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Increasing Energy Self-Consumption in Residential Photovoltaic Systems with Heat Pumps in Poland

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Abstract: Currently, the use of air-source heat pumps (ASHP) in combination with a photovoltaic (PV) installation is a very promising option for a necessary and urgent energy transformation in European countries. It is extremely important to develop solutions that will help maximize the use of energy generated from renewable energy sources. Such issues include the problem of insufficient use of generated electricity in PV on-grid microinstallations in residential buildings. This paper's aim is to analyse the results of a one-year-round operation of a PV array grid-connected hybrid installation with ASHP for domestic hot water preparation in a residential building in Cracow, Poland, in the context of increasing self-consumption of PV energy. Models of systems are built and simulated in the Transient System Simulation software in release 18.05.0001. Simulations were carried out for different scenarios involving different building electricity consumption profiles, PV system capacity and specified runtime management of ASHP. The novelty of this study lies in the evaluation of the impact of a certain range of conditions on the energy performance of the system and in particular on increasing self-consumption. The results showed that the use of ASHP, with specified runtime management, results in an increase in monthly self-consumption values from 7% to 18%, and annual values up to 13%. Moreover, determining the appropriate size of the used PV system depending on whether it is present ASHP in the installation is crucial to increasing the value of this parameter. Overall, this study provides valuable insights into the potential benefits of PV panels and ASHP operating together, particularly on self-consumption values.

Keywords: photovoltaics; air-source heat pumps; TRNSYS; hybrid installations; self-consumption

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1. Introduction

In recent years, due to political and economic events in the world that have largely hit European Union (EU) countries, in particular, the armed conflict between Ukraine and Russia, interest in renewable energy sources (RES) technologies has increased significantly. The relevance of RES installation technology growth in the EU is affirmed by a number of actions, funds and policies [1]. The latest legislative changes in the EU assume the achievement of very ambitious goals, including the usage of RES in the total energy mix up to at least 40% by 2030, cutting greenhouse gas emissions to 55% from 1990 levels and reaching climate neutrality by 2050 [2]. These activities are expected to have a remarkable impact on stimulating sustainable development in the UE countries but also reducing energy-import dependency [3]. The EU has identified the energy transition as a critical strategic goal in its efforts to address climate change and enhance energy security [4]. As RES technologies continue to evolve and become more widely adopted, their impact is likely to become even more significant.

Currently, systems with PV panels and heat pumps (HPs) of various types are the most dynamically developing sector in environmentally friendly technologies. In particular, PV energy is gaining interest internationally and in the EU as a provider of low-cost, energy-efficient and clean energy [5]. In 2021, 18.7% of the world's total PV capacity, which corresponds to 158 GW, was installed in EU [6]. Germany leads the way with PV capacity installed of 58.5 GW, second is Italy with 22.7 MW and third is France with 14.7 GW [6]. The expansion of the PV installations market is particularly visible in Poland, which ranked 10th in the world regarding investment made in new PV power capacity installed in 2021 [2]. It is expected that there will be further growth of PV capacity in Poland, reaching approximately 7.3 GW in 2030 and 16 GW in 2040 [7].

Over the past few years, HPs technology has also made great inroads into the EU market by increasing energy efficiency, reducing greenhouse gas emissions and promoting RES. HPs are now particularly seen as devices that can significantly reduce energy consumption in buildings for both heating and cooling purposes. According to the European Heat Pump Association, the HPs market in Europe has been growing steadily over the last decade and in 2021 have exceeded 34%, surpassing two million units sold per year for the first time [8]. This big growth has been driven by several factors, including increasing energy prices, energy efficiency regulations and the push towards decarbonization. ASHPs have the largest share in the HPs market in 2021, which is equal to 94% with the remaining 6% being ground- or water-based [4]. ASHPs are considered less expensive compared to other existing HP-based technologies.

There is a need to develop solutions that will help maximize the use of energy generated from RES and reduce or even limit existing development barriers [9]. Such issues include the problem of insufficient use of generated electricity in PV on-grid microinstallations (<50 kWp) in residential buildings. The coefficient of SC is used to determine the degree of use of the generated energy in a PV installation. It can be calculated as the share of the self-consumed energy E_{SC} in total energy generated E_{gen} in the PV system as shown by the following equation:

$$\mathrm{SC} = \frac{E_{\mathrm{SC}}}{E_{gen}} \quad (1)$$

SC parameter is calculated over an assumed period of time, usually during a given day, month or year. It can be a value between 0% and 100%, where 100% means that all E_{gen} is consumed by the loads and 0% means that the entire stream of generated electricity was transferred to the grid (in on-grid PV system). The greater the SC value, the higher the profits associated with the operation of PV systems [10]. It also brings other positive aspects, which include the reduction of energy losses in the network, increased grid stability due to lower load fluctuations, reduced energy costs for consumers due to self-sufficiency and lower electricity storage capacity, enabling reduction in the capacity of conventional power plants in the long term to promote the integration of renewable energy and reduce the need for power system infrastructure improvements [11]. Additionally, the growth of SC in PV installations is a major issue due to the fast-growing number of such systems and the overloading in the distribution grid [12], which can lead to grid instability and, in extreme cases, problems with electricity availability and inverters operation [13].

