POLITYKA ENERGETYCZNA – ENERGY POLICY JOURNAL

2024 ✦ Volume 27 ✦ Issue 3 ✦ 71–86

DOI: 10.33223/epj/186877

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Analysis of the possibility of increasing the self-consumption rate in a household PV micro-installation due to the storage of electricity and heat

Abstract: Between 2019 and 2023, over one million PV micro-installations were built in Poland. Most of them have the option of settling prosumer discounts: net-metering (80% of energy sent to the grid returns to the user for PV installation power up to 10 kWp and 70% for power between 10 and 50 kWp). Owners of new PV micro-installations (from 2022) are subject to net-billing settlements, which is economically unfavorable due to the coexistence of low energy prices and high productivity of PV panels. This, however, favors efforts to increase self-consumption of energy in prosumer PV micro-installations. Therefore, for the selected PV installation, the use of electricity storage and thermal energy storage (for the purposes of preparing domestic hot water) was analyzed. The calculations were based on data from the installation collected during one year of operation. A calculation methodology for energy distribution for the consumption and storage of electricity and heat was developed, and thus for estimating the value of energy sent to the grid, taking into account the above-mentioned. The use of electrical and thermal energy storage resulted in an increase in the value of self-consumed energy, with the self-consumption coefficient ranging from 30 to over 80%. The self-consumption rate in the first year of operation of the installation (without energy storage)

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reached 27.1%, and in the second year 30.7%. A 3 kWh electricity storage would increase the self-consumption rate in the following years to 51 and 57.2%, and for a 6 kWh capacity 58.5 and 64.1%.

Keywords: heat storage, electricity storage, energy in Poland, PV, implementation of renewable energy

Introduction

In Europe, as well as in Poland, the economy is facing an energy transformation; this transformation distinguishes various types of problems that need to be overcome (Adamska 2022; Gielen et al. 2019) and they vary depending on the current conditions in the country, e.g. problems with access to energy are not uncommon (Milian Gómez et al. 2023). Due to the energy transformation, there is a need for forecasting and storing energy from surpluses produced in RES installations (Augustyn and Kamiński 2018), especially wind turbines and photovoltaics, both on a macro and micro scale in home micro-installations, among others, to reduce the impact of the phenomenon called the duck curve (Olczak et al. 2021a). This phenomenon is caused by an increase in the installed capacity of RES in the world, in Europe and in Poland (Benalcazar et al. 2024; Dzikuć and Dzikuć 2022; Piwowar et al. 2023).

Photovoltaic micro-installations have been tested many times in Polish conditions (Mirowski and Sornek 2015; Rogus et al. 2019). Iglinski et al. (2023) analyzed the increase in the number of photovoltaic installations in Poland and also performed a SWOT analysis. The number of installations has increased due to subsidies (Olczak et al. 2021b), a decrease in LCOE (Nieto-Diaz 2022) and an increase in the cost of electricity (Komorowska and Olczak 2024). Ceran et al. (Ceran et al. 2021) analyzed the impact of using photovoltaic installations on reducing peak energy demand in office buildings. Sornek et al. (2022) and Luboń et al. (2020) investigated the effect of a water cooling PV panel in Polish conditions. Sawicka-Chudy et al. (2018) analyzed the demand energy in a building with a PV installation. Tapia et al. (2022) investigated ways of increasing the self-consumption ratio for energy from photovoltaic sources. A lot of prosumer settling discounts: net-metering (80% of energy sent to the grid returns to the user for PV installation power up to 10 kWp and 70% for power between 10 and 50 kWp) (Bartecka et al. 2020; Fikru et al. 2022; Olczak et al. 2022; Szablicki et al. 2019).

The issue of storing electricity and solving new systems, including those related to heat (Chmielniak 2019; Kinelski 2022; Komorowska and Gawlik 2018; Krupa et al. 2018; Olczak 2020), and those using PCM materials (Kuta et al. 2016) and cogeneration systems (Matuszewska et al. 2017; Żołądek et al. 2021). Barsegyan et al. (2022) performed technical and economic optimization of the use of energy storage together with renewable energy sources.

The increase in installed capacity in renewable energy sources and the quantitative values of the productivity of these sources are also influenced by climate change (Canales et al. 2020; Ceran et al. 2021).

Extensive work on the use of energy storage for household needs and improving efficiency, but it does not cover both heat and electricity. There are no studies on the possibility of increasing the self-consumption rate of energy from a photovoltaic installation for the purposes of storing electricity and heat (for domestic heat water preparation). In particular, there is lack of studies of conditions in Poland (Dzikuć et al. 2022; Piwowar and Dzikuć 2019) based on real data (electricity production from PV, electricity consumption).

The second section contains materials and computational methods, the third section contains the results and discussion, and the fourth section contains conclusions.

