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Increase of energy self-consumption in hybrid RES installations with PV panels and air-source heat pumps

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Abstract
In recent years, European countries have experienced a noteworthy surge in the interest surrounding renewable energy sources, particularly the integration of photovoltaic (PV) panels with various types of heat pumps. This study aims to evaluate the energy performance of a grid-connected hybrid installation, combining a PV array with an air-source heat pump (AHP), for domestic hot water preparation in a residential building located in Cracow, Poland. The primary focus of this evaluation is to assess the extent to which self-consumption (SC) of energy can be increased. The study utilizes Transient System Simulation Tool 18 software to construct and simulate various system models under different scenarios. These scenarios include building electricity consumption profiles, PV power systems, and the specified management of AHP. Analyses were conducted over a period of 1 year to assess the operational performance of the systems. In the considered installations, the differences in SC values between PV installation ranged from 9 to 25%. Notably, the highest SC values were observed during the winter months. AHP with operation control allows to obtain in some months of the year up to 35% higher value of the SC parameter compared to systems without AHP. The highest annual SC value recorded reached 83.9%. These findings highlight the crucial role of selecting an appropriate PV system size to maximize the SC parameter.

Keywords
PV systems, heat pumps, renewable energy sources, on-grid systems, transient simulations

1. INTRODUCTION

Recent political and economic events that have affected European countries, forced the European Union to take action and amend legislation to achieve very ambitious goals having remarkable impact on promoting sustainable development and reducing energy import dependency (Kurz and Nowak, 2023; Zastempowski, 2023). The transition to sustainable energy sources and reducing dependence on non-renewable energy is a critical strategic objective to tackle the issue of climate change and improve energy security (Gul et al., 2023). The building sector, accounting for approximately 40% of primary energy, is a significant focal point in the pursuit of decarbonization and the exploration of energy consumption reduction methods (Saffari et al., 2023).

The sector of renewable energy sources (RES) that is currently experiencing the most rapid growth involves the integration of PV panels with various types of heat pumps. In light of this trend, it is crucial to develop solutions that enable the optimal utilization of energy generated from RES while simultaneously address and minimize the existing barriers hindering their widespread adoption and development (Hassan, 2022). The convergence of declining PV power costs, the reduction of feed-in-tariffs, and the rise in retail electricity prices for residential customers drives a shift towards self-consumption of PV energy (Yu, 2021). Nowadays, there is a growing interest among owners of grid-connected PV array systems to increase the level of self-consumption (SC) coefficient of electricity produced (Gulkowski, 2022). SC coefficient is a metric used to quantify the extent to which energy generated in a PV installation is self-consumed. It can be calculated as the ratio of the self-consumed energy to the total energy generated by the PV system (Pater, 2023). The SC is typically calculated over a defined time period such as a day, month, or year. A maximum value of 100% indicates that all generated energy is consumed by the loads (Ciocia et al., 2021). Studies have shown that in the absence of a storage system or energy management system, a PV system in a grid-connected installation can achieve an SC between approximately 15% and 40% over the course of a year (Hassan, 2022).

Improving SC has the potential to boost profits associated with the operation of PV systems (Luthander et al., 2015). Furthermore, given the rapidly increasing number of PV installations, the issue of increasing SC value is of critical importance due to the potential for overloading the distribution network (Vivian et al., 2022). Overloading can cause grid instability and in extreme cases, lead to issues with electricity availability and inverter operation faults (Karimi et al., 2016). The uncontrolled and extensive integration of PV systems can have a more pronounced impact on the energy system (Yu, 2021).

A higher SC value in PV systems leads to several benefits, such as increased profits from the operation of the system, reduced energy losses in the network, and improved grid stability with fewer fluctuations in loads (Zhan et al., 2023). It also allows consumers to become more self-sufficient and lowers their energy costs because they rely less on grid electricity, which needs to be paid for (Ciocia et al., 2021). In the longer term, the integration of renewable energy enables to downsize traditional power plants, thereby facilitating a transition towards cleaner energy sources. This transition also results in a reduced need for extensive modernization of the electrical power system infrastructure.

Self-consumption in PV systems can be enhanced through various measures implemented in system design and operation. One common solution involves the addition of an energy storage system, such as a battery. By storing excess solar energy generated during the day, the stored energy can be utilized at night or during periods of low sunlight, leading to a significant increase in self-consumption (Hassan et al., 2023) and also reducing the amount of energy that must be drawn directly onto the grid. Another approach is to shift the operation of energy-consuming appliances (washing machines, ovens, dishwashers, dryers, power tools, or electric vehicles) to daylight hours, during which energy is generated from solar radiation (Schram et al., 2018). For practical reasons, it is quite a difficult solution to implement in practice. Nevertheless, the incorporation of PV systems and electric vehicles within the built environment has experienced substantial growth over the past decade, giving rise to fresh technical hurdles (Fachrizal et al., 2022).

A further approach are energy management tools that adjust and optimize energy consumption and utilization in real time, as well as the proficient combination of PV systems with RES-based electrical equipment, such as heat pumps, to produce heat and/or for cooling purposes (Zheng et al., 2022). Especially in conjunction with PV systems, heat pumps, which continue to gain market share in the heating equipment industry, can significantly enhance the overall energy efficiency of systems (Alhuyi Nazari et al., 2023). The reason for this is quite straightforward: heat pumps rely on electrical energy to power certain components, such as compressors, and this required electrical energy can be supplied by PV systems. Even greater opportunities arise when the heat pump is used additionally for cooling purposes during the summer (Alhuyi Nazari et al., 2023).

The paper (Matute et al., 2022) presented another research, which considered an optimal dispatch model for scheduling the operation of PV-electrolysis plants in a self-consumption regime to operate hydrogen production facilities considering project pro?tability and sustainability. On the other hand, the paper (Zaik and Werle, 2023) presents various scenarios for sustainable renewable hydrogen production in Polish conditions using solar cells.

The problem that this study addresses is associated with a large increase in the number of low-power PV installations and air heat pumps (AHP) installed in residential buildings in European Union countries, including Poland (Gulkowski, 2022). To the best of the author's knowledge very few research studies assessed the impact of a wide range of conditions on the energy performance of a hybrid system including PV panels and a heat pump, especially in terms of increasing SC coefficient. In order to fill this research gap this paper deals with the analysis of the operation of a hybrid system consisting of PV panels operating in on-grid mode together with an AHP for domestic hot water (DHW) preparation in a residential building in Cracow, Poland. It was assumed that the single-family building under consideration was occupied by 4 people (2 adults and 2 children). A key guideline from the simulations presented in this article is to look at the issue of SC in hybrid systems with PV and AHP globally and to seek a compromise between the value of SC, the power of the PV installation, and the amount of electricity returned to the transmission grid. The results presented will provide very valuable guidance for those who own on-grid, low-power PV installations and account for electricity production according to the principles of the net-metering system as it is in Poland.

The term "hybrid system" refers to a configuration in which RES devices work in conjunction with other energy-consuming devices, aiming to reduce the overall electrical energy consumption from the grid (Pater, 2019; Saffari et al., 2023). This integration results in decreased operational costs of the installation, making it more economically viable. By combining different RES technologies or using them in tandem with conventional energy systems, hybrid installations can leverage the benefits of each technology to optimize energy efficiency and reduce reliance on non-renewable energy sources.

The simulation work was conducted in Transient System Simulation Tool 18 software (TRNSYS), focusing on three key aspects: the impact of PV installation size, electricity consumption profile, and specified management of AHP. Analyses were performed over a one-year period of system operation. The novelty of this study lies in evaluating the influence of a wide range of conditions on the system's energy performance, particularly with respect to SC, which has not been extensively explored in the existing literature so far. The main goal of this paper is to analyse the significance of different system parameters on the SC value in low-power RES installations with PV panels.