In the literature, some ways to grow SC parameter in PV systems have been reported. In the article [2], the authors pointed out that installing a smart monitoring system for tracking energy usage patterns and identifying areas for improvement maximizes SC. Moreover, in shifting energy consumption devices (washing machines, dishwashers, dryers or electric vehicles) to daytime hours when energy from solar radiation is being generated [12] and using energy management tools that adjust and optimize in real-time, energy consumption and usage will have a positive effect on this parameter [14]. Similar conclusions were presented in the paper [15], where a model for adequate matching of PV power for prosumers was proposed, taking into consideration the day-ahead load distribution. On the other hand, in the paper [16], the authors indicated that determining the appropriate size of the PV system and installing a battery storage system which can store excess energy produced during the day for later use, increases SC during non-sunlight hours. An interesting proposal related to hydrogen generation can also be found in the paper [16], in which the authors suggested producing green hydrogen during water electrolysis from solar-generated electricity. Moreover, a good solution is skilfully combining PV systems with RES-based electrical equipment, such as HP, to produce heat and/or cooling [17].

When investigating the feasibility of the above-mentioned solutions, it is important to bear in mind the savings generated by greater self-consumption, resulting in a shorter investment payback time, which is usually the main parameter considered by investors [18]. It should also be noted that current battery technologies suffer from short lifetimes and high initial investment costs correlated with the storage capacity [19]; shifting energy consumption devices to daytime hours in most cases could be difficult or sometimes almost impossible and cause a loss of comfort for users of these devices [18].

A number of articles have analysed ways and results of increasing SC values. In the study [20], the comparison of demand response and battery operations focused on increasing SC and storing surplus PV energy have been presented. In the article [21], the author presented results from grid-connected PV installations without storage systems and special energy management systems where reported SC from around 16% to 50% in a one-year period. The improvement of SC with different approaches (demand-side management, battery storage or a mix) allows obtaining SC from 28% to 78%. In the next article [19], authors proposed and implemented a predictive control model which improved the PV SC by 19.5%. In a subsequent article [18], in PV microinstallation in a household located in Poland, the authors reported SC equal to 27% for the PV system facing south and 30% for the PV system facing east–west. The review paper [10] summarized research in the field of SC in residential PV systems, with two techniques in particular: battery storage and demand side management. In the paper [17], authors analysed a new control strategy for the operation of an ASHP, based on the actual PV availability. The results showed an increase in system SC by 22% in comparison to a standard control strategy, taking into account a highly insulated building in Bolzano, Northern Italy [17]. The paper [22] analysed self-producing and sharing electricity with distributed rooftop PV systems and HP. In conclusion, the authors showed that PV installation could help decrease operating costs for district heating systems with large numbers of HP [22]. In the article [23], authors presented the results of SC under various installed capacity conditions, orientation and inclination of the PV panels in Córdoba, Spain. In another study [24], authors proposed a simulation model for residential PV–battery systems under Spanish regulation. The solutions proposed in the work allowed for achieving SC growth by 25% [24]. In the simulation work [25], authors evaluated terms of performance control strategies for the heating system with ASHP and PV installation and utilization of energy in storage in a single-family house. Results show that using developed algorithms leads to greater final energy savings and a higher SC parameter [25]. A smart charging plan for electric vehicle in residential buildings based on installed PV power output and electricity consumption were presented in [26]. The main conclusion of the research was that minimizing the net load variability implies increasing the PV self-consumption and reducing the peak loads [26]. As pointed out in [27], using a heuristic scheduling optimize system of HP and PV can achieve a high level of SC. The results show that an intelligent control algorithm allows for obtaining SC values from 25.3% to 41.0% during a year [27].

In spite of the growing interest in SC in PV installation in recent years, studies on this topic are still quite scarce and should be further investigated [10]. This paper's aim is to complement previous research and to analyse the results of one year-round operation of a PV array grid-connected hybrid installation with ASHP for a domestic hot water (DHW) system in a residential building in Cracow, Poland, in the context of increasing SC of energy. The term hybrid installation means that RES-consuming devices work together to achieve a reduction in the overall electrical energy drawn from the grid, which contributes to cheaper overall operational costs of the installation [28]. Models of systems with PV panels and other devices are built and simulated in Transient System Simulation Tool (TRNSYS) 18 software. TRNSYS, thanks to the flexibility of the software and the high number of available components presented as black boxes called "types", allows the building of sophisticated systems with RES. Simulations were carried out for different scenarios involving different building electricity consumption profiles, PV system capacity and specified runtime management of ASHP. The novelty of this study is the evaluation of the impact of a certain range of conditions on the energy performance of the system, particularly on SC.

This paper is structured as follows: In Section 2, the simulation model, location and consumption profiles are presented and an overview is provided of the devices and details of the simulation settings used (specification of installation components in TRNSYS and their pre-set main parameters). Section 3 provides and discusses the results for the considered various systems parameters. The paper ends in Section 4 with conclusions and recommendations.

2. Materials and Methods

2.1. Location and Meteorological Data

The case study was of a residential building located in Cracow, South Poland. The city climate is described as a temperate oceanic climate. In the Köppen–Geiger climate classification system, the area is classified into group D (continental/microthermal climates) and sub-group Dfb (warm summer continental or hemiboreal climates without a dry season) [29]. Climatic data is necessary for calculations, including, e.g., dry bulb temperature, beam radiation for surface, sky diffuse radiation for surface, humidity ratio and percent relative humidity, which were obtained for the PL-Cracow-Balice climate station from the Meteonorm Type 2 database. These data were then processed and if necessary interpolated at timesteps of less than one hour and available to other TRNSYS components by the weather data processor Type 15-6 implemented in the TRNSYS program.