1. Materials and methods

1.1. Object of research (and location)

The research implemented the results of measurements recorded from 06/2020 to 05/2022 in a PV micro-installation (with a power of 5.04 kWp) located in the Lesser Poland Voivodeship. This installation was the subject of research in works on the use of a frame for PV panels (Olczak and Komorowska 2021) and a comparison of real and calculated specific yields (based on ERA5 weather data and HOMER methodology) (Olczak 2022a). The installation consists of fourteen Longhi HPH360 PV panels located on the roof of the building. The nominal capacity of PV panel is 360 Wp with a temperature coefficient of the power 0.37%/°C, a nominal operating cell temperature (NOCT) of 45°C (Olczak 2022a) and an inverter capacity of 5 kW. Examples of measurement results of parameters recorded in the installation are shown in Figure 1 and the total values for the first two years of operation of the installation are as follows: energy received from the grid (*ER*) 6,532.9 kWh, value of energy sent to the grid (*ES*) 7,016.1 kWh, PV energy production (*EPV*) 9,859.8 kWh.

The hourly values of energy produced from the installation (calculated at the inverter output) reach 4.2 kWh. This value was reached in the afternoon due to the orientation of the photovoltaic panels on the roof of the building (south-west). Hourly values of energy sent to the grid (*ES*) reach a maximum of 3.8 kWh. Only in the morning and evening hours were zero *ES* values recorded with non-zero *EPV* values (relatively low values – below 0.4 kWh). The case of *EPV* values greater than zero with simultaneous zero *ES* values means that the auto-energy consumption coefficient is 100%. During the presented period (three days, Fig. 1), the value of energy consumed from the grid *ER* was never equal to zero. However, *ER* values lower than 0.1 kWh occurred nine times (hours).

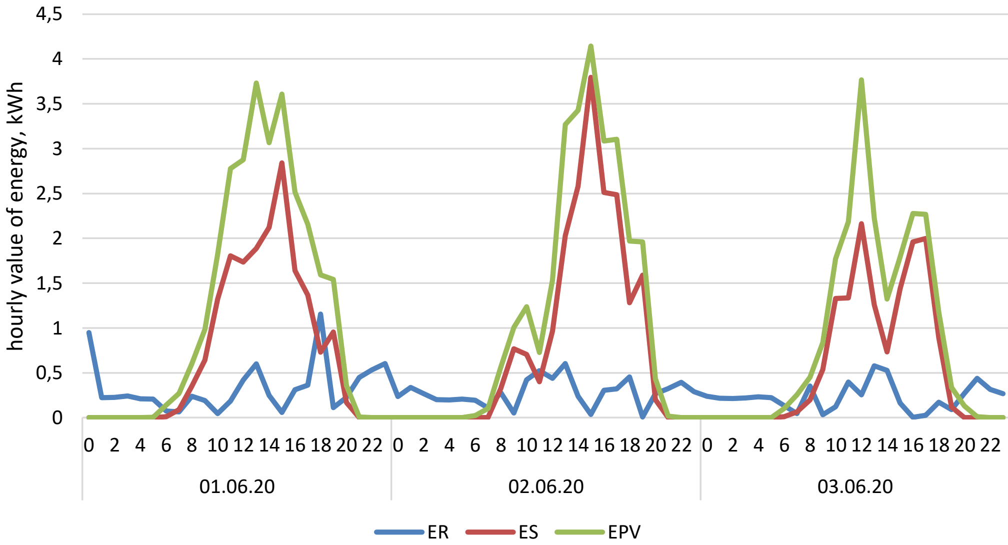

Fig. 1. Measured data (energy received *ER*, energy sent to the gird *ES*, PV energy production *EPV*) in PV installation at Łęki village for three days (from 1st June 2020 to 3rd June 2020)

Rys. 1. Dane pomiarowe (energia otrzymana *ER*, energia wysłana do sieci *ES*, produkcja energii PV *EPV*) w instalacji PV w Łęki w ciągu trzech dni (od 1 czerwca 2020 r. do 3 czerwca 2020 r.)

1.2. Calculation method

1.2.1. Calculating *EC* (Energy Consumption) and *ESC* (Energy Self-Consumption) – case without energy storage

In first step, energy self-consumption *ESC* and energy consumed *EC* was calculated based on measured values. *ESC* was measured by subtracting *ES* from PV energy production (*EPV*) value:

$$ESC(\tau) = EPV(\tau) - ES(\tau) \tag{1}$$

The *EC* value is connected to *ESC*, because the energy consumption (*EC*) is the value of energy received plus energy self-consumption from photovoltaic *ESC*:

$$EC(\tau) = ER(\tau) + ESC(\tau) \tag{2}$$

Additionally, the hourly energy flow (*HEF*) values as the difference between energy sent to the grid and energy received from the grid were calculated as:

$$HEF(\tau) = ES(\tau) - ER(\tau) \tag{3}$$

If the *HEF* value is above zero, it means that there is surplus energy in the installation (energy production is higher than consumption). If *HEF* value is below zero, it means that the recent value of energy production is less than energy consumption.