2. MATERIALS AND METHODS

2.1. Location, climatic data and electricity consumption in considered building

Cracow, which is located in the south of Poland, in Małopolskie Voivodeship, was chosen as the localisation of the considered residential building with the installation. Cracow is situated at a latitude of about 50 degrees North and has an

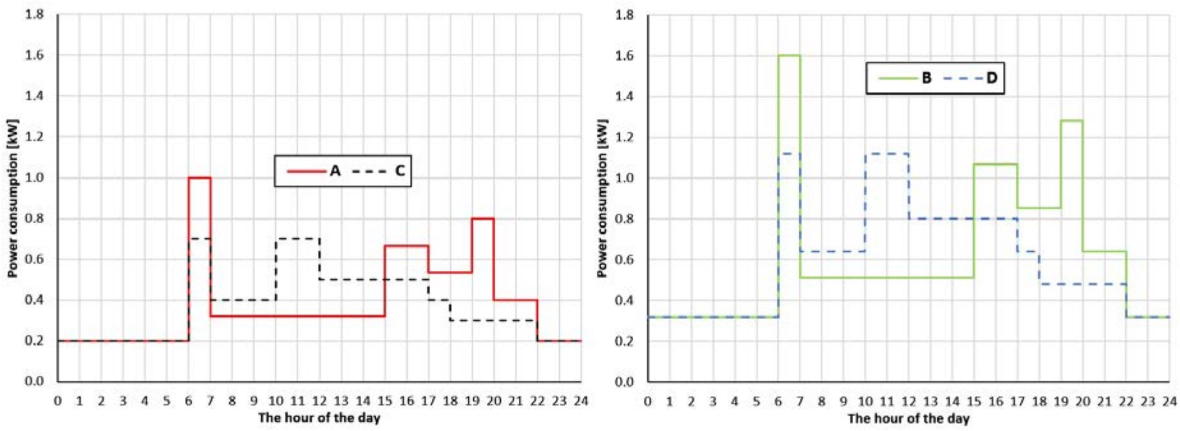


Figure 1. Hourly changes of power consumption for all examined profiles.

elevation of around 220 meters above sea level. It has a moderate continental climate with winters usually quite harsh and summers warm and humid with temperatures frequently exceeding 25 °C (Piotrowicz, 2006). The annual insolation for horizontal surface, which refers to the amount of solar radiation received during the year is estimated to be around 1040 kWh/m^2 meter per year (Pater, 2021). Climatic data for Cracow (including beam radiation for surface, dry bulb temperature, various types of radiation for surface, air humidity) that were necessary for simulation calculations in TRNSYS program were obtained from the Meteonorm database using weather data processor type 15-6.

Meanwhile, Table 1 summarizes the basic information about the 4 electricity consumption profiles used in the simulations for the considered building. The basic differences between the profiles can additionally be seen in Fig. 1 showing daily changes in power consumption.

Table 1. Electricity consumption profiles in considered building.

Profile name	Daily electricity consumption	Annual electricity consumption	Electricity consumption from 8 am to 4 pm	
	[kWh/day]	[kWh/year]	[kWh/day]	[%]
A	9.0	3 285	3.20	36
B	14.4	5 256	5.12	36
C	9.0	3 285	4.60	51
D	14.4	5 256	7.36	51

In each examined energy consumption profile (Fig. 1), daily energy consumption pattern remains consistent throughout the year. Profiles do not take into account variations in energy usage on weekends, or other days (e.g., vacations). Profiles A and C as well as B and D are designed to consume the same amount of energy per day and per year. However, their dissimilarity lies in the different distribution of power consumption, which is influenced by the presence of householders in the building. In profiles A and B, the highest power consumption in buildings occurs between 6–7 am and 3–8 pm, while in profiles C and D, increased power consumption occurs between 6 am and 6 pm. Comparing all profiles with each other, it can be seen that from 8 am to 4 pm 15% more energy is consumed for profiles C and D in contrast to A and B. Furthermore, daily electricity consumption for profiles B and D is 60% higher compared to profiles A and C.

2.2. TRNSYS simulation model

The evaluation of the energy performance of a PV grid-connected hybrid installation with AHP for domestic hot water preparation in a residential building, under various scenarios, was conducted using TRNSYS Tool 18 software. Figure 2 presents a layout showing the connections between the various installation components built in TRNSYS Simulation Studio. In this layout, under the graphic symbols, the type number of TRNSYS components are given. Table 2 summarizes the names and brief descriptions of the components used. On the other hand, more detailed descriptions of TRNSYS program components (parameters, inputs, outputs) can be found in the paper (TRNSYS, 2017). The dashed or continuous lines between components shown in Fig. 2 in the program are referred to as "Link" and denote the connection of the variable outputs of one component to the variable inputs of another component.

The main devices in the installation (Fig. 2) are PV panels, specifically type 103b, which models the electrical performance of mono- and polycrystalline PV panels, and type 917, which models a single-stage AHP. The electricity generated by PV panels, depending on the weather conditions taken from the type 15-6 component (weather data processor), is fed back to the grid by an inverter operating at 95% efficiency (the inverter is not visible in the installation diagram). Whether AHP is enabled or disabled depends on the control signals received from type 14h and 2b components processed in advance by Equa1 component.

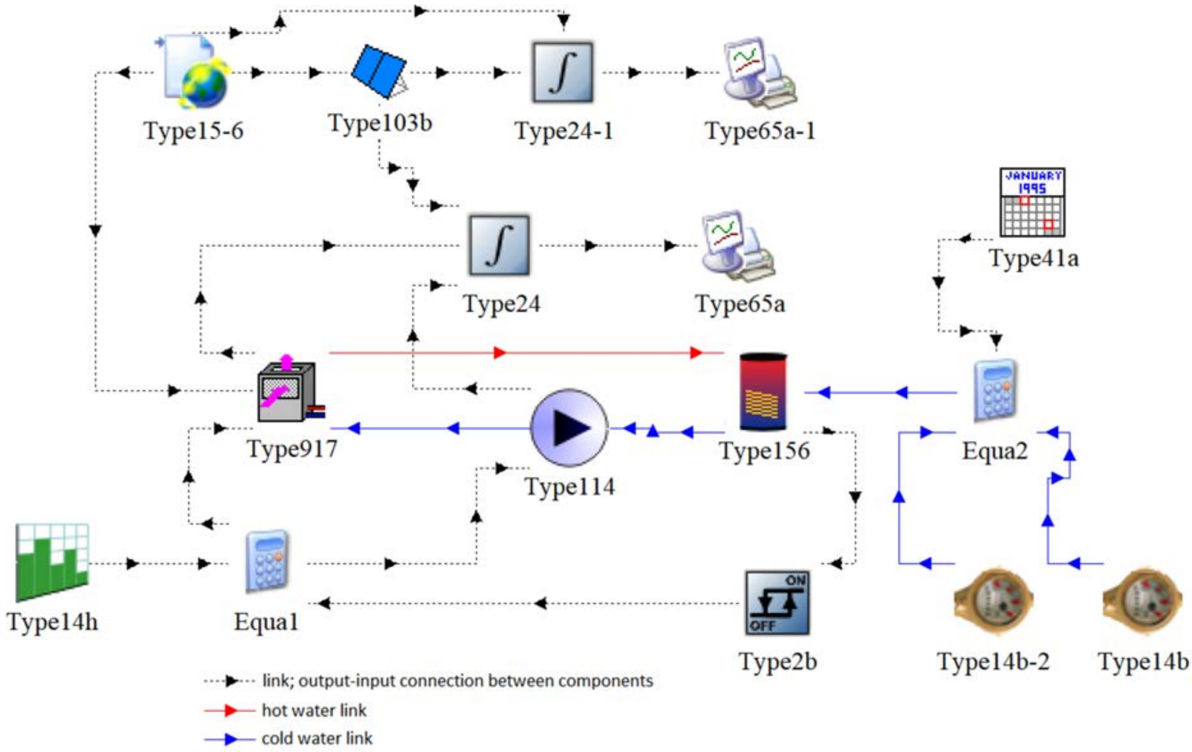


Figure 2. The layout of PV installation with AHP built in TRNSYS Simulation Studio.

Table 2. TRNSYS short component description.

