeg	I	84.6%	94.4%	126.8%	102.5%	145.0%	93.3%
Poznan	II	69.1%	77.2%	103.7%	84.2%	119.0%	70.0%
Krakow	III	70.0%	78.2%	105.0%	88.0%	120.5%	67.8%
Warsaw	III	61.4%	68.6%	92.1%	76.2%	105.7%	60.3%
Mikolajki	IV	66.4%	74.2%	99.7%	79.1%	114.1%	64.3%
Suwalki	V	63.8%	71.3%	95.8%	74.4%	109.6%	59.3%

After summing up the hourly results for the whole year, it can be seen that, depending on the analyzed Variant and climate zone, the photovoltaic panels are able to cover the heat pump's electricity demand by 59.3% to as much as 145%. The lowest value was obtained in Variant 6 in Suwalki, while the highest was obtained in Variant 5 in Kolobrzeg.

Analogous to energy generation, regardless of the climate zone, the highest values were achieved in Variant 5. In turn, the lowest values were achieved in Variants 1 and 6.

3.6. Energy Balance

Figure 10 shows the distribution of energy consumption and generation by month throughout the year using the examples of the most and the least favorable scenarios in terms of energy generation—Variant 5 and Variant 1, respectively, for climate zone IV.

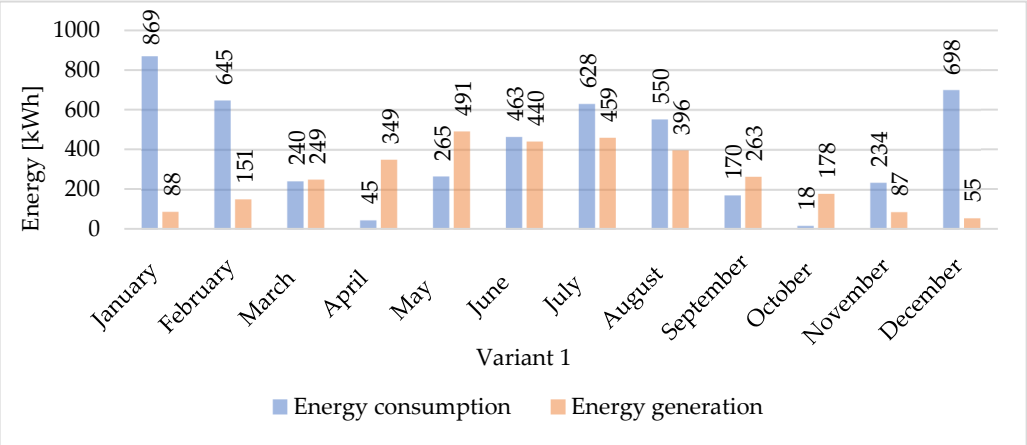


Figure 10. Distribution of energy consumption and generation during the year based on the example of Variant 1 in Mikolajki.

The total amount of energy generated during the year in Variant 1 in Mikolajki was 3206 kWh, while the energy consumed by the heat pump was 4825 kWh. The highest shortfall in energy generated relative to the demand occurred in December and January (about 90%). In March, April, May, September, and October, the photovoltaic panels were able to cover the full energy demand for heat pump operation.

The total amount of energy generated during the year in Variant 5 in Mikolajki was 5504 kWh, while the energy consumed by the heat pump was 4825 kWh. The highest shortfall in energy generated relative to the demand occurred in December and January (about 80–85%). From March to October, the photovoltaic panels were able to cover the full energy demand for the heat pump operation.

Using the example of Variant 5 (Figure 11) and the other Variants, where the amount of energy generated exceeds 100% (Table 5), it is worth noting that, despite a fairly favorable

annual energy balance, during the winter period, when the heat pump works most intensively and consumes the most energy, the photovoltaic panels generate the least amount of energy, which could a problem and indicates the need for energy storage, which was also confirmed by Zhang et al. [56].

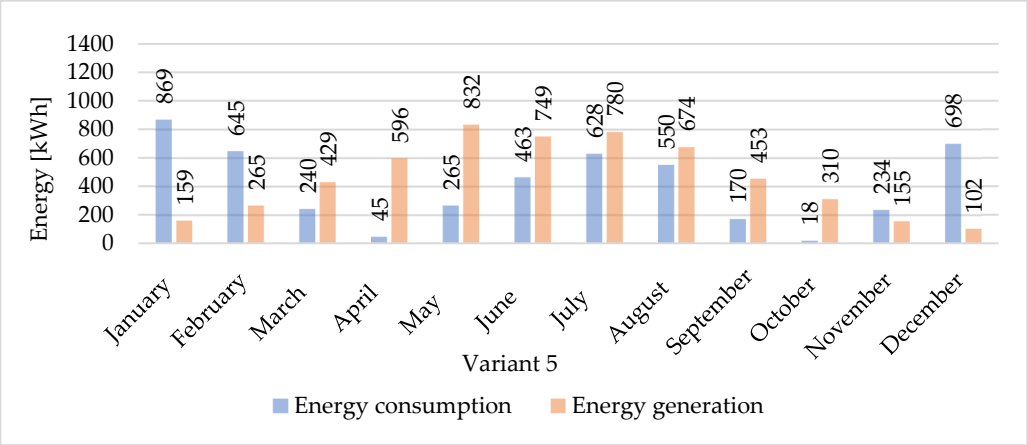


Figure 11. Distribution of energy consumption and generation during the year based on the example of Variant 5 in Mikolajki.

3.7. Operating Costs

The estimated operating costs of the air-source heat pump for each Variant and city are summarized in Table 6.