The main limitations in the study were the adoption of specific types and capacities of electrical and thermal energy storage facilities as well as the test facility. In terms of current values of energy consumption in the building: for electricity, the actual value of energy consumed in the building selected for analysis was assumed; for thermal energy (for DHW), the model consumption of domestic hot water during the day was assumed. For the analyzed building, the impact of introducing energy storage on the electricity and heat consumption profile was omitted. Additional limitations were related to technology: the efficiency of the energy storage processes.

1.2.2. The case of using electricity storage

In the first step, the recent value energy in the storage value (*ESV*) was calculated by the following equation It was assumed that in the first hour of calculation, *ESV* is equal to the useful capacity of electricity storage (*ES*0) (Olczak 2022b):

$$ESV(\tau) = \begin{cases} ES0 & if\ ESV(\tau-1) + HEF(\tau) > ES0 \\ 0 & if\ ESV(\tau-1) + HEF(\tau) \le 0 \\ ESV(\tau-1) + HEF(\tau) & if\ 0 < ESV(\tau-1) + HEF(\tau) \le ES0 \end{cases} \tag{4}$$

The first case (*ESV* = *ES*0) could have occurred when:

- Actual energy stored in previous hour was equal *ES*0 (*ESV*(τ–1) = *ES*0) and there was higher or equal energy production than consumption in hour τ.
- Actual energy stored was less than *ES*0 (*ESV* (τ–1) < *ES*0) and there was higher energy production than the sum of energy consumption in hour τ and difference between *ES*0 and *ESV*(τ–1).

The second case means that actual useful energy stored was zero: when *ESV* (τ–1) was zero and energy production was not higher than energy consumption in hour τ; when *ESV*(τ–1) was higher than zero and energy consumption was higher than the sum of energy production in hour τ and *ESV*(τ–1). The third case occurred when ESV was between zero and *ES*0; *ESV* value was the sum of *ESV*(τ–1) and the difference between energy production and energy consumption in hours τ.

In the next step, the energy received from the grid with storage (*ERwS*) is calculated:

$$ERwS(\tau) = \begin{cases} -HEF(\tau) - ESV(\tau-1)\ if\ ESV(\tau) = 0\ and\ HEF(\tau) < 0 \\ 0\ \ if\ ESV(\tau-1) = 0\ and\ HEF(\tau) \ge 0 \\ 0\ if\ ESV(\tau) > 0 \end{cases} \tag{5}$$

The first case occus when the *ESV* value equals zero and energy consumption is higher than energy production in hours τ; *ERwS* equals energy consumption minus energy production (and also *ESV*(τ–1) if it is not equal to zero) in hour τ. The second case occurs when *ESV*(τ–1) value equals zero and energy production is higher than or equal to energy consumption in hours τ. The third case *ERwS* is zero when energy storage is not empty (*ESV*(τ) > 0).

The value of energy charging to electricity storage (*Ech*) is calculated with the following equation (Olczak 2022b):

$$Ech(\tau)=\begin{cases} HEF(\tau) \; if \; HEF(\tau)>0 \, and \, HEF(\tau)\le ES0-ESV(\tau-1) \\ ES0-ESV(\tau-1) \; if \; HEF(\tau)>0 \, and \, HEF(\tau)>ES0-ESV(\tau-1) \\ 0 \; if \; HEF(\tau)\le 0 \, or \, ESV(\tau-1)=ES0 \end{cases} \tag{6}$$

The electricity charging value in the first case is equal to the difference between energy production and energy consumption in hours τ, if *HEF* is less than *ES*0 – *ESV*(τ–1); in the second case, *ES*0 – *ESV*(τ–1) because the *HEF* value is higher than maximum energy possible to storage; in the third case, 0 when energy production is lower than energy consumption or electricity storage is full.