Type number	Component description
Equa	Equations (functions of outputs of other components, numerical values, or defined equations)
2b	On/off differential controller
14b, 14h	Time-dependent forcing function
15–6	Weather data processor
24	Quantity integrator
41a	Load profile sequencer on weekdays and weekends
65a	Online graphical plotter with output file
103b	Photovoltaic array
114	Single (constant) speed pump
156	Cylindrical storage tank with immersed coiled-tube heat exchanger
917	Air source heat pump water heater

The heat generated by the AHP is transferred by immersed coiled-tube heat exchanger to type 156, which is the DHW storage tank. Meanwhile, Type 14b simulates the DHW draw profile for a building from storage tank, which additionally depends on the load profile sequencer (Type 41a). Both of these signals are pre-processed by Equa2. Type 24 and 65a components are used for processing, online visualization and saving in an appropriate form the results of simulations carried out.

In the program, simulation calculations were carried out with a time step of 6 min, and tolerance convergence equal to 0.001. The program uses a built-in numerical solver called "successive method".

2.3. Model equations

Each component shown in Fig. 2 is actually a mathematical model. A detailed reference on all TRNSYS components used in this article, including the mathematical basis of the model, equations, algorithms, parameters, inputs, outputs as well as other elements that the user should take into consideration when using each Type (e.g. data file format, etc.) in TRNSYS, are included in book section (TRNSYS, 2023). Due to the very extensive description of each Type, this information is not included in this article. The exception applies only to the Equa1 and Equa2 components, whose operation depends on the user-set equations. For Equa1, the output signal 0 or 1, transferred to Type 917 and 114 in a given time step, is calculated as the minimum value from the two input values obtained from Type 14h (Input_Day) and 2b (Input_Temp) according to Equation (1):

$$\text{Signal} = \text{MIN}(\text{Input\_Temp}, \text{Input\_Day}) \tag{1}$$

For more information on the operation of Type 14h and 2b components, see Section 2.5. On the other hand, the output signal for Equa2 is calculated from Equation (2):

$$\text{Signal} = \text{EQL}(1, \text{Schedul}) \cdot \text{Days} + \text{EQL}(2, \text{Schedul}) \cdot \text{Weekend} \tag{2}$$

where: Schedul – signal from Type41a (1 for weekday, 2 for weekend), Days – signal from Type434b (hourly DWH consumption for weekday in a given time step), Weekend – signal from Type434b-2 (hourly DWH consumption for weekday in a given time step), EQL – a mathematical function that returns 1 if the first expression is equal to the second; returns 0 otherwise; expressions are separated by a comma.

2.4. PV installations

Three on-grid PV installations composed of 390 Wp monocrystalline panels were assumed in the calculations. Table 3 presents the specification of PV panels used in simulations of electrical performance of PV panels in Type 103b.

Table 3. PV panel specification.

Parameter	Value
Panel area [m^2]	1.868
Nominal maximum panel power [Wp]	390
Short-circuit current at reference conditions [A]	11.58
Current at max power point and reference conditions [A]	11.04
Open-circuit voltage at reference conditions [V]	41.94
Voltage at max power point and reference conditions [V]	35.33
Temperature coefficient of I_{sc} [A/K]	0.045
Temperature coefficient of V_{oc} [V/K]	–0.113

The assumption made in the calculations was that the PV array is installed on a south-facing roof surface at a constant angle of inclination. Meanwhile, optimal slope of the panels was determined by examining the data obtained from simulating the operation of the on-grid PV system shown in Fig. 3 for different slope angles of the PV panels (Fig. 4).

The analysis of the data in Fig. 4 shows that the highest amount of energy per m^2 of PV panel area per year is possible for a slope of 36 degrees and is equal to 217.65 kWh/m^2/a. However, PV panels do not achieve their maximum annual efficiency at this slope; the highest efficiency, reaching approximately 18.3%, is observed at a slope of 48 degrees. This can be attributed to the fact that PV panels at higher tilt angles during spring and autumn exhibit better energy conversion capabilities due to reduced exposure to higher outdoor temperatures, thereby enhancing their overall efficiency. For more information about the impact of the temperature coefficient of PV cells on their long-term operation, see the paper (Pater, 2021). In the tilt range of PV panels $36 \pm 4°$, the difference between annual energy production is only 0.22%, i.e. less than 0.5 kWh. In the simulation calculations presented in the next section, it was decided due to the information presented above, that the PV panels would be inclined at 36°.

Table 4 summarizes information on the specification of the PV systems used in the simulations. The power of the first two PV systems was chosen relative to electricity consumption profiles in the considered building and nominal maximum panel power. It was assumed that for 1000 kWh annual electricity consumption in the building, a PV installation of about 1.1 kWp was needed. Since the building consumes 3285 kWh per year (profile A and C) and 5256 kWh (profile B and D), the power of the PV installation should be about 3.6 kW and 5.8 kW. This corresponds to installations with 10 and 14 PV panels of 390 Wp, since this number of panels makes it possible to ensure that each PV installation had two strings of PV panels of equal power. The power of the 3rd installation (PV-3) was determined by increasing the power of the PV-2 installation by the difference in the number of panels between PV-2 and PV-1 equal to 4.

Table 4. Specification of the PV systems used in the simulations.

Number of PV installation	Installation power [kWp]	Number of PV panels	PV array surface [m^2]
PV-1	3.90	10	18.68
PV-2	5.46	14	26.15
PV-3	7.02	18	33.62

2.5. AHP

The AHP used in the installation was for DHW preparation only; it is not used for the building central heating and cooling needs. In the Type 917 component, the most important settings of used parameters are: rated heating capacity and power equal respectively to 1.3 kW and 0.4 kW; rated air

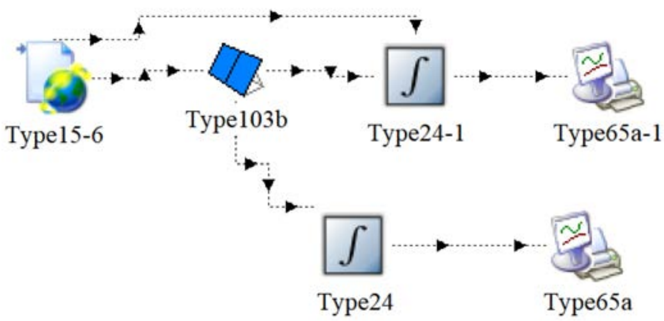


Figure 3. TRNSYS model of PV on-grid installation.

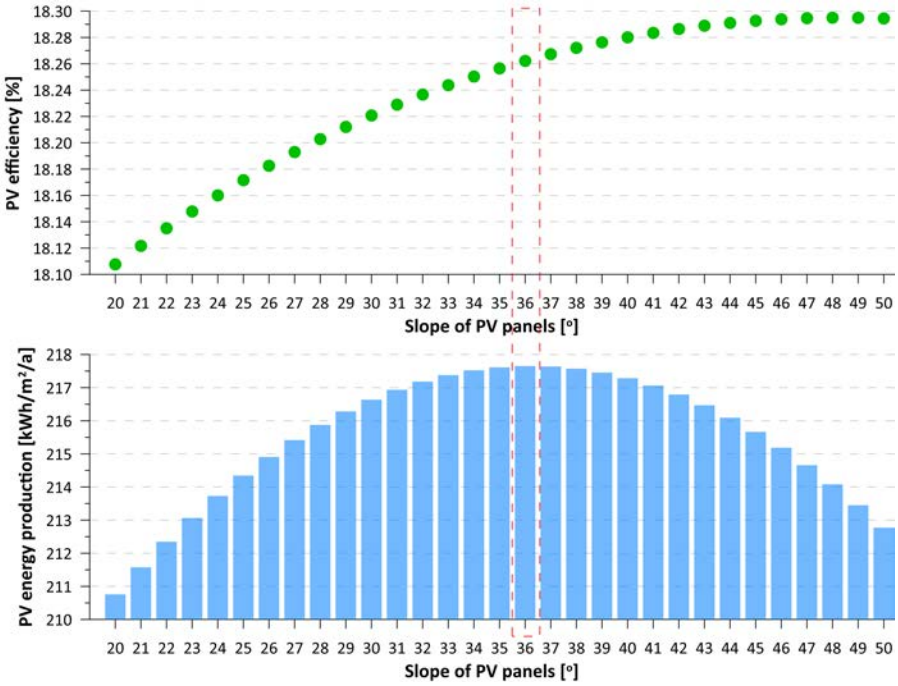


Figure 4. The effect of PV panel slope on annual electricity production and PV panel efficiency.

flowrate equal to 350 m^3/h. An extremely important aspect affecting the overall efficiency of the system and thus the value of SC is the AHP work control strategy. AHP is on or off depending on the control signals received from Type 14h and 2b components processed by Equa1 component (Fig. 2). In component Type 14h two scenarios were used during the simulation:

- system with AHP control – it was set that on every day of the year, the time interval in which the AHP can be turned on are the hours from 6 am to 6 pm,
- system without AHP control – AHP can be turned on at any hour of the day, with no imposed time range.