In Cracow, the lowest average dry bulb air temperatures (-15 °C) are observed from December to February, and the highest ones (30 °C) are from May to August. During the year, 1041 kWh/m^2 of total horizontal solar radiation is available with the highest daily values of 5.0–7.5 kWh/m^2 between the end of May and the beginning of September, which is consistent with the data presented in the study [30]. From 1 April to 30 September, yearly insolation reaches 76%.

2.2. Electricity Consumption Week Profiles in Analysed Household

In the conducted simulations of the installation's operation, three different week profiles of residential household electricity consumption were assumed. Basic information about them is provided in Table 1 and Figure 1. The shape of the first weekly profile of energy consumption (Profiles A and A') was developed based on self-reported data from the electricity metre of the single-family building where the author of the article lives. Subsequent profiles correspond to an increase in the value of this profile A and A′ by 1/3 for profiles B and B′ and by 2/3 for profiles C and C′.

Table 1. Energy consumption profiles in the analysed household.

Profile	**Electricity Consumption in Building (E_c)**	
	kWh/Year	**kWh/Day**
A (A′ in weekends)	3285	9
B (B′ in weekends)	4380	12
C (C′ in weekends)	5475	15

On Monday through Friday, it was assumed that the highest energy consumption by residents occurs between 6–7 a.m. and 3–8 p.m. The profiles take into account the fact that between 7 a.m. and 3 p.m. residents are out of the household (at work, school). On the other hand, on weekends, i.e., Saturdays and Sundays, the electricity consumption profiles (A′, B′, C′) consider the fact that the highest activity of residents is during the day around 12 p.m.

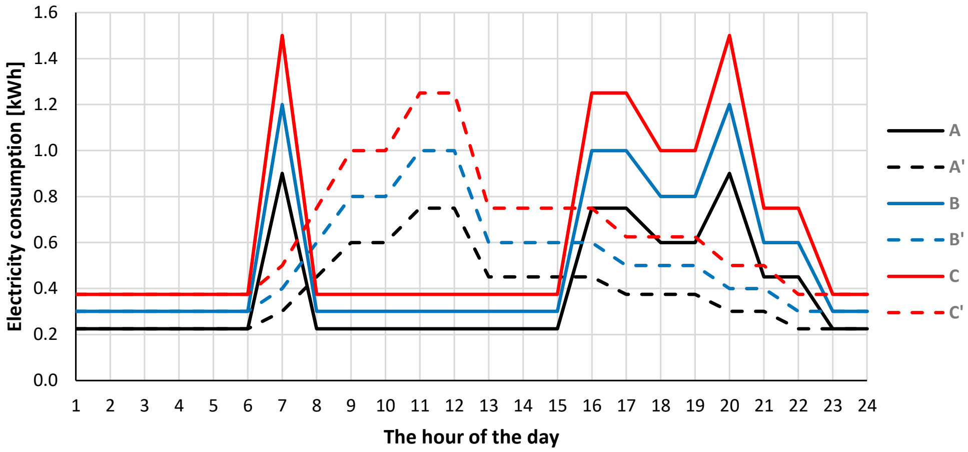

Figure 1. Hourly changes in electrical energy consumption for individual profiles.

It should be mentioned here that the presented profiles do not take into account the energy consumption of the ASHP used in the considered installations. Moreover, PV daily and weekly variation in energy consumption profiles throughout the year and depending on the season has not been taken into consideration. Author of the paper wanted to focus on evaluating only the impact of the change in annual electricity consumption on the percentage change in the value of self-consumption energy with identical weekly energy consumption profiles throughout the year.

2.3. PV Installations

In the considered simulations, an on-grid PV installation consisting of 380 Wp monocrystalline panels was adopted. It was designed to be mounted on a south-facing roof of the building inclined at 35°. The power of the three proposed installations P_{PV} depended on the E_c presented in Section 2.2 and was determined from Equation (2) and developed based on information in [2]:

$$P_{\text{PV}} = \frac{E_c \cdot \beta_o}{SR \cdot \eta_{\text{PV}}} \tag{2}$$

where:

SR—Total horizontal solar radiation during year for Cracow (1041 kWh/m^2/a);
η_{PV}—Efficiency of the PV installation, taking into account losses on wires, on modules due to temperature, inverter losses and others (0.8);
β_o—Oversizing factor (1.1) for a system capacity up to 10 kW.

The results of the calculations of P_{PV} are presented in Table 2. Meanwhile, Table 3 summarizes information on the PV panels used in the simulations.

Table 2. Results of calculations P_{PV}.

PV Installation	P_{PV} (kWp) from Equation (2)	Number of PV Panels	Selected P_{PV} (kWp)
PV1	4.34	12	4.56
PV2	5.78	16	6.08
PV3	7.23	20	7.60

The presented data in Table 3 have been entered into the component Type 103b appropriate for modelling the electrical performance of mono and polycrystalline PV panels in TRNSYS. This model assumes that the PV array is connected to the load via a maximum power point tracker.

Table 3. PV panels main parameters.