In the next step, the value of energy sent to the grid with storage (*ESwS*) was calculated. *ESwS* is dependent on the energy left after charging the storage (*HEF* minus *Ech*, if it higher than zero):

$$ESwS(\tau)=\begin{cases} HEF(\tau)-Ech(\tau) \; if \; HEF(\tau)-Ech(\tau)>0 \\ 0 \, if \; HEF(\tau)-Ech(\tau)\le 0 \end{cases} \tag{7}$$

In the case of using electricity storage: energy self-consumption with storage (*ESCwS*) was calculated by the following equation:

$$ESCwS(\tau)=\left(EPV(\tau)-ESwS(\tau)\right) \tag{8}$$

The percentage ratio of *ESCwS* (compare to *EPV*) was calculated by the following equation:

$$ESCwS'(\tau)=\frac{ESCwS(\tau)}{EPV(\tau)} \tag{9}$$

1.2.3. The case of using electricity and heat storage

In the calculation, the priority is the storage of electricity due to higher unit investment expenditures on electricity storage than heat storage and higher electricity than heat price in Poland (Komorowska and Olczak 2024; wnp.pl 2021). *ESwH* (energy sent to the grid with heat storage) is subtracting the energy needed to charge the heating storage (heat charging, *Hch*) from the energy sent with electricity storage.

*HS*0 – value of full capacity of heat storage (assumption: *HS*0 = 5 kWh):

$$Hch(\tau) = \begin{cases} ESwS(\tau)\ if\ ESwS(\tau) \leq HS0 - HSV(\tau-1) - HC(\tau) \\ HS0 - HSV(\tau-1) - HC(\tau) if\ ESwS(\tau) > HS0 - HSV(\tau-1) - HC(\tau) \\ 0 if\ ESwS = 0 \end{cases} \tag{10}$$

where:

HSV – recent value of energy accumulated in heat storage.

The value of heat charging is equal to the energy sent with storage (in the case with only electricity storage) when it is possible to accumulate energy in heat storage in the first case in equation no. 10; the difference between capacity heat storage and heat stored in previous hour and heat consumption. In the next step, energy sent to the grid with heat and electricity storage (*ESwH*) is calculated:

$$ESwH(\tau) = \begin{cases} 0\ if\ ESwS(\tau) \leq HS0 - HSV(\tau-1) - HC(\tau) \\ ESwS(\tau) - HS0 - HSV(\tau-1) - HC(\tau) if\ ESwS(\tau) > HS0 - HSV(\tau-1) - HC(\tau) \end{cases} \tag{11}$$

Energy sent to the grid with electricity and heat storage equals zero if the *ESwS* value is zero or less than the difference between *HS*0 and *HSV*(*τ*–1) and heat consumption *HC*(*τ*). In the next step, the actual value of *HSV* is calculated as:

$$HSV(\tau) = \begin{cases} HSV(\tau-1) + ESwS(\tau) - HC(\tau)\ if\ ESwS(\tau) \leq HS0 - HSV(\tau-1) - HC(\tau) \\ HS0 \quad if\ ESwS(\tau) > HS0 - HSV(\tau-1) - HC(\tau) \end{cases} \tag{12}$$

Energy self-consumption with storage electricity and heating (*ESCwH*) was calculated as:

$$ESCwH(\tau) = \left(EPV(\tau) - ESwH(\tau)\right) \tag{13}$$

Energy self-consumption ratio with storage electricity and heating (*ESCwH'*) was calculated as:

$$ESCwH'(\tau) = \frac{ESCwH(\tau)}{EPV(\tau)} \tag{14}$$

For calculation of the typical profile of heat consumption for domestic heat water preparation (for the analyzed house) was included (Fig. 2).

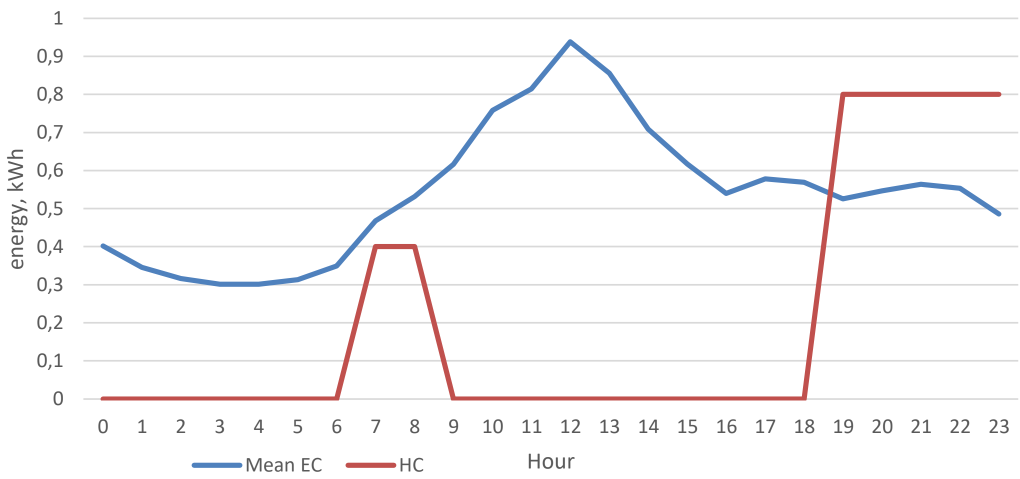

Fig. 2. Data of the means of the *EC* (energy consumption) and the assumption for typical day *HC* (energy heat consumption for domestic heat water) from an installation at the Łęki village