Such AHP operating scenarios will allow to determine the impact of AHP control on SC values. The component Type 2b is an on/off differential controller which generates a control function which can have a value of 1 or 0 depending on the calculated average value of DHW and dead band temperature differences. The flow rate of fluid-water through the pump (type 114) during the operation was set at 1000 l/h.

2.6. DHW consumption in building

For the study, the assumption was made that the electricity generated by the PV panels would be consumed for DHW preparation by the air source heat pump (AHP). Fig. 5 shows the estimated profiles for DWH consumption throughout the weeks of the year. The first profile represents consumption for Monday through Friday, while the second for weekends. It

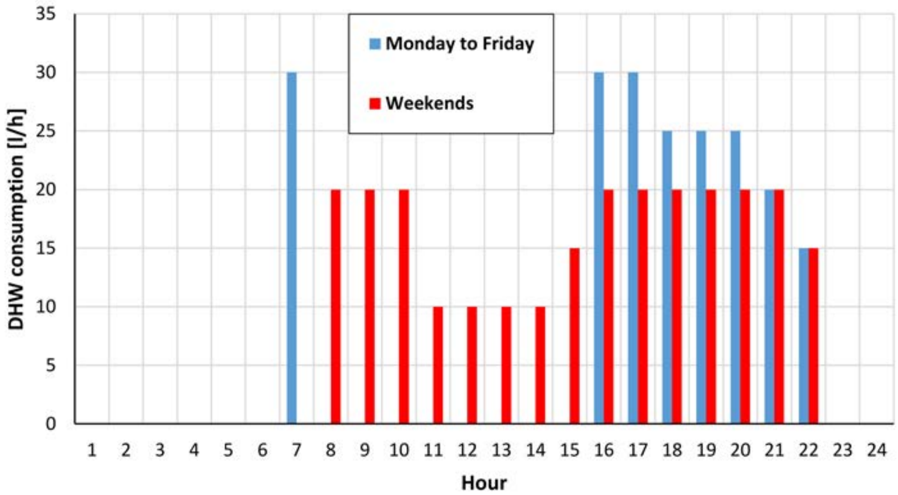


Figure 5. DWH consumption profiles in the weeks of the year.

was assumed that in the considered single-family building occupied by 4 people (2 adults and 2 children) the total demand for DHW was 200 l/day for Monday to Friday and 250 l/day at weekends. The monthly DWH consumption was about 6 m^3. DHW was stored in a cylindrical storage tank with immersed coiled-tube heat exchanger (type 156) with a capacity of 300 litres. In the program, the heat loss coefficient for the all edges of the storage tank was set to 3.325 kJ/(hr·m^2·K).

3. RESULTS AND DISCUSSION

As mentioned earlier, the installation being analysed involved studying the impact of various factors, including different electricity consumption profiles within the building, on the obtained SC values. Fig. 6 displays graphs illustrating the variations in selected operational installation parameters for a specific day, namely the 200th day of the simulation year. These results were determined for PV-2 photovoltaic installation (14 PV panels). The grey field in the graphs was used to show the course of change in electricity consumption in the building according to the selected profile, assuming that AHP was not present in the installation. It is evident from these graphs that profiles C and D relative to profiles A and B have a course of energy consumption higher during the period, i.e. from 8 am to 6 pm, in which the production of electricity by PV panels occurs. This finding significantly influences the SC values obtained for these installations, which will be presented in subsequent graphics within this study. Across all profiles, from 8 am to 5 pm, the amount of electricity consumed in the building does not exceed the amount of energy produced by the PV system. This indicates a high level of self-consumption during this time.

The red and blue lines in Fig. 6 show the course of electricity consumption in the building when a heat pump is installed, whose operating hours are set at a predetermined time (AHP control), i.e. from 6 am to 6 pm. and are arbitrary (AHP without control). In the case of controlling the operation of the AHP in the installation, more energy consumption is obtained during the generation of power by PV panels. On this day, the AHP without control operation produced heat mainly after 3 pm, thus not using the available electricity from the PV panels in the earlier hours of the day.

3.1. PV panel energy generation

Figure 7 shows the fluctuations in daily solar radiation and energy generation per m^2 of PV panels for all considered PV installations. Based on the observed energy production patterns, it can be concluded that the largest amounts of energy in the region of 1.8 kWh per 1 m^2 of PV panels surface are generated in the summer (between 128 and 238 days of the year), with simultaneous high values of daily solar radiation reaching values of about 7 kWh per 1 m^2 of surface. Conversely, energy generation is at its lowest during the beginning and end of the year, attributable to the lower values of daily solar radiation. During the year for the considered installations, the total amount of AC electricity generated,

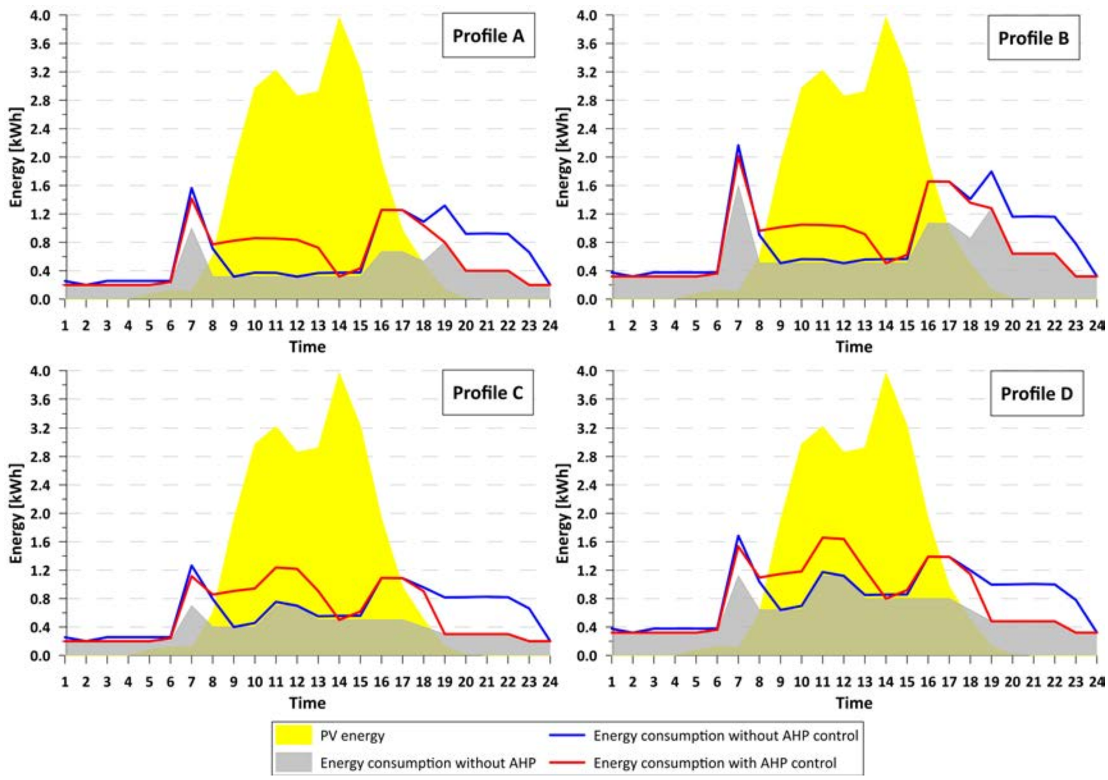


Figure 6. Changes of selected operating installation parameters for the 200th day of the simulation year and PV-2.