Parameter	Value
Panel area [m^2]	1.868
Nominal maximum panel power [Wp]	380
Short-circuit current at reference conditions [A]	11.47
Current at max power point and reference conditions [A]	10.93
Open-circuit voltage at reference conditions [V]	41.62
Voltage at max power point and reference conditions [V]	34.77
Temperature coefficient of I_{sc} [A/K]	0.045
Temperature coefficient of V_{oc} [V/K]	−0.113

2.4. ASHP for Domestic Hot Water (DHW) Preperation

The simulation assumes that the ASHP (Type 917 in TRNSYS) with rated heating capacity 2.0 kW and power 0.49 kW will only supply heat to the vertical DHW tank (Type 156 in TRNSYS) with a capacity of 300 litres. Consciously, the rated heating capacity of the ASHP is not high, because its lower power extends the working time and the possibility of using energy generated from PV. The power of the blower motor when the ASHP is operating was set on 100 W and controller power on 10 W. The flowrate on the air-side of the ASHP was set on 429 m^3/h. The heat generated by ASHP is transferred through one coil mounted in the lower part of the 1.33 m high tank to the DHW.

The main influence on ASHP activity was DHW consumption. Figure 2 shows the DWH consumption profiles set in the Type 14b component for Monday through Friday and for weekends. The total DHW demand was 220 L/day on weekends and 190 L/day on normal weekdays.

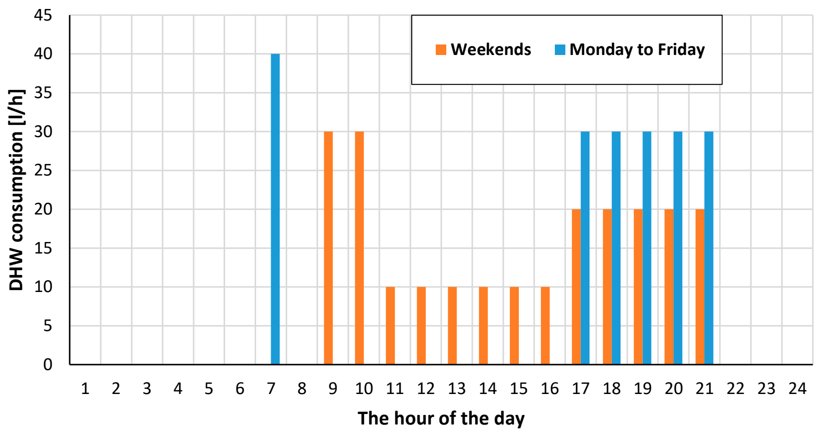

Figure 2. Hourly changes of DHW consumption.

Switching on ASHP is accomplished by the Equa1 component, which processes the control signals coming from the two components of the plant: on/off differential controller Type 165 and time-dependent forcing function Type 14h. Controller Type 165 sends the value of the control signal depending on the difference between the upper (55 °C) and lower (average tank temperature) temperatures compared with two dead band temperature differences. The time-dependent forcing function Type 14h allows ASHP to work only from 4 a.m. to 6 p.m.

2.5. Transient Model of PV and ASHP Hybrid Installation

The transient installation model was created in Simulation Studio in TRNSYS. TRNSYS is a graphical software environment for simulating the behaviour of transient systems, particularly involving RES devices. Thanks to the flexibility of the software and the many available components known as black boxes called “Types”, TRNSYS allows for efficient and accurate modelling of complex systems and conducting parallel analyses. A further strong advantage of TRNSYS is that during a simulation, TRNSYS executes the procedures of each component in a sequential manner, but it also employs advanced algorithms to ensure that the simulation converges to a steady state solution within a reasonable amount of time. This means that the component procedures are called and executed simultaneously, but the simulation as a whole progresses in a sequential manner, following a defined time step [31].

Brief descriptions of the components used in the simulated system are summarized in Table 4.

Table 4. Short description of the components used in the TRNSYS model of the analysed system based on [31,32].

Component	Short Description
Equa	The equations statement; allows variables to be defined as algebraic functions of constants, previously defined variables, and outputs.
Type 165	Differential controller; generates a control function (1 or 0) chosen as a function of the difference between upper and lower temperatures compared with two dead band temperature differences.
Type 14b	The time-dependent forcing function; specifies the value of the water drawn at various times throughout one cycle.
Type 14h	Time-dependent forcing function; allows activation of the device operation in a specific time and repeated pattern.
Type 15-6	Weather data processor; allows for reading data at regular time intervals from an external weather data file and makes it available to other TRNSYS components.
Type 24	Quantity integrator; this component integrates a series of specified quantities over a specified period of time.
Type 41a	Load profile sequencer; allows the user to specify forcing functions for each day of the week, which forms an annual schedule.
Type 65a	Online graphical plotter with output file; displays chosen system variables during the simulation.
Type 114	Single speed pump; models a single (constant) speed pump that is able to maintain a constant fluid outlet mass flow rate.
Type 156	Cylindrical storage tank with immersed coiled-tube heat exchanger; it simulates a water-filled, vertical, cylindrical, constant volume storage tank.
Type 917	Air-to-water heat pump; this component models a single-stage air source heat pump.

A schematic diagram of the used installation model generated in the Simulation Studio of the TRNSYS program is shown in Figure 3. Simulation time step was set to 6 min and tolerance convergence was set to 0.001. A build-in numerical solver called “successive method” was used in the program. The calculations were carried out on a computer equipped with an AMD Ryzen 7 4800H processor, 16 GB RAM memory, graphics card NVIDIA GeForce GTX 1650 and SSD hard drive. The average iterative calculation time was about 10 min.

