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Increasing Energy Self-Consumption in Residential Photovoltaic Systems

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Abstract: Nowadays Air-Source Heat Pumps (ASHP) in combination with a Photovoltaic (PV) installation are a very promising option for a necessary and urgent energy transformation in European Union (EU). It is extremely important to develop solutions that will help maximize the use of energy generated from renewable energy sources (RES). 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 analyze the results of one-year-round operation of a PV array grid-connected hybrid installation with ASHP for domestic hot water (DHW) preparation in a residential building in Cracow, Poland in the context of increasing self-consumption (SC) of PV energy. Models of systems are built and simulated in Transient System Simulation Tool 18 (TRNSYS) software. 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, in particular on SC. The results showed that the use of ASHP, with specified runtime management, results in an increase in monthly SC values from 7 to 18%, and annual SC values up to 13%. Also determining the appropriate size of the used PV system depending on whether it is present ASHP in the installation is crucial to increase the value of the SC parameter. Overall, this study provides valuable insights into the potential benefits of PV panels and ASHP operating together, in particular on SC 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 EU countries, in particular, the armed conflict between Ukraine and Russia, interest in RES technologies has increased significantly. The importance of the development of RES installations in the EU is confirmed 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 use of RES in the overall energy mix to at least 40% by 2030, reducing greenhouse gas emissions to 55% when compared to levels in 1990, 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 reduce energy-import dependency [3]. Energy transformation in EU is one of the most important strategic goals of counteracting climate change, as well as increasing energy security [4]. As RES technologies continue to evolve and become more widely adopted, their impact is likely to become even more significant.

Nowadays systems with PV panels and heat pumps (HPs) of various types are the most dynamically developing sector in RES technologies. Especially PV energy is getting more interest worldwide and in UE as a source of cheap, environmentally friendly and clean energy [1,5]. In 2021, 18.7% of the total capacity in PV globally, which corresponds to 158 GW, was installed in EU [6]. Germany is the leader, with a PV installed capacity of 58.5 GW, second is Italy with 22.7 MW and third France with 14.7 GW [6]. The development of the PV installations market is particularly visible in Poland, which was ranked 10th in the world in terms of investment in new PV generation capacity implemented in 2021 [2]. It is expected that there will be further growth of PV capacity in Poland, achieving about 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 2 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 equal 94% and only 6% use ground or water [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:

SC

$$SC = \frac{E_{SC}}{E_{gen}} \tag{1}$$

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% meaning that all E_{gen} is consumed by the loads. 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, enhancing the grid stability with less fluctuating loads, reducing consumers' energy costs through self-sufficiency and lower electricity storage capacity, enabling the downsizing of traditional power plants in the longer term to facilitate renewable energy integration, and a smaller needs to modernize the infrastructure of the electrical power system [11,12]. In addition, the growth of SC in PV installations is a very important issue due to the rapidly increasing number of such systems and the overloading of the distribution network, 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 can be found:

- determining the appropriate size of the PV system,
- installing a battery storage system which can store excess energy produced during the day for later use, increasing SC during non-sunlight hours,
- shifting energy consumption devices (washing machines, dishwashers, dryers or electric vehicles) to daytime hours when energy from solar radiation is being generated,
- installing a smart monitoring system for tracking energy usage patterns and identifying areas for improvement to maximize SC,
- using energy management tools that adjust and optimize in real-time energy consumption and usage,
- skillfully combining PV systems with RES-based electrical equipment, like HP, to produce heat and/or cooling,
- producing green hydrogen during water electrolysis from solar-generated electricity [2,11,14–17].

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 correlated with storage capacity; shifting energy consumption devices to daytime hours in most cases could be difficult or sometimes almost impossible and induce a loss of comfort [11,18].