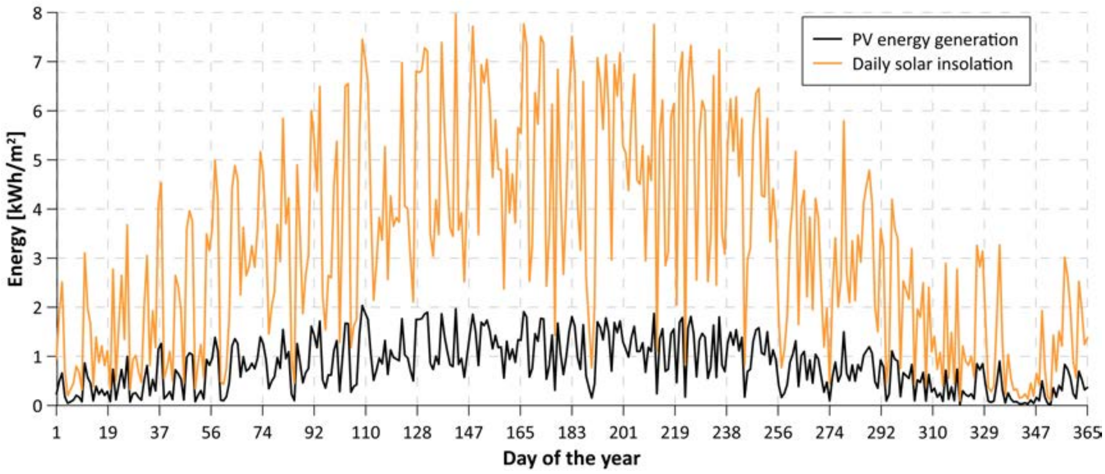


Figure 7. Changes of daily solar radiation and energy generation per m^2 of PV panels.

assuming 95% inverter efficiency, was for PV-1: 3 955 kWh, for PV-2: 5 537 kWh and the highest for PV-3: 7 119 kWh. This translates into an average energy production of about 211.7 kWh of energy per year from 1 m^2 of PV panel area in the considered installations.

3.2. Analysis of SC values

The next two graphs (Fig. 8 and Fig. 9) illustrate the course of changes in the calculated SC values over the year for two energy consumption profiles A and C (3 285 kWh/year) and for the PV-2 installation. From the provided visual representations, it is evident that the highest SC values are obtained during the initial and final months of the year, irrespective of the presence of AHP. During the summer months, daily SC values are lower due to the increased availability of electricity generated by PV panels, making it more challenging to fully utilize it. Notably, the SC values are greatly influenced by the specific energy consumption profile employed. Profile C consumes from 8 am to 4 pm 15% more energy per day than profile A, leading to a higher SC value over the course of the year, representing an almost 8% increase. For profile C, the minimum SC values are around 20%, while for profile A, these values fluctuate around 16%.

Figures 8 and 9 also display SC values for the system when operating hours of AHP are controlled and not controlled. Upon analysing the course of the black and red lines, it is observed that the presence of AHP raises the SC value by a few percent when AHP operating hours are uncontrolled and by several percentage points when the AHP operating hours are regulated.

However, due to the significant daily variability in the data shown in Figs. 8 and 9, it is not possible to draw conclusive findings regarding general trends in SC values. Consequently, an additional chart of the radar type (Fig. 10) has been pre-

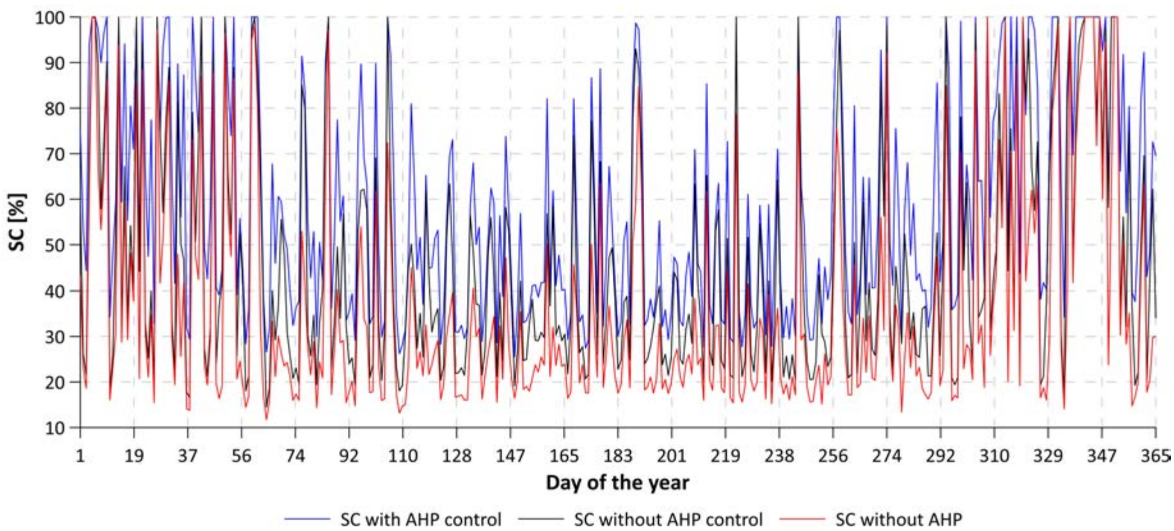


Figure 8. Course of SC changes for different configurations of installation with profile A energy consumption and PV-2.

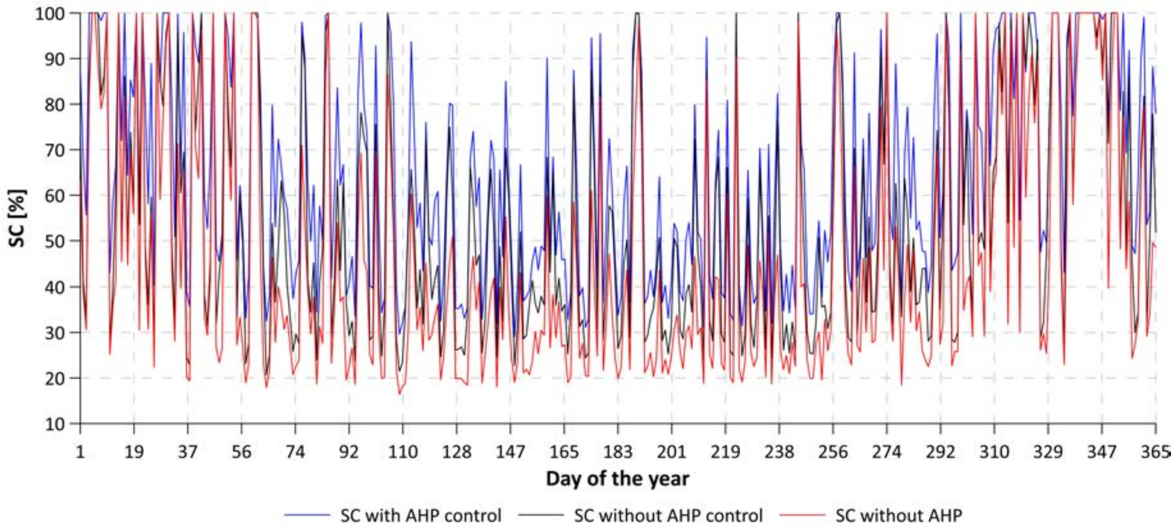
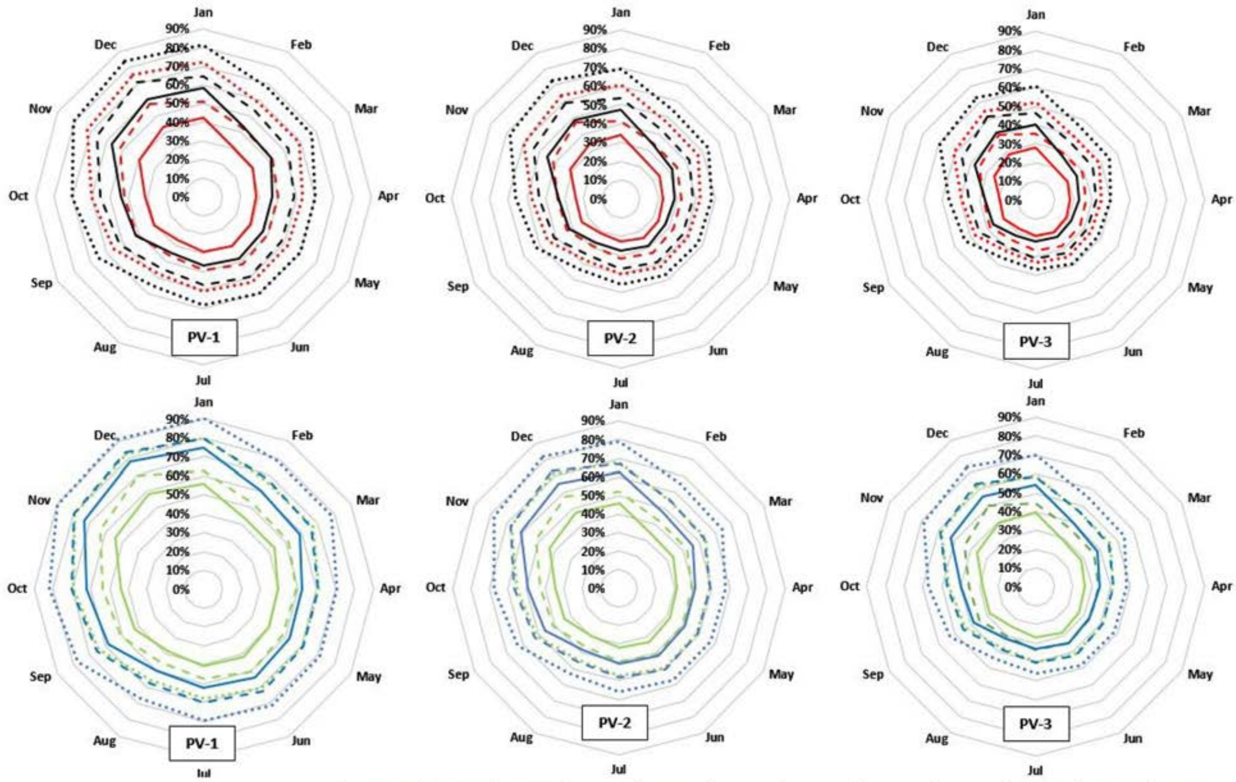