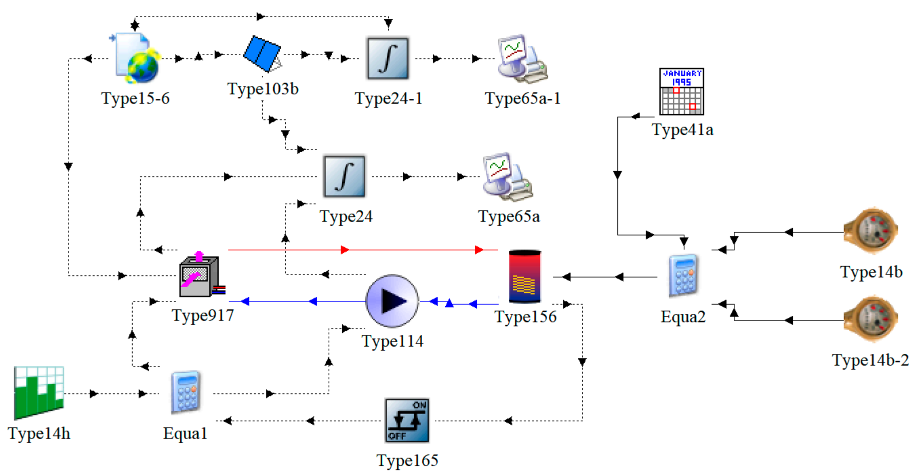

Figure 3. TRNSYS model of the analysed system.

3. Results and Discussion

This section provides an overview and comments on the results obtained from simulation calculations performed in the TRNSYS software for the range of boundary conditions defined in Section 2. For practical reasons and a better presentation of the results obtained, this section is divided into several subsections.

3.1. Energy Efficiency of PV Panels

Figure 4 shows the monthly and annual changes in electricity production for the various PV systems analysed. The largest amounts of energy were produced in the months of May–August, while the smallest amounts were produced in December and January, which is typical of Poland's climatic conditions. The largest monthly amounts of energy reaching up to 130 kWh per 1 kWp of PV panel capacity were generated in the considered PV installations in May and July. In these months, daily energy production reached 4.2 kWh per 1 kWp of PV installation capacity. Annually, the individual systems produced 4634 kWh for PV1, 6178 kWh for PV2 and 7723 kWh for PV3. This provided a value of 1016.3 kWh per 1 kWp of PV installation capacity or 203.7 kWh per square meter of PV panel area. These results are similar to those presented in the paper [2].

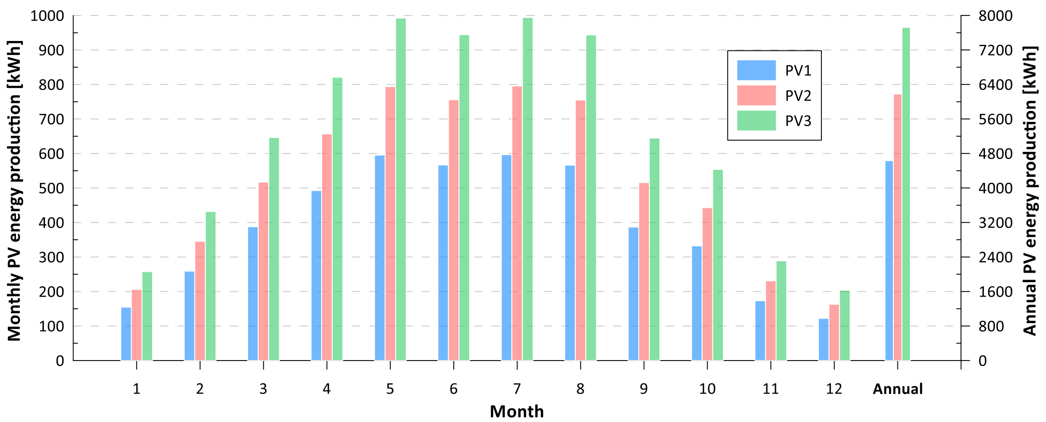

Figure 4. Monthly and annual electricity production in the considered PV installations.

Figure 5 shows the monthly and annual electricity production per unit surface of the PV panels. Additionally, on this graph can be seen the values of monthly and annual insolation (for a 35° slope of the surface and south facing) and PV installation efficiency. The highest values of monthly electricity production of 26 kWh/m^2/month were achieved in summer with insolation reaching 155 kWh/m^2/month. Annually, from 1 m^2 of PV surface in the considered installations, 206.6 kWh of electricity was achieved from the available 1191.3 kWh (annual insolation). Due to the increase in ambient temperature, the efficiency of PV panels in the summer period was almost 2% lower compared to the winter period, where it is was high as 18.45% in January. The annual average energy efficiency of the PV systems considered in the simulations was equal to 17.34%. The values presented above were calculated assuming that the efficiency of the inverter converting DC to AC was equal to 95%.

3.2. SC Parameter in PV Systems

Monthly SC values depending on the PV installation power and energy consumption profile for simulations with and without ASHP in the considered installation are presented as radar charts in Figure 6.