A number of articles have provided analyses of ways and results of increasing SC values. In the study [19] the comparison of demand response and battery operations focused on increasing SC and storing surplus PV energy have been presented. Hassan in the article [14] presented results from grid-connected PV installations without storage system and special energy management systems where obtain SC from around 16% to 50% in a one-year period. The improvement of SC with different approaches (demand-side management, battery storage or mix) allows getting SC from 28% to 78%. In the article [11] authors proposed and implemented a predictive control model which improved by 19.5% the PV SC. Cieślak in the work [18] for PV microinstallation in a household located in Poland get SC equal to 27% for the PV system facing S and 30% for the PV system facing E-W. The review paper [10] has summarized research in the field of SC in residential PV systems in particular two techniques: battery storage and demand side management. In the paper [20] Pinamonti et al. analyzed a new control strategy for the operation of an ASHP, based on the actual PV availability. The results show an increase of system SC by 22% in comparison to a standard control strategy, considering a high-insulated building in Bolzano, Northern Italy [20]. Vivian et al. analysed self-producing and sharing electricity with distributed rooftop PV systems and HP [21]. In conclusion, authors showed that PV installation could help reduce operational costs for district heating systems with a high number of HP [21]. Varo-Martínez et al. in the article [22] presented the results of SC under different conditions of installed power, orientation and inclination of the PV panels in Córdoba, Spain. In the paper [23] Domenech et al. 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% [23]. In the simulation study [24] 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 higher SC parameter [24]. Fachrizal et al. presented a smart charging plan for electric vehicle in residential buildings based on installed PV power output and electricity consumption [25]. The main conclusion of the research is that minimizing the net load variability implies increasing the PV self-consumption and reducing the peak loads [25]. Kemmler and Thomas using a heuristic scheduling optimize system of HP and PV in order to achieve a high level of SC [26]. The results show that intelligent control algorithm allows to obtain SC values from 25.3% to 41.0% during a year [26].

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 analyze the results of one year-round operation of a PV array grid-connected hybrid installation with ASHP 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 [27]. Models of systems with PV panels and other devices are built and simulated in TRNSYS 18 software. TRNSYS due to software flexibility and the large number of available components represented as black boxes called 'Types' enable the creation of complex systems with RES devices. 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, in particular on SC.

This paper is structured as follows: in Section 2 the simulation model is presented, overview of the devices and details of the simulation settings used. Section 3 gives information about the results for the considered various systems parameters; in this chapter they are also discussed. 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 is classified into a group D (continental/microthermal climates) and sub-group Dfb (warm summer continental or hemiboreal climates without a dry season) [28]. Climatic data necessary for calculations, including e.g. dry bulb temperature, beam radiation for surface, sky diffuse radiation for surface, humidity ratio, percent relative humidity were obtained from Meteonorm Type 2

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database for the PL-Cracow-Balice climate station. These data were then processed and if necessary interpolated at timesteps of less than one hour and available to other TRNSYS components by 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 year 1 041 kWh/m² of total horizontal solar radiation is available with the highest daily values of 5.0–7.5 kWh/m² between the end of May and the beginning of September. From 1 April to 30 September, 76% of yearly insolation reaches.

2.2. Energy consumption profiles in analysed household

In the conducted simulations of the installation's operation, three different profiles of residential household energy consumption were assumed. Basic information about them is provided in Table 1 and Figure 1. 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. Between 7 a.m. and 3 p.m., it was assumed that 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') take into account the highest activity of residents during the day, around 12 p.m. 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.

Table 1. Energy consumption profiles in analysed household.

Profile	Electricity consumption in building (E_c)	
	kWh/year	kWh/day
A (A′ in weekends)	3 285	9
B (B′ in weekends)	4 380	12
C (C′ in weekends)	5 475	15

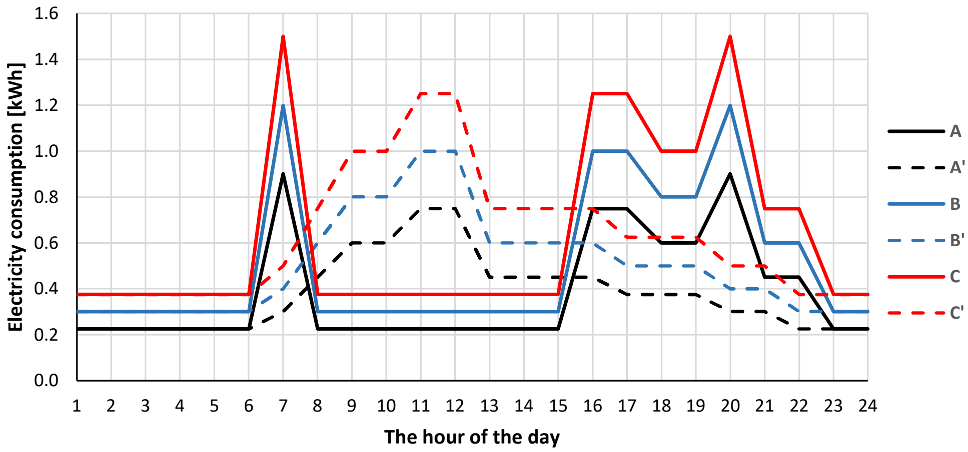

Figure 1. Hourly changes in electrical energy consumption for individual profiles.