Rys. 2. Dane dotyczące średnich wartości *EC* (zużycie energii) i założenia typowe dla dziennej wartości *HC* (zużycie energii cieplnej na potrzeby podgrzania wody użytkowej) z instalacji we wsi Łęki

Figure 2 displays a summary of energy consumption. According to the data, we can assume that the *EC* value is the lowest in the night and evening, whereas the *HC* significantly rises in the early morning hours and the early evening. The energy consumption is highest at midday. The evaluation shows that we can in general assume that the heat consumption for all housings will be the highest in the morning and evening, whereas the energy consumption will be the highest at midday; because of the location of the Łęki village, the solar radiation intensity is the highest at noon.

For each day (during a two-year period), real electricity consumption was implemented.

2. Results and discussion

2.1. Electricity storage

The impact of the use of an energy storage facility on the value of energy sent to the grid was calculated – the results are shown in Figure 3.

For these three analyzed days, the difference in energy sent to the grid occurred only at 2 p.m. on June 2nd, 2020. This was due to a larger discharge of the storage with a useful capacity of 12 kWh. This explains the non-zero value of energy consumed from grid the *ERwS* value in the

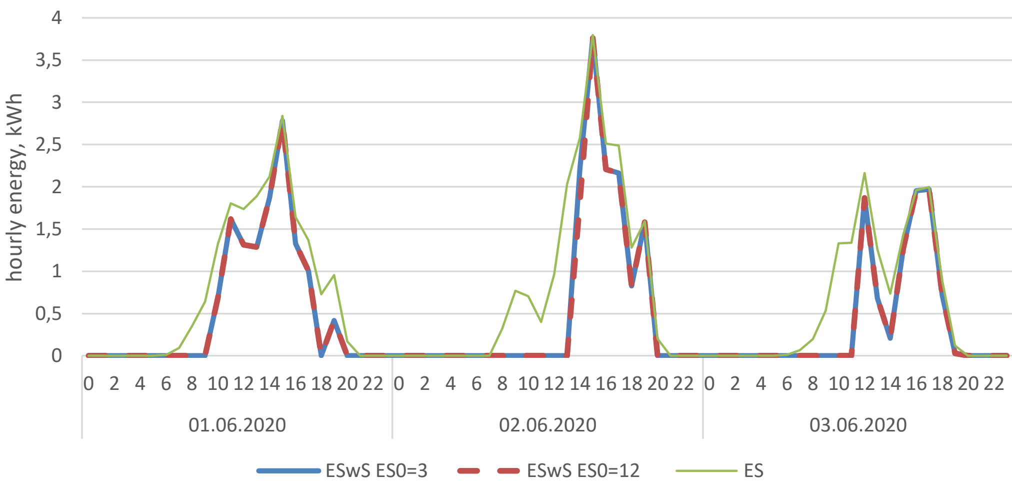

Fig. 3. *ES* and *ESwS* for *ES*0 = 3, compared to *ESwS* for *ES*0 = 12 of three days from an installation at Łęki village

Rys. 3. Wartości *ES* i *ESwS* dla ES0 = 3 w porównaniu do *ESwS* dla *ES*0 = 12 z trzech dni z instalacji we wsi Łęki

case of using the *ES*0 3 kWh energy storage in the morning of the second analyzed day. *ER* and *ERwS* values are presented in Figure 4.