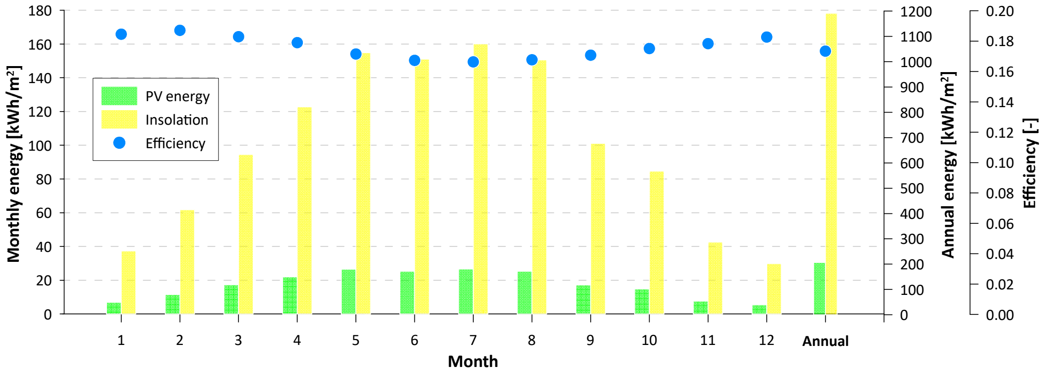

Figure 5. Monthly and annual electricity production per unit surface of a PV panel, insolation and PV installation efficiency.

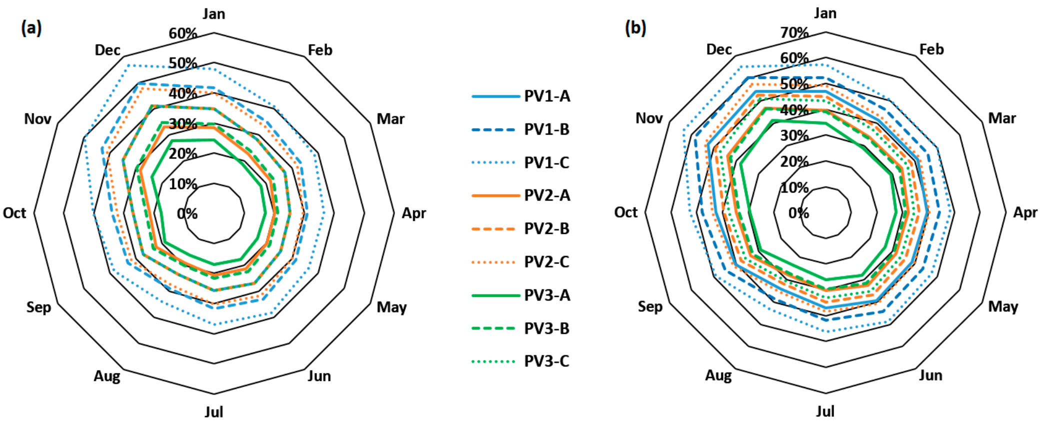

Figure 6. Monthly SC values depending on the PV installation power and energy consumption profile for simulations: (**a**) without ASHP, (**b**) with ASHP in the considered installation.

In analysing the data shown in Figure 6, the following conclusions can be drawn:

- An increase in the power of PV installations results in a decrease in the SC parameter; this is due to the fact that with greater generation of energy from PV installations, it is more difficult to self-consume this energy;
- The higher the energy consumption of the installation (resulting from the change in the energy consumption profile), the higher the SC values can be obtained; between profiles A and C, the differences in SC range from 7.5% to as much as 15.5% for installations without ASHPs and from 7.0% to 11.0% for installations with ASHPs;
- In both installation cases, it can be seen that the highest SC values were obtained during the winter time. This is due to the fact that in this period the generation of energy from PV panels is much smaller and thus there is a greater possibility of self-consumption of this generated energy to a higher degree. In the winter term, compared to the summer period, the differences in SC range from 14.0% to 20.8% for installations without ASHPs and from 17.0% to 21.5% for installations with ASHPs;
- Application of ASHP utilizing energy generated by PV caused an increase in monthly SC values from 7% to 18%.

Figure 7 shows a comparison of annual SC values depending on PV installation capacity and energy consumption profile. The highest SC values of up to 49% were obtained for the PV1 installation and energy consumption profile C in the installation with ASHP, and the lowest of 18.12% were obtained for the PV3 installation and profile A. The presence of ASHP in the installation caused an increase in annual SC values in the considered installations by up to 13%.

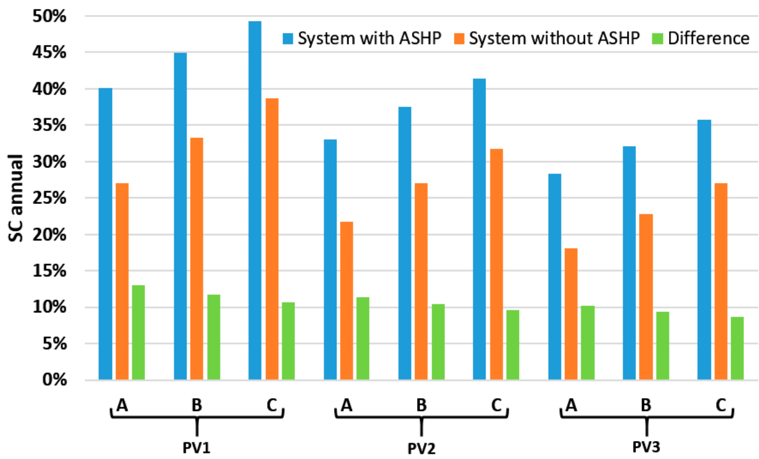

Figure 7. Annual SC values depending on PV installation capacity and energy consumption profile.