2.3. PV installations

In the considered simulations, an on-grid PV installations 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 developed based on information in [2]:
where:

$$P_{PV} = \frac{E_c \cdot \beta_o}{N \cdot \eta_{PV}} \quad (2)$$

N - total horizontal solar radiation during year for Cracow (1041 kWh/m²/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 Eq. 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

Table 3. PV panels main parameters.

Parameter	Value
Panel area [m²]	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

The presented data in Table 3 has been entered into the component Type 103b appropriate for modeling the electrical performance of mono and polycrystalline PV panels in TRNSYS. In this model the PV array is assumed to be connected to its load through a maximum power point tracker.

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 liters. 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 m³/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.

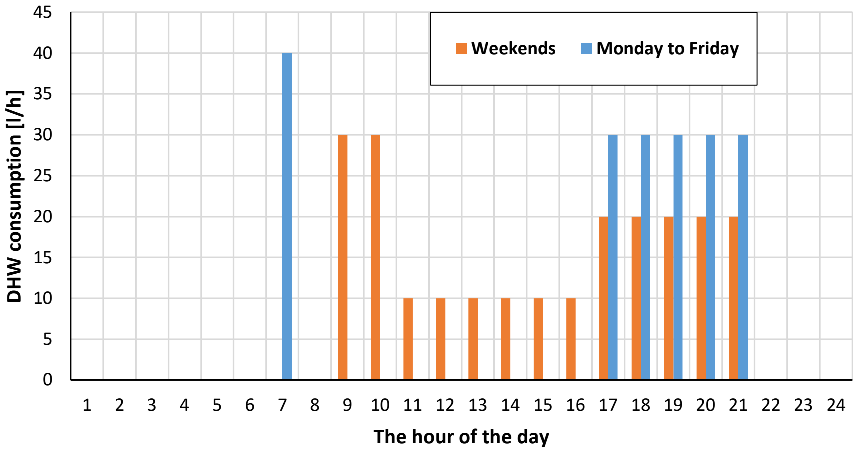

Figure 2. Hourly changes of DHW consumption.

Switching on ASHP is done 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 sending value of the control signal depending on the difference between upper (55°C) and lower (average tank temperature) temperatures compared with two dead band temperature differences. While 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

A schematic diagram of the used installation model generated in the Simulation Studio of the TRNSYS program is shown in Figure 3. Brief descriptions of the components used in the simulated system are summarized in Table 4. Simulation time step was set to 6 min and tolerance convergence 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 of RAM, NVIDIA GeForce GTX 1650 graphics card, SSD hard drive. The average iterative calculation time was about 10 minutes.

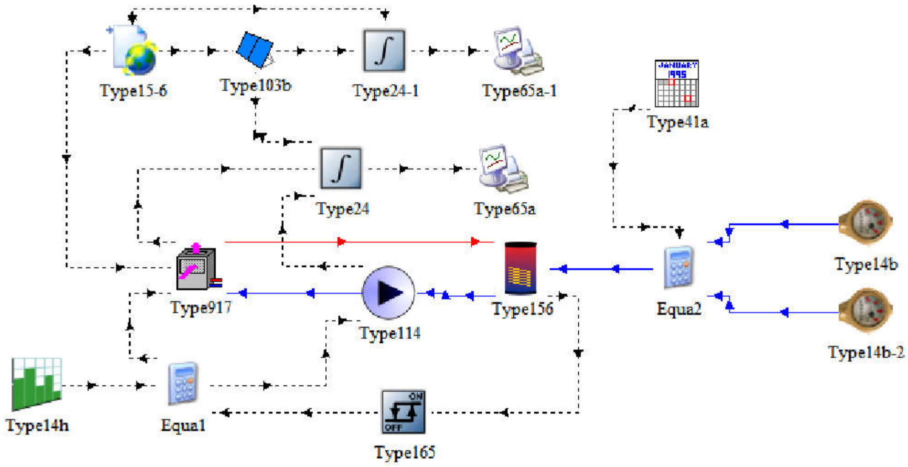

Figure 3. TRNSYS model of analyzed system.

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Table 4. Short description of the components used in TRNSYS model of analyzed system based on [29,30].