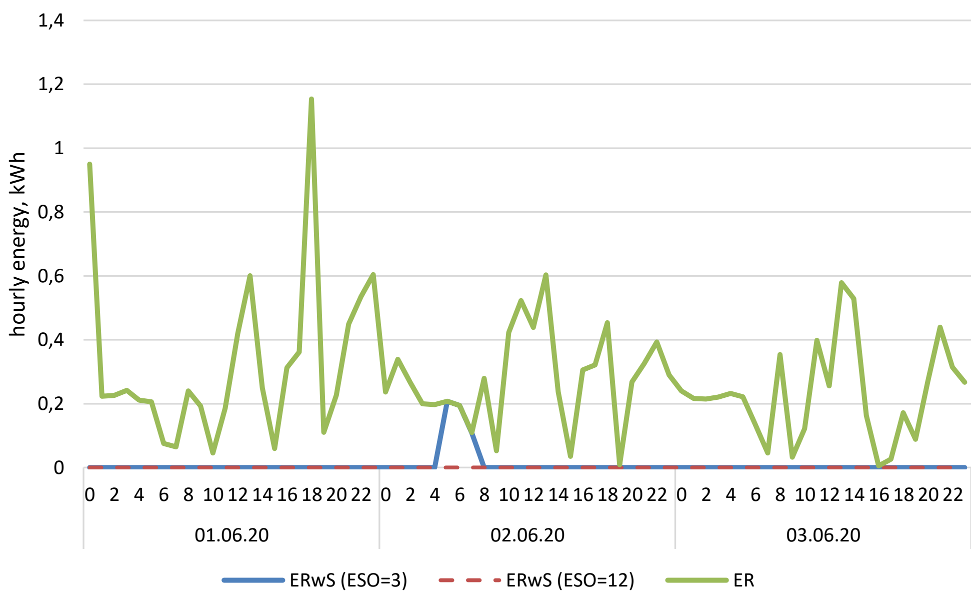

Fig. 4. Data *ERwS* (*ES*0 = 3 kWh) compared to *ERwS* (*ES*0 = 12 kWh) and *ER* over three days for an installation at Łęki village

Rys. 4. Dane *ERwS* (*ES*0 = 3 kWh) w porównaniu z *ERwS* (*ES*0 = 12 kWh) i *ER* w ciągu trzech dni dla instalacji we wsi Łęki

Increasing the value of the useful storage capacity (*ES0* from 3 to 12 kWh) does not significantly reduce the energy sent to the grid on sunny days in June. In this respect, the possibility of discharging the electricity storage at night is important, i.e. energy consumption between the energy surpluses occurring on subsequent days from the current energy production in the photovoltaic installation. A similar result was shown in terms of energy consumed from the grid on the corresponding days.

A summary of the simulation of 2-year sums of *ERwS* and *ESwS* values is presented in Figure 5.

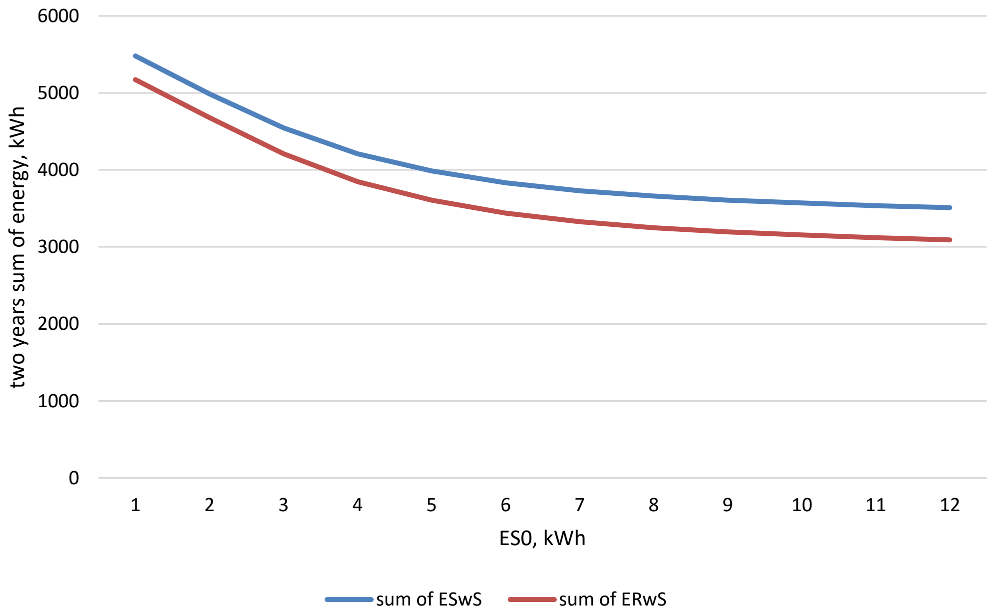

Fig. 5. 2-years sum of *ESwS* and *ERwS* as a function of different *ES*0 values: between 1 to 12 kWh an installation at Łęki village

Rys. 5. Suma *ESwS* i *ERwS* w ciągu 2 lat w funkcji różnych wartości *ES*0: od 1 do 12 kWh instalacja we wsi Łęki

Higher values of *ESwS* than *ERwS* are caused by the relationship between *EPV* and *EC* in a given installation. Energy storage sizes of up to 5 kWh significantly reduce energy flows from and to the grid, and higher *ES0* values reduce them to a low extent.

Electricity and heat storage

An example of the use of *ES*0 3 kWh and *HS*0 5 kWh electricity storage is presented in Figure 6.

The *ESV* value for *ES*0 = 3 kWh varies between 3 kWh and 0 kWh, *HSV* value for *HS*0 = = 5 kWh varies between 5 and 0.619 kWh. The total sum of energy storages (electricity and heat) is not enough for accumulation PV production on 2nd and 3rd June 2020. 1st June is not a typical day because it is the start of the analyses.