3.3. The Relationship between E_{gen} and the Demand for Electricity in Building

A very important point to check is to determine how the amounts of electricity generated by PV (E_{gen}) and overall energy consumed in the building (with and without ASHP) relate to each other. In this study, this relation is defined by the net energy parameter E_{net} and for installations with ASHP ($E_{net,\mathrm{HP}}$) and without ASHP (E_{net}) was calculated from Equations (3) and (4):

$$E_{net,\mathrm{HP}} = \varphi(E_{gen,a} - E_{\mathrm{SC-HP},a}) - (E_{\mathrm{C},a} + E_{\mathrm{HP},a} - E_{\mathrm{SC-HP},a}) \quad (3)$$

$$E_{net} = \varphi(E_{gen,a} - E_{\mathrm{SC},a}) - (E_{\mathrm{C},a} - E_{\mathrm{SC},a}) \quad (4)$$

where:

φ—Grid compensation factor;
$E_{\mathrm{SC},a}$—The annual amount of PV energy self-consumed [kWh];
$E_{\mathrm{SC\text{-}HP},a}$—The annual amount of PV energy self-consumed in installation with ASHP [kWh];
$E_{\mathrm{HP},a}$—The annual amount of electrical energy consumed by ASHP [kWh].

A positive value of parameter E_{net} or $E_{net,\mathrm{HP}}$ means that there is unused PV energy available in the installation. On the other hand, a negative value means that the PV energy production is insufficient for the building's electricity needs.

In Poland, energy policies allow owners of RES systems, including PV systems up to 50 kW, to feed excess electricity generated by their system, and measured by a bidirectional meter back, into the grid. Mechanisms for compensating owners' energy injected into the grid are accomplished using one of two systems (depending on the date of connection of the installation to the grid or the decision of the owner of the PV installation): net metering or net billing. In the net metering system, the grid is treated as a virtual energy storage, and excess electricity can be taken when the photovoltaic installation supplies too little or none at all. However, in this system, when PV installation capacity is up to 10 kW, a grid compensation factor φ of 0.8 is applied as compensation for the possibility of storing energy in the grid. In the net billing system, the owner is credited for the excess electricity at the retail electricity rate. This credit can then be used to offset the owner's future electricity bills.

Table 5 summarizes the results of calculating the relevant parameters needed to determine E_{net} and $E_{net,\mathrm{HP}}$. Between $E_{SC\text{-}\mathrm{HP},a}$ and $E_{\mathrm{SC},a}$, the difference was from about 500 to 790 kWh. This difference determines how much more PV-generated energy was consumed in installations with ASHPs through self-consumption. What is important to emphasize is that the last two columns in Table 5 represent the amounts of PV energy potentially available for use in the considered installations (taking into account self-consumption of

PV energy). Obviously, the highest values of this energy can be obtained for installations with the energy consumption profile A and PV3 installation.

Table 5. Results summary of the relevant parameters necessary to determine E_{net}.

PV System	$E_{gen,a}$ [kWh]	$E_{c,a}$ [kWh]	$E_{HP,a}$ [kWh]	$E_{SC\text{-}HP,a}$ [kWh]	$E_{SC,a}$ [kWh]	$E_{gen,a} - E_{SC\text{-}HP,a}$ [kWh]	$E_{gen,a} - E_{SC,a}$ [kWh]
PV1	4634	3285	2039	1858	1253	2776	3381
		4380		2085	1541	2550	3093
		5475		2286	1793	2348	2841
PV2	6178	3285		2044	1340	4135	4839
		4380		2315	1671	3864	4508
		5475		2558	1964	3621	4215
PV3	7723	3285		2185	1400	5538	6324
		4380		2482	1762	5241	5962
		5475		2757	2089	4966	5635

During the year, the ASHP produced an average of 356 kWh of heat per month and consumed 166 kWh of electricity. This resulted in an average annual coefficient of performance (COP) of 2.14, which is a relatively low value. It should be kept in mind that in the installation under consideration, the HP operates year-round, producing DHW with a high temperature of up to 55 °C and using directly atmospheric air, outside the building, not from inside it. These two facts had a significant impact on the COP values in the simulations carried out.

Very interesting results of the simulation of the operation of the considered installations are shown in Figure 8. Depending on the adopted value of φ, a different balancing of the amount of energy produced by the PV panels was obtained. When $\varphi = 1$ (i.e., for a situation in which in a 1:1 ratio the same amount of energy is obtained from the grid as was previously injected into it from the PV installation) and the installation had an ASHP (the blue colour of the bars in Figure 8), then in the case of PV1 and profile A, PV2 and profile B and PV3 and profile C, the energy fluxes E_{gen} and overall energy consumed in the building relatively balanced each other (i.e., the value of $E_{net,\mathrm{HP}}$ is close to 0). On the other hand, when $\varphi = 0.8$ (i.e., 80% of the PV energy injected into the grid can be taken back from the grid), only in the case of PV2 and profile A there is a balancing of energy fluxes.