Figure 9. Course of SC changes for different configurations of installation with profile C energy consumption and PV-2.

pared to depict the course of changes in monthly SC values for all photovoltaic installations, energy consumption profiles and different configurations of hybrid systems with AHP. An initial observation derived from the analysis of the data presented in Figure 10 is that for profiles B and D, higher SC values are achieved each month compared to profiles A and C. This can be attributed to the higher electricity consumption in the building for these profiles. The differences in the obtained SC values reach about 10%.



Line	——	– – –	······	——	– – –	······	——	– – –	······	——	– – –	······
Consumption Profile	A	A	A	B	B	B	C	C	C	D	D	D
Installation without AHP	YES	NO	NO	YES	NO	NO	YES	NO	NO	YES	NO	NO
Installation with AHP	NO	YES	YES	NO	YES	YES	NO	YES	YES	NO	YES	YES
Installation with controlled working of AHP	NO	NO	YES	NO	NO	YES	NO	NO	YES	NO	NO	YES

Figure 10. Comparison of monthly values of the SC parameter for different configurations of the considered installations.

Another significant conclusion, which can be seen in Fig. 10, pertains to the difference in the results of SC values obtained between profiles A and C, as well as B and D. It can be seen that SC reaches higher values for profiles C and D than for A and B due to their poorer alignment with the utilization of PV-generated energy. The discrepancy in the SC results obtained between profiles A and C, as well as B and D, depending on the month, varies from a few percent to as much as 20% in November-February, while in May-August this difference is smaller, around 10%. It can also be noted that an increase in the power of PV installations causes a decrease in the SC parameter. This is attributed to the fact that with more energy generation from the PV installation, it is more difficult to achieve an adequate level of energy self-consumption. In the considered installations, the differences in SC values between PV-1 and PV-3 ranged from 9 to 25%. In all installations, it can be seen that the highest SC values are obtained during the winter months. This is due to the fact that in this period the generation of energy from PV panels is much lower, and therefore there is a greater possibility of self-consumption to a greater extent.

Regarding the impact of utilizing AHP in the installations on the obtained SC values, the analysis of data presented in Fig. 10 highlights a consistently positive effect, regardless of whether the operation time of the AHP is controlled. Installing AHP yields up to 35% higher SC values in certain months compared to systems without AHP. Another observation is that the presence of AHP significantly improves the SC value in installations employing energy consumption profiles A and C, that is less matched to the energy production of the PV installation.

The complete overview regarding the performance of different systems and their impact on SC can be seen in Fig. 11, where the annual SC values for each system configuration are summarized. The highest SC value, amounting to 83.9%, was obtained for an installation of PV-1, profile D and a working time-controlled AHP. In contrast, the lowest SC value equal to 19.7% was achieved for an installation with a PV-3, profile A and the absence of AHP. The difference between these extreme results was as much as 64.2%.

In the considered installations, the presence of a time-controlled AHP increases the annual SC value by approximately 15% to 25% (Fig. 11). Conversely, in the absence of the time-control function, the presence of AHP raises the annual SC value by 7 to 11%. Simulation calculations yielded very similar results for SC values between profiles B and C, although it should be noted that these profiles differ in annual energy consumption (profile B: 5256 kWh, profile C: 3285 kWh). This example shows the positive impact of intensification of electricity consumption during the day.

As mentioned in the literature introduction, reaching large SC values in PV on-grid systems reduces the costs associated with purchasing electricity from the grid. So achieving large SC values is generally desirable. However, as shown in Fig. 11, larger SC values can be achieved by reducing the size of PV installations. To provide a comprehensive understanding of the issue discussed here, it is necessary to analyse the amount of energy generated by a PV system and transmitted to the grid after subtracting self-consumed energy. This issue is illustrated in Fig. 12. It is evident from this diagram that the PV-1 installation, due to its undersized power, allows much less electricity to be given back to the grid than the PV-3 installation (about twice as much).

In PV installations where electricity production is accounted by net-metering principles, it is crucial to verify how the amount of electricity generated by the PV system and partially stored on the grid balances with the total amount of energy consumed in the building. In this study, this relationship is defined by the net energy parameter. A positive value

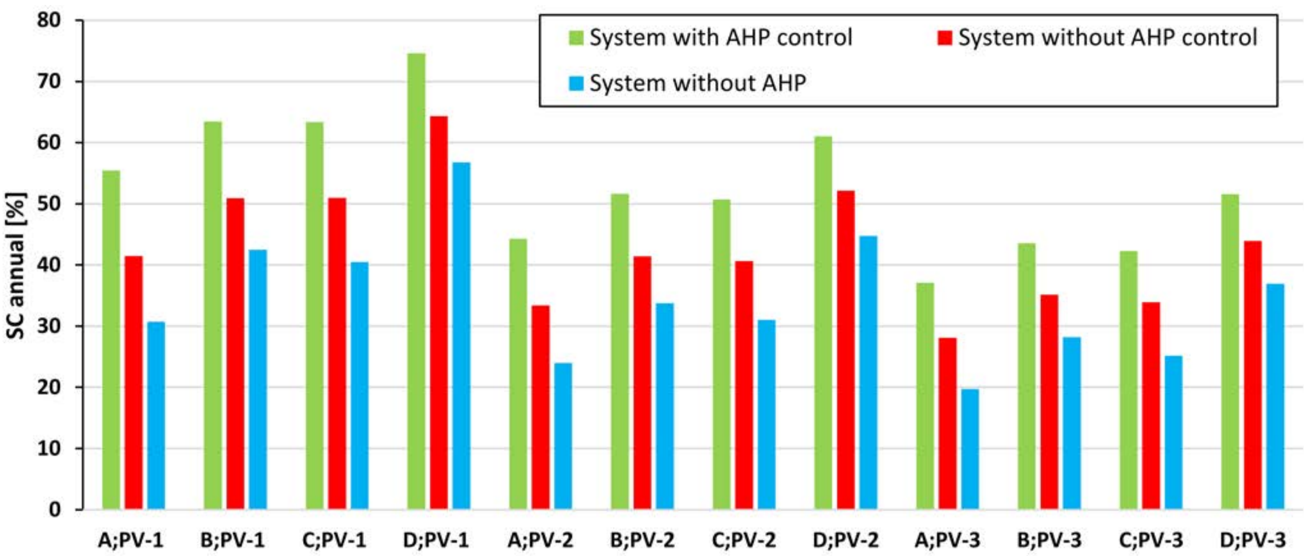


Figure 11. Differences between annual SC values depending on installation configuration.