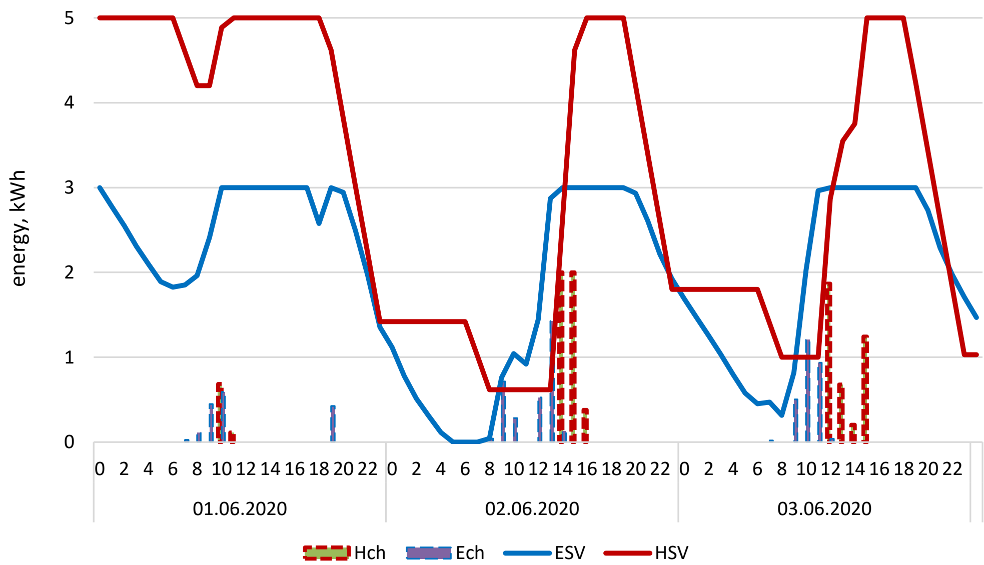

Fig. 6. 3-days *ESV*, *HSV* and *Ech*, *Hch* values in installation at Łęki village

Rys. 6. Wartości *ESV*, *HSV* i *Ech*, *Hch* w ciągu 3 dni w instalacji we wsi Łęki

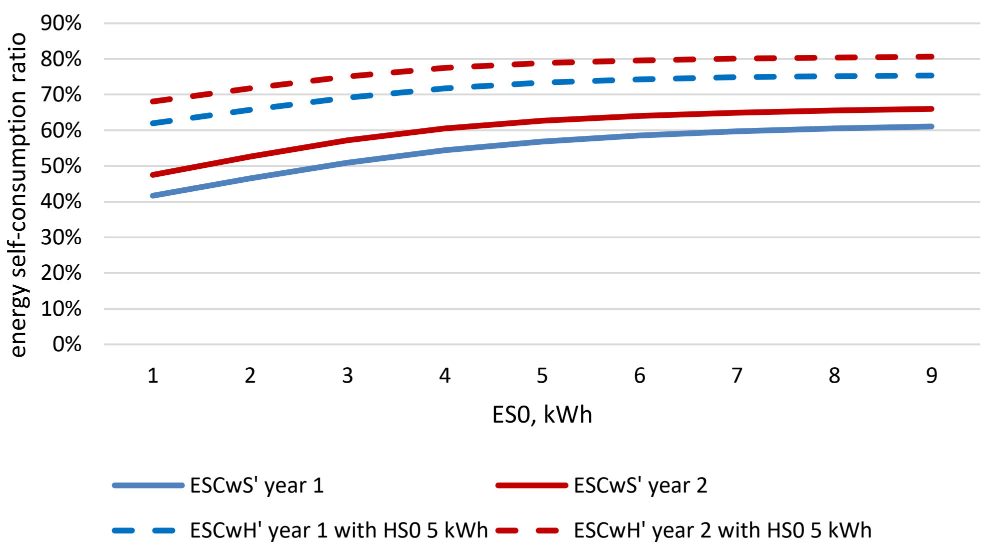

Fig. 7. Results of calculation energy self-consumption ratio for first and second year in function of the useful capacity of electricity storage

Rys. 7. Wyniki obliczeń wskaźnika własnego zużycia energii dla pierwszego i drugiego roku w funkcji użytecznej pojemności magazynów energii elektrycznej

The self-consumption coefficients were then calculated depending on the capacity of the electricity storage (from 1 to 9 kWh) and thermal energy. The results divided into two years are shown in Figure 7. The baseline values of the self-consumption ratio for the option without energy storage were: 27.1% and 30.7%.