Component	Short Description
Equa1, Equa2	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 to force device operation in a specific time and repeated pattern.
Type 15-6	Weather data processor; allows reading data at regular time intervals from an external weather data file and making 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 that 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.

3. Results and Discussion

This section provides an overview and comments on the results 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 analyzed. The largest amounts of energy are produced in the months of May-August, while the smallest amounts are produced in December and January. Annually, the individual systems produce 4 634 kWh for PV1, 6 178 kWh for PV2 and 7 723 kWh for PV3. This gave a value of 1 016.3 kWh per 1 kWp of PV installation capacity, a result similar to those presented in the paper [2].

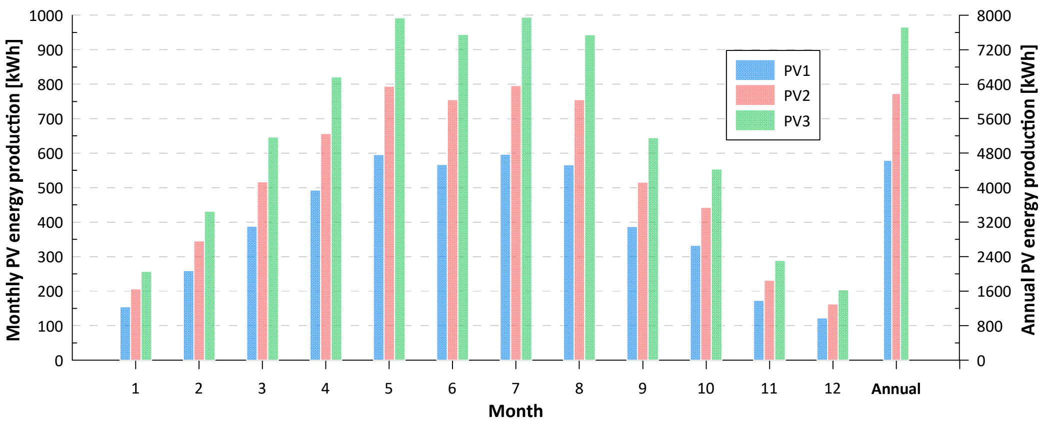

Figure 4. Monthly and annual electricity production in the considered PV installations.

Figure 5 shows the monthly and annual electricity production per unit surface of a PV panels. Also on this graph can be seen the values of monthly and annual insolation (for 35° slope of the surface and south facing) and PV installation efficiency. The highest values of monthly electricity production of 26 kWh/m²/month are achieved in summer with insolation reaching 155 kWh/m²/month. Annually, from 1 m² of PV surface in the considered installations, 206.6 kWh of electricity can be 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 is almost 2% lower compared to the winter period, where it is as 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 95%.

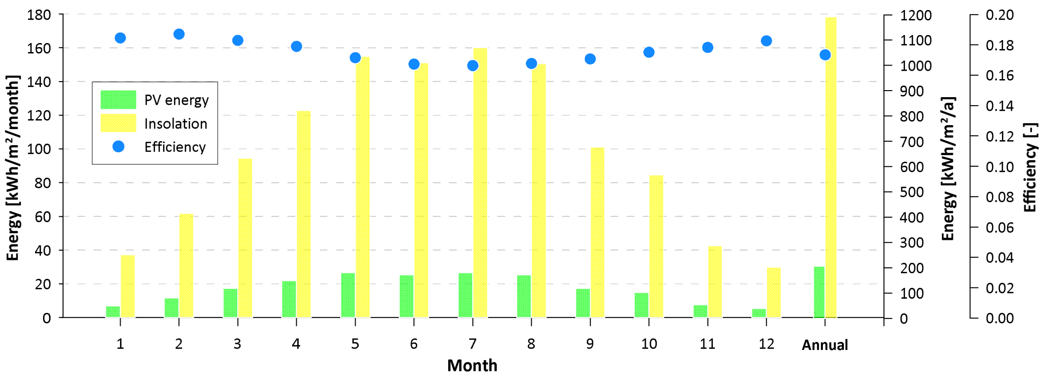

Figure 5. Monthly and annual electricity production per unit surface of a PV panel, insolation and PV installation efficiency.

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. Analyzing the data shown in this figure, the following conclusions can be drawn:

- an increase in the power of PV installations results in a decrease of 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 are 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 causes an increase in monthly SC values from 7 to 18%.