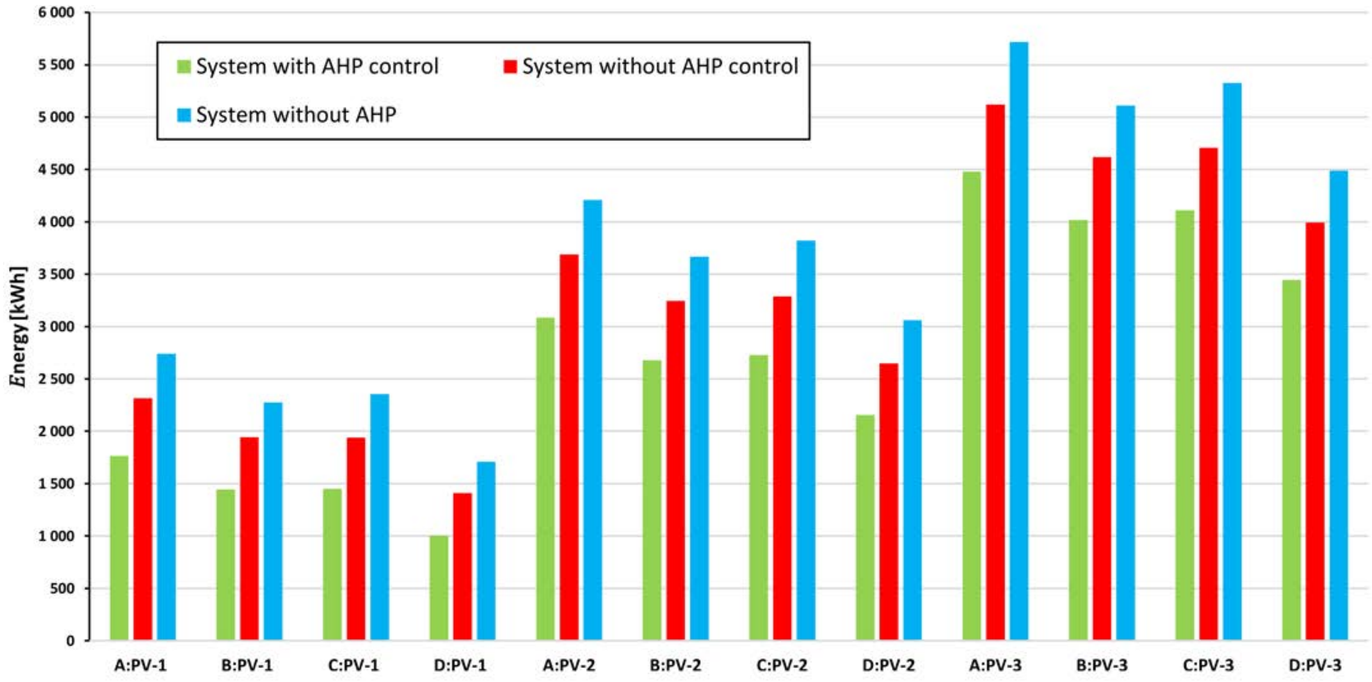


Figure 12. The amount of energy generated by a PV system and transmitted to the grid after subtracting self-consumed energy.

of this parameter 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. The best situation occurs when this value oscillates around 0.

Figure 13 shows the net energy parameter considered for each installation. It was calculated by assuming that the owner of the installation accounts for the generated PV energy through net-metering system and by subtracting the following components from the electricity generated from the PV installation during the year:

- amounts of self-consumed energy,
- energy quantities resulting from own electricity consumption in the building for profiles A, B, C and D,
- the amount of energy consumed by the AHP and circulating pumps (2 153 kWh for AHP with control of working time and 2710 kWh for AHP without control),

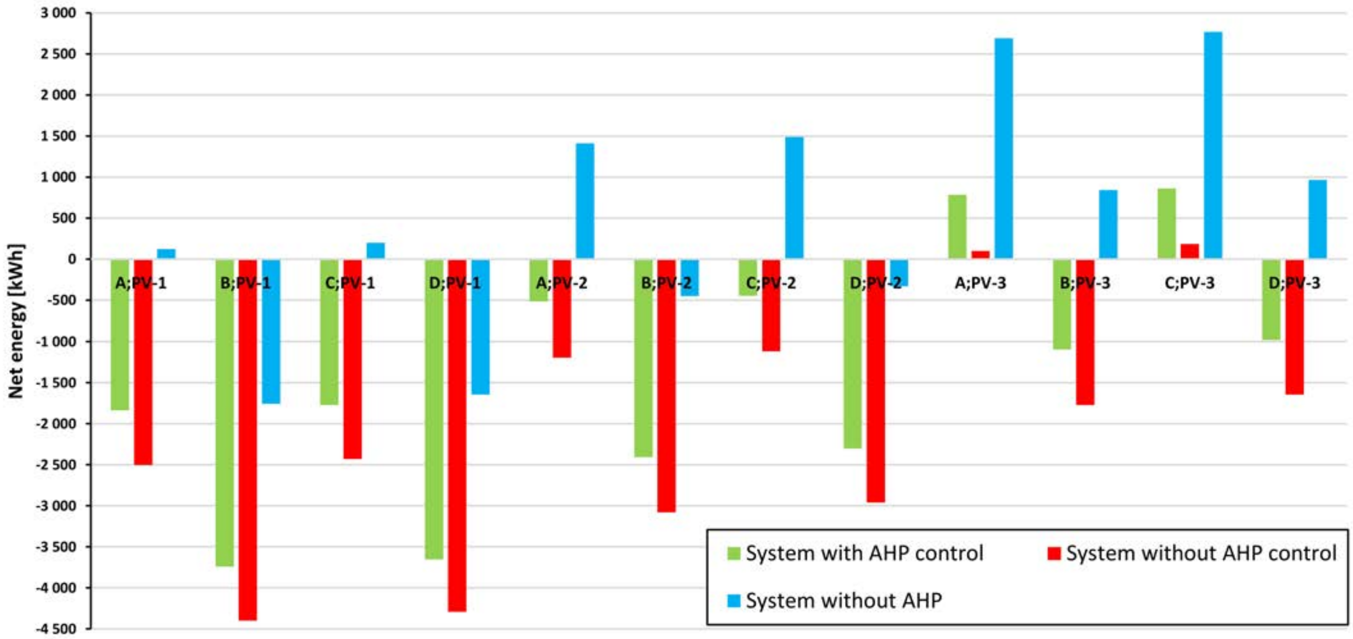


Figure 13. Differences between annual net energy values depending on installation configuration.

- also that 20% of the amount of energy put into the grid is charged for putting electricity into the grid, storing it and then receiving it (grid compensation factor of 0.8).

As can be seen in Fig. 13, if AHP is not be present in the installation, the achieved net energy values are closest to 0 in configurations A;PV-1 and C;PV-1. In the other cases of PV-2 and PV-3 installations, there remains an excess amount of energy from PV. On the other hand, if an AHP will be used in the installation, the power of the PV installation should be around 7 kW, because only this will provide enough energy needed to meet the demand for the electricity consumption and that is only for profiles A and C, because for B and D the PV power should be even higher. The value of net energy is also affected by whether the AHP operates only during selected hours of the day (system with AHP control) or at any hours (system without AHP control). In the former case, since the AHP operating time coincides with the period of the day when PV power production is possible, higher net energy values of about 650 kWh are obtained compared to the system without AHP control.