Conclusion

A PV micro-installation was tested for the effects of using electricity storage for utility purposes and thermal energy storage for domestic hot water. For this purpose, a calculation methodology was developed to determine changes in the value of energy consumed and sent to the grid and the self-consumption coefficient as a result of the use of storage facilities. The self-consumption rate in the first year of operation of the installation (without energy storage) reached 27.1%, and in the second year, it reached 30.7%. A 3 kWh electricity storage would increase the self-consumption rate in the following years to 51 and 57.2%, and for a 6 kWh capacity 58.5 and 64.1%. Thermal energy storage with a capacity of 5 kWh for the needs of domestic hot water would increase the self-consumption rate to 69.2 and 75.1% in cooperation with electricity storage with a capacity of 3 kWh; 74.3 and 79.6% for cooperation with an electricity storage facility with a capacity of 6 kWh.

In terms of energy policy, it is worth political decision-makers considering (especially in context of subsidy) aspects related to supplementing various forms of energy storage, especially since thermal energy storage is significantly cheaper than electricity. It is also worth considering the collaboration of additional energy sources including solar collectors, and perhaps photovoltaic thermal collector, as well as heat pumps.

Further research directions include analysis of diversified domestic hot water needs over the years for heating purposes, wider range of power and storage capacities and the total efficiency of electricity and heat storage.

Nomenclature and abbreviations

Abbreviation	Definition	Unit
EC	Energy consumption	kWh
Ech	Energy charging	kWh
EPV	PV energy production value (energy photovoltaic inverter)	kWh
ER	Energy received from the grid (source: energy meter)	kWh
ERwH	Energy received from the grid with electricity and heat storage	kWh
ERwS	Energy received from the grid with storage	kWh
ES	Energy sent to the grid (source: energy meter)	kWh

*ES*0	Useful capacity of electricity storage	kWh
ESC	Energy self-consumption	kWh
ESCwH	Energy self-consumption with electricity and heat storage	kWh
ESCwH'	Percentage ratio of energy self-consumption with electricity and heat storage	%
ESCwS	Energy self-consumption with storage	kWh
ESCwS'	Percentage ratio of energy self-consumption with storage	%
ESV	Value of energy in electricity storage	kWh
ESwH	Energy sent to the grid with heat storage	kWh
ESwS	Energy sent to the grid with storage	kWh
HC	Heat consumption for domestic heat water preparation	kWh
Hch	Heat charging	kWh
HEF	Hourly Energy flow	kWh
*HS*0	Full capacity of heat storage	kWh
HSV	Value of Energy in heat storage	kWh
PV	Photovoltaic	
RES	Renewable Energy Sources	

Greek symbols

Abbreviation	Definition	Unit
τ	hour of calculation	

The Authors have no no conflicts of interest to declare.

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Analiza możliwości zwiększenia wskaźnika autokonsumpcji w przydomowej mikroinstalacji fotowoltaicznej dzięki magazynowaniu energii elektrycznej i ciepła

Streszczenie

W latach 2019–2023 w Polsce przybyło ponad milion mikroinstalacji PV. Większość z nich ma możliwość rozliczania bonifikat prosumenckich – net-metering (80% energii wysłanej do sieci wraca do użytkownika dla mocy instalacji PV do 10 kWp i 70% dla mocy od 10 do 50 kWp). Właściciele nowych mikroinstalacji PV (od 2022 r.) podlegają rozliczeniu typu net-billing, co jest niekorzystne ekonomicznie ze względu na współwystępowanie niskich cen energii i wysokiej produktywności paneli PV. Sprzyja to jednak działaniom na rzecz zwiększenia autokonsumpcji energii w prosumenckich mikroinstalacjach PV. Dlatego dla wybranej instalacji PV przeanalizowano wykorzystanie magazynowania energii elektrycznej i magazynowania energii cieplnej (na potrzeby przygotowania ciepłej wody użytkowej). Obliczenia oparto na danych z instalacji zebranych w ciągu jednego roku eksploatacji. Opracowano metodykę kalkulacji rozdziału energii na potrzeby zużycia i magazynowania energii elektrycznej i cieplnej, a tym samym szacowania wartości energii przesyłanej do sieci, uwzględniającą powyższe. Zastosowanie magazynowania energii elektrycznej i cieplnej spowodowało wzrost wartości energii zużywanej na własny użytek, przy czym współczynnik autokonsumpcji wahał się od 30 do ponad 80%.

Wskaźnik autokonsumpcji w pierwszym roku eksploatacji instalacji (bez magazynowania energii) wyniósł 27,1%, a w drugim roku 30,7%. Magazyn energii elektrycznej o pojemności 3 kWh zwiększyłby wskaźnik samozużycia w kolejnych latach do 51 i 57,2%, a dla pojemności 6 kWh odpowiednio 58,5 i 64,1%.

Słowa kluczowe: magazynowanie ciepła, magazynowanie energii elektrycznej, energetyka w Polsce, PV, wdrażanie odnawialnych źródeł energii