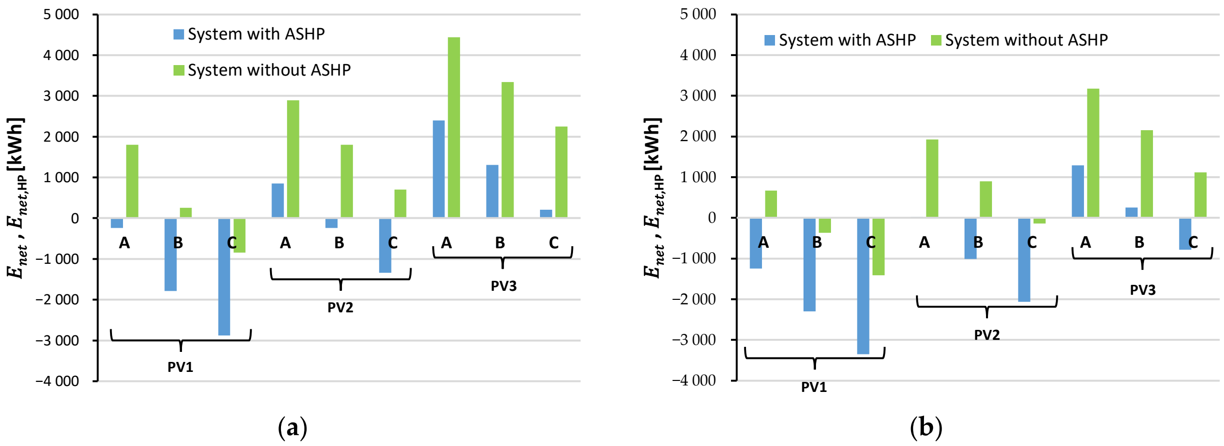

Figure 8. E_{net} and $E_{net,\mathrm{HP}}$ for installations with and without ASHP for: (**a**) $\varphi = 1.0$; (**b**) $\varphi = 0.8$.

However, when considering systems without ASHPs (the green colour of the bars in Figure 8), in most cases there was a large excess of generated energy from PV relative to the amount of energy that could theoretically be consumed in the building (especially for $\varphi = 1$). Relatively balanced energy fluxes were obtained for $\varphi = 1$ for PV1 installation and profile B and for $\varphi = 0.8$ for PV2 installation and profile C. This means that in the case of on-grid PV installations, it is crucial to properly match the PV array capacity to the electricity demand of the facility or otherwise the system will be unbalanced.

As can be seen from the results presented above, in further research it would be interesting to include a realistic load (energy consumption profile) and a better adjustment of the ASHP operation time and heating power with PV production. Future considerations should also be extended to the aspect of ASHP cooperation for the purposes of building heating and DHW preparation and more extensive control systems with storage of electricity produced by PV and heat produced by ASHP. It would also be interesting to study the effect of HP power modulation on SC values.

4. Conclusions

The study mainly focused on analysing the cooperation of a PV array grid-connected hybrid installation with ASHP for DHW production in hybrid installation for a residential building in Poland, i.e., Cracow. Results of a one year-round operation in the context of increasing SC of energy were presented. The impact of different building electricity consumption profiles, PV system capacity and specified runtime management of HP have been evaluated.

Several conclusions can be drawn from this study:

- In Polish conditions, due to the increase in ambient temperature, and thus photovoltaic cells, the efficiency of PV panels in the summer was almost 2% lower compared to the winter period.
- Determining the appropriate size of the used PV system depending on whether it is present ASHP in the installation is crucial to increasing the value of the SC parameter.
- An increase in the power of PV installations (without changing the energy consumption profile) resulted in a decrease in the value of the SC parameter.
- In winter (with lower insolation values) compared to summer, the differences in SC values ranged from 14.0 to 20.8% for installations without ASHP and from 17.0 to 21.5% for installations with ASHP.
- The use of ASHP for DHW production, with specified runtime management using PV-generated energy, resulted in an increase in monthly SC values from 7% to 18%, and annual SC values up to 13%.

To sum up, it is necessary to further develop RES technologies and seek ways to increase the level of SC energy produced by the PV array. These topics are extremely important in terms of the development of PV technology and the search for solutions resulting in the reduction of energy consumption and the development of environmentally friendly technologies.

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Nomenclature

a	annual
AC	alternating current
ASHP	air-source heat pump
β_o	oversizing factor [-]
COP	coefficient of performance
DC	direct current
DHW	domestic hot water
E_c	electricity consumption [kWh]
E_{gen}	energy generated [kWh]

$E_{\mathrm{HP},a}$	the annual amount of electrical energy consumed by ASHP [kWh]
E_{net}	net energy parameter for installations without ASHP [kWh]
$E_{net,\mathrm{HP}}$	net energy parameter for installations with ASHP [kWh]
EU	European Union
E_{SC}	self-consumed energy [kWh]
$E_{\mathrm{SC},a}$	the annual amount of PV energy self-consumed [kWh]
$E_{\mathrm{SC\text{-}HP},a}$	the annual amount of PV energy self-consumed in installation with ASHP [kWh]
HP	heat pump
η_{PV}	efficiency of the PV installation [-]
P_{PV}	PV installation power [kWp]
PV	photovoltaic
RES	renewable energy sources
SC	self-consumption
SR	total horizontal solar radiation during year [kWh/m^2/a]
TRNSYS	Transient System Simulation
φ	grid compensation factor [-]

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