Table 6. Estimated operating costs of the ASHP.

Location	Climate Zone	Operating Costs [€]	
		Variants 1–5	Variant 6
Kolobrzeg	I	1782.2	2422.0
Poznan	II	2068.0	3065.0
Krakow	III	2068.6	3201.0
Warsaw	III	2259.2	3449.5
Mikolajki	IV	2323.8	3603.1
Suwalki	V	2410.3	3892.2

Depending on the Variant and the city analyzed, the operating costs of the heat pump ranged from 1782.2 € to 3892.2 €. The lowest operating costs were obtained in Variants 1–5 in Kolobrzeg, while the highest were obtained in Variant 6 in Suwalki.

Operating costs were directly proportional to the amount of energy consumed by the heat pump; therefore, they depended on the energy demand in a particular climate zone and whether a control strategy was used.

3.8. Investment Costs

In view of the dynamic volatility of heating equipment prices, as well as the wide choice of manufacturers and types of pumps, for the purposes of this simple analysis, we assumed an average investment cost of 3500 € for the purchase and installation of an air heat pump, according to [57].

Furthermore, taking into account the estimated investment costs for the purchase and installation of photovoltaic panels in the building analyzed, as determined in the previous study [42], the simple payback time for the photovoltaic panels would be between 2 and 5 years depending on the variant, assuming that the needs of the heat pump, other devices, and lighting are covered. This result is consistent with or similar to the results of other studies [58–60].

It should be noted that the above simplified analysis also does not take into account seasonal inconsistencies between the availability of solar energy and the thermal load of the building.

4. Conclusions

This study provides a simulation and analysis of the use of the air-source heat pump and photovoltaic panels system in a service building (vehicle diagnostic station) in different climate zones of Poland. The building model was developed to reflect the real conditions in the basic variant as accurately as possible. For each of the six cities—Kolobrzeg, Poznan, Krakow, Warsaw, Mikolajki and Suwalki, representing five climate zones—the effect of changing five parameters (area, efficiency, type and location of photovoltaic panels, and the use of a heat pump control strategy) on the amount of energy generated and consumed by the heat pump, the amount of energy generated by the photovoltaic panels, and the possibility of providing thermal comfort in the service room was studied. We also estimated the degree to which the photovoltaic panels cover the energy demand for heat pump operation, and a simplified analysis of the system's operating costs and capital expenditures was made. The main conclusions of the work are summarized below:

- The highest electricity consumption of the heat pump was obtained in Suwalki (climate zone V) and the lowest was in Kolobrzeg (climate zone I).
- Abandoning the exemplary control strategy of the heat pump increased electricity consumption by 36–62% (depending on the location), which highlights the importance of control strategies.
- Generally, the highest values of energy generation were reached in Variant 5, where uncovered panels with an area of 30 m^2 and efficiency of 20%, placed on the southeast-facing slope of the roof, were adopted, while the lowest energy generation was in Variant 2, due to the lower area of the panels (20 m^2).
- Changing the location of the photovoltaic panels (from the southeast- to the northwest-facing slope of the roof) resulted in a decrease in the amount of energy generated by 16–22% (depending on the location), while changing the type of panels (from covered to uncovered) resulted in a 14–15% increase.
- Assuming temperature limits of 18–26 °C, the analyzed PV-ASHP system was able to provide thermal comfort in the service room 79% to 95% of the year, depending on the location and Variant, while assuming temperature limits of 17.5–26.5 °C 90.8% to 99.9% of the year.
- Taking into account the annual balance, photovoltaic panels were able to cover the heat pump's demand for electricity 59.3% to as much as 145% (depending on the location and the Variant); however, using the example of the most favorable scenario in Mikolajki (Variant 5), it was shown that in the winter season, when the heat pump works most intensively and consumes the most energy, photovoltaic panels generate the least energy, indicating the need for energy storage.
- Estimated operating costs of the heat pump range from 1782.2 € to 3892.2 €—the lowest operating costs were obtained in Variants 1–5 in Kolobrzeg, while the highest was in Variant 6 in Suwalki.
- Estimated simple payback time for the photovoltaic panels range between 2–5 years (depending on the location and Variant).
- All the analyzed results differ to some extent for Warsaw and Krakow, located in the same climatic zone—despite the same design outdoor temperature and average annual outdoor temperature, simulations based on meteorological data for the whole year lead to different results.

The results obtained in this study provide valuable information on the potential benefits and limitations of cooperation between photovoltaic panels and an air-source heat pump, both in terms of energy and economics. They also give a starting point for further consideration of the desirability of using renewable energy sources in service buildings.

According to our findings, future research should focus on the incoherence of renewable energy sources in Polish climatic conditions, the need to store surplus energy generated during the year, the need to use appropriate automation (control strategies) for heat pumps, the selection of the location, type, and size of photovoltaic panels, depending on external conditions, and the methods and possibilities of storing surplus energy and reducing energy demand with appropriate automation. When considering the annual energy balance in a climate dominated by heating, these are the most problematic and topical. Moreover, the inconsistency of renewable energy sources is even more apparent with other types of buildings, where heat gains (need for cooling) during the summer are lower.

Author Contributions: Conceptualization, A.O. and D.A.K.; methodology, A.O.; formal analysis, A.O.; writing—original draft preparation, A.O.; writing—review and editing, A.O. and D.A.K.; visualization, A.O.; supervision, D.A.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was carried out as a part of the works no. WI/WB-IIŚ/9/2022 and WZ/WB-IIL/2/2023 at the Bialystok University of Technology and was financed from the research subvention provided by the Minister responsible for science.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

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