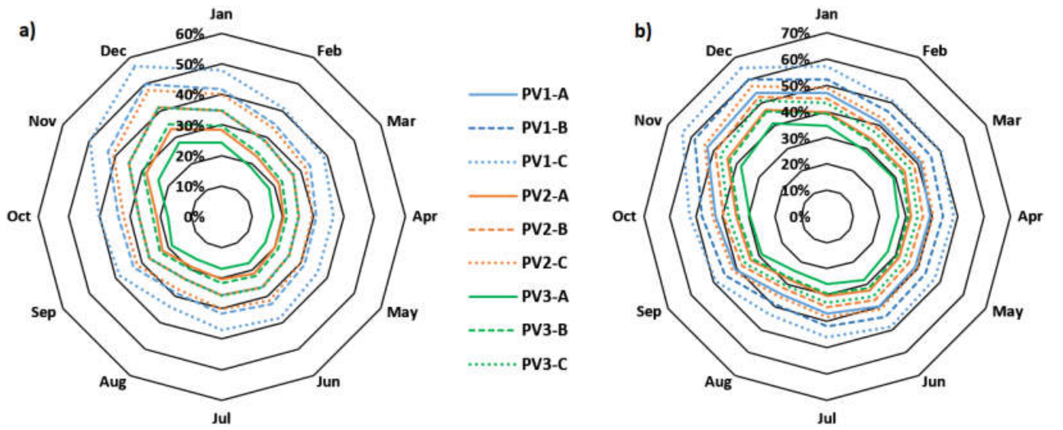

Figure 6. Monthly SC values depending on the PV installation power and energy consumption profile for simulations: a) without ASHP, b) with ASHP in the considered installation.

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% for the PV3 installation and profile A. The presence of ASHP in the installation causes an increase in annual SC values in the considered installations by up to 13%.

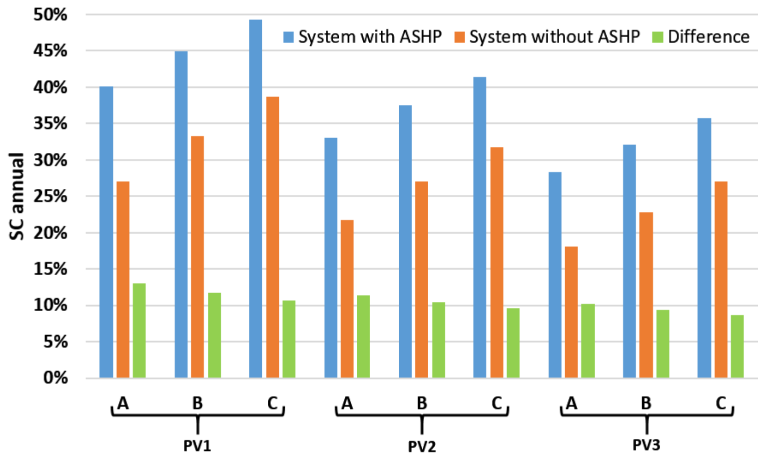

Figure 7. Annual SC values depending on PV installation capacity and energy consumption profile.

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 work, this relation is defined by the net energy parameter E_{net} and for installations with ASHP ($E_{net,HP}$) and without ASHP (E_{net}) was calculated from formulas 3 and 4:
where:

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

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

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φ – grid compensation factor;
$E_{SC,a}$ – the annual amount of PV energy self-consumed [kWh];
$E_{SC\text{-}HP,a}$ – the annual amount of PV energy self-consumed in installation with ASHP [kWh];
$E_{HP,a}$ – the annual amount of electrical energy consumed by ASHP [kWh];
A positive value of parameter E_{net} or $E_{net,HP}$ 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 done in 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. But in this option, when PV installation capacity is up to 10 kW, grid compensation factor φ of 0.8 is applied as compensation for the possibility of storing energy in the grid. In the net billing 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 $E_{net,HP}$. Between $E_{SC\text{-}HP,a}$, and $E_{SC,a}$ 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 energy consumption profile A and PV3 installation.