Analysis of the data for energy consumption profiles A and C shown in Figures 14 and 15 enables us to draw deeper conclusions about the operation of the considered installations. From this data, some quantitative relationships between the factors influencing the design decisions can be extracted. Well, as can be seen from the presented data, an increase in the power of the PV installation lowers the annual SC coefficient values by 4% per 1 kW of PV power (in installations without AHP). For installations without AHP, SC of about 31% for profile A and 41% for profile C can be achieved with a PV installation capacity of about 3.7 kW and an annual net energy value of 0 (i.e., an energy-balanced installation in terms of energy production and consumption). It follows that adjusting the energy consumption profile to work with the PV installation raises, by as much as 10%, the SC value at the most favourable value of net energy parameter.

Another important fact from the data presented in Figures 14 and 15 is that the use of AHP without controlling its operation does not increase the SC value, and in fact it is possible to achieve lower SC values compared to installations with no AHP at a value of annual net energy equal to 0. On the other hand, setting appropriate hours of AHP operation makes it possible to achieve a few (in the case of profile C) to several % (for profile A) higher SC values compared to installations without AHP. The results presented here are a very valuable guideline for those who own PV installations and account for their electricity production according to the principles of through net-metering system. In this system, net energy not consumed within 12 months is irretrievably lost, which is why it is so important to obtain net energy values around 0 in PV installations operating in residential buildings.

4. CONCLUSIONS

This paper presents the findings of a study on a hybrid system that combines an on-grid PV array with an AHP for DHW production. The study involved creating and simulating models of the system and its controls using TRNSYS software

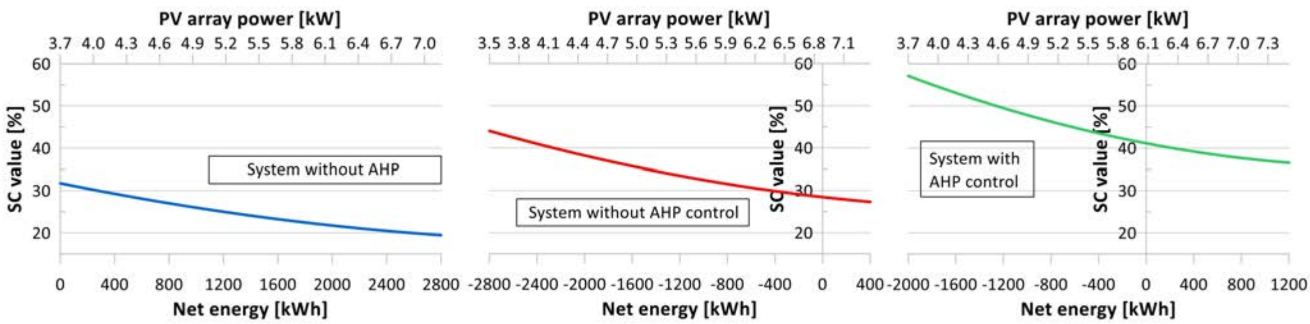


Figure 14. Effect of PV installation power and annual net energy for profile A on annual SC coefficient values.

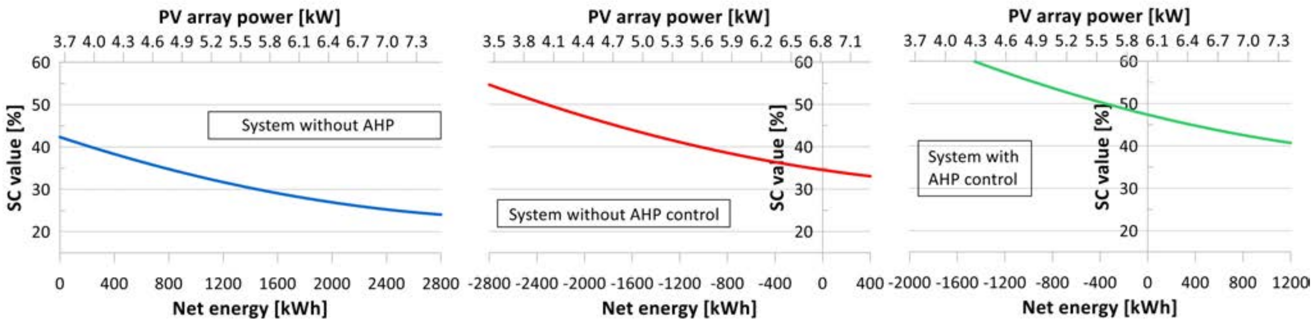


Figure 15. Effect of PV installation power and annual net energy for profile C on annual SC coefficient values.

under various boundary conditions. Additionally, the effects of different factors such as building electricity consumption profiles, PV system capacity, and specific management of the heat pump's runtime were analysed. The study covered one year of operation and aimed to investigate methods of increasing the system's SC value. The simulations presented in this paper emphasize the importance of a holistic approach when evaluating SC in on-grid PV systems, and highlight the need to find a balance between SC value, PV installation capacity, AHP working time and the amount of electricity exported to the grid.

In the examined systems, assuming appropriate operating parameters of PV panels, 211.7 kWh of energy was obtained from 1 m^2 of PV panel area. The highest SC values throughout the year were observed at the beginning and end of the year, regardless of the presence of an AHP. During the entire year, the SC values ranged from about 40% to 85%. In the summer, daily SC values were relatively lower due to the greater availability of electricity generated by PV panels, making it more challenging to utilize all of it (from about 10% to 60%). However, annual SC values reached higher levels (even 20% bigger) in installations that were well-matched to the utilization of PV energy produced (installations with consumption profiles C and D). The highest annual SC value of 74.6% was achieved for an installation of PV-1, profile D and containing AHP with controlled working time.

Based on the simulation studies presented in the article, the following guidelines for users of PV on-grid installations without or cooperating with AHP can be formulated:

1. In residential PV installations, special attention should be paid to the possibility of shifting the operation of electrical appliances (e.g., washing machines, dishwashers, clothes dryers, ovens) to hours when there may be solar radiation reaching PV panels. It is relatively simple and requires no major investment. In the research conducted adjusting the energy consumption profile to work with the PV installation raises, by as much as 10%, the annual SC value at the most favourable value of net energy parameter (equal 0) in installations without AHP. To further enhance the energy self-consumption in PV installations and consequently increase the SC value in residential building systems, it is crucial to intensify electricity consumption from PV installations. This issue should be of particular concern especially during the peak hours from 8 am to 6 pm when the highest electricity generation from PV occurs, assuming appropriate weather conditions are present.
2. In terms of PV installations up to 8 kW that do not cooperate with a heat pump, PV installation power increase results in a decrease of the annual SC coefficient values by 4% for every 1 kW of PV power.
3. It is recommended to consider programming the AHP operation during daytime rather than nighttime, as this significantly impacts energy self-consumption. Application of AHP for DHW preparation only in installations with restriction of working hours at night allowed a potential increase in some months of the year up to 35% higher value of the SC parameter compared to systems without AHP. The presence of a time-controlled AHP increases the annual SC value by approximately 15% to 25%. Conversely, in the absence of the time-control function, the presence of AHP raises the annual SC value only by 7 to 11%.
4. At a value of annual net energy equal to 0 the use of AHP without controlling its operation does not increase the SC value, and in fact it is possible to achieve SC values lower by a few percent compared to installations with no AHP.
5. When the AHP operating time coincides with the period of the day when PV power production is possible, higher net energy values of about 650 kWh during the year are obtained compared to the system without AHP control. This is due to the fact that the AHP takes the energy produced from the PV panels, increasing the SC value.
6. In PV installations where electricity production is accounted by net-metering principles, it is crucial to verify the value of the net energy parameter whose value should be as close as possible to 0. Lack of verification of this parameter may lead to a situation in which the user of a PV installation with or without a heat pump produces too little or too much electricity. It may also result in extending the payback time of investment outlays on installations.

SYMBOLS

AHP	air-source heat pump
DHW	domestic hot water
PV	photovoltaic
RES	renewable energy sources
SC	self-consumption

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