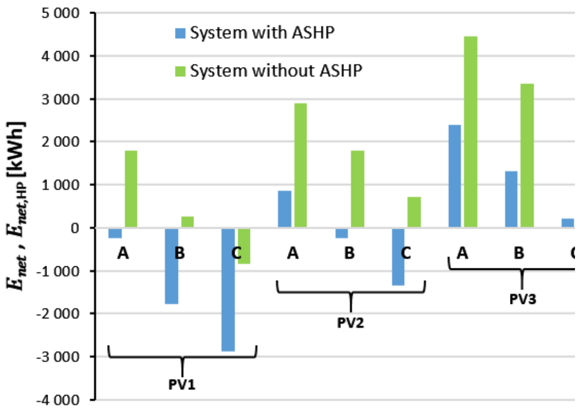
Table 5. Results summary of the relevant parameters necessary to determine E_{net}.

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

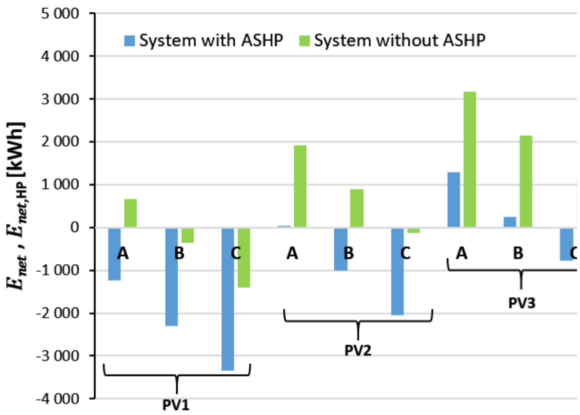
During the year, the ASHP produced an average of 356 kWh of heat per month and consumed 166 kWh of electricity. This resulted in an average annual Coefficent Of Performance (COP) of 2.14, which is a relatively low value. It should be kept in mind that in the installation under consideration, the HP operates 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 7. Depending on the adopted value of φ, different balancing of the amount of energy produced by 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 has an ASHP (the blue color of the bars in Fig. 7), 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 balance each other (the value of $E_{net,HP}$ is close to 0). On the other hand, when φ = 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.

However, when considering systems without ASHPs (the green color of the bars in Fig. 7), in most cases there is a large excess of generated energy from PV relative to the amount of energy that could theoretically be consumed in the building (especially for φ = 1). Relatively balanced energy fluxes are obtained for φ = 1 for PV1 installation and profile B, and for φ = 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, otherwise the system will be unbalanced.



(**a**)



(**b**)

Figure 7. E_{net} and $E_{net,HP}$ for installations with and without ASHP for: (**a**) $\varphi = 1{,}0$; (**b**) φ = 0,8.

4. Conclusions

The article mainly focuses on analyzing the cooperation in a residential building of PV panels and ASHP, devices that have a very strong impact in the EU market on reducing fossil fuel consumption, greenhouse gas emissions and promoting RES. This influence can be seen especially in Poland. For this reason, one of the cities in the south of this country, i.e. Cracow, was chosen as the location for the conducted analyses. In this paper, results of one year-round operation of a PV array grid-connected hybrid installation with ASHP for DHW production in the context of increasing SC of energy were presented. Models of systems and the controls were built and simulated for a wide range of boundary conditions in TRNSYS software. 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 is 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 increase the value of the SC parameter.
- An increase in the power of PV installations (without changing the energy consumption profile) results in a decrease in the value of the SC parameter.
- In winter (with lower insolation values) compared to summer, the differences in SC values range 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, results 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. In further research, it would also 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

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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.

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Nomenclature

Nomenclature	Description
a	annual
AC	Alternating Current
ASHP	Air-Source Heat Pump
β_o	oversizing factor [-]
COP	Coefficent Of Performance
DC	Direct Current
DHW	Domestic Hot Water
E_c	electricity consumption [kWh]
E_{gen}	energy generated [kWh]
$E_{HP,a}$	the annual amount of electrical energy consumed by ASHP [kWh]
E_{net}	net energy parameter for installations without ASHP [kWh]
$E_{net,HP}$	net energy parameter for installations with ASHP [kWh]
EU	European Union
E_{SC}	self-consumed energy [kWh]
$E_{SC,a}$	the annual amount of PV energy self-consumed [kWh]
$E_{SC\text{-}HP,a}$	the annual amount of PV energy self-consumed in installation with ASHP [kWh]
HP	Heat Pump
N	total horizontal solar radiation during year [kWh/m^2/a]
η_{PV}	efficiency of the PV installation [-]
P_{PV}	PV installation power [kWp]
PV	Photovoltaic
RES	Renewable Energy Sources
SC	Self-Consumption
TRNSYS	Transient System Simulation
φ	grid compensation factor [-]

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