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Storing Electric Energy Generated by a Photovoltaic Installation to Increase Profit from Its Sale—Case Study in Poland

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Abstract: Battery systems enable the sustainable use of energy from renewable energy installations that are characterized by variable time availability. The present study investigated the benefits of implementing an electrical energy storage system to a photovoltaic (PV) installation in the Polish climatic conditions. The impact of such a system on increasing profits from energy sales was verified. The use of storage allows for shifting the process of feeding energy into the grid to later hours when it is more expensive. The production volume and timing of energy generation were considered using the example of a 5 kWp research installation located in the Laboratory of Renewable Energy. The yields and energy prices were analyzed on an hourly basis for the year 2023. The considered system is additionally equipped with a battery with a capacity of 15 kWh. Analyses have shown that this system covers 55.6% of days in a year where the entire daily production from the PV installation can be stored. Additionally, the feasibility of using different energy storage capacities to shift the sale of the maximum energy volume was examined. Also the payback period of investments was considered for four scenarios (from the most expensive devices to the cheapest ones with subsidies). Prices were compared with profits resulting from the use of storage systems of a given capacity, as well as with the lengths of warranties covering the devices.

Keywords: photovoltaic installation; energy storage system; sustainable operation

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1. Introduction

Sustainable operation of renewable energy sources is possible thanks to the use of energy storage systems. This applies to both thermal and electricity storage systems. Currently, photovoltaic installations are an integral part of Poland's power system. In recent years, there has been a dynamic increase in their numbers in Poland, which is continuously monitored in reports by the Institute of Renewable Energy [1]. This growth is a result of the country's adopted policy and subsidies for such implementations. Photovoltaic systems have also been the subject of research and analysis by numerous scientific teams worldwide for many years.

In the literature, there are studies concerning the comparative analysis of operational photovoltaic installations over the years in different locations. In 1998, Ronald J. Spiegel et al. [2] examined emission reduction and demand management from 16 photovoltaic systems installed throughout the United States between 1993 and 1994. The results presented the analysis of each PV system's ability to offset emissions of sulfur dioxide, nitrogen oxides, carbon dioxide, and particulate matter, and to provide power during peak demand hours. Johannes Schardt and Henrik te Heesen [3] evaluated data obtained from photovoltaic systems in the Netherlands, Belgium, Luxembourg, Germany, France, and Italy. They assessed the configuration and location of 32,744 rooftop photovoltaic systems during the period from 2012 to 2019. The evaluation focused on a long-term analysis of the performance ratio.

A significant portion of research focuses on economic and financial aspects, which through production forecasting or proper management of installation components' cooperation, allow for savings in the design or operation stages. Francesco Nicoletti and Piero Bevilacqua [4] addressed the topic of forecasting energy production from photovoltaic installations for the next day, which is increasingly necessary for grid operators and energy communities. The work proposed two computational models based on forward-forward neural networks that determine hourly photovoltaic production. Sergio F. Contreras et al. [5] presented a new method for managing PV micro-installations, treating them as a whole with the ability to provide system services. The authors' results demonstrate the benefits of planning methodology seen as a comprehensive problem rather than a set of independent tasks. W.C.S. Amorim et al. [6] wrote about selecting energy storage battery systems to smooth out the power from photovoltaic power plants. The case study involves a 1 MW photovoltaic system evaluated based on a yearly work profile including solar radiation intensity and ambient temperature from Goiânia, Brazil. The photovoltaic installation is connected to a 440 V grid linked to a controlled storage system that smooths out 10%/min oscillations. The selection of the storage was conducted in terms of capacity, durability, and the overdimension factor for power and energy. The proposed methodology reduces the storage volume by 57.14% compared to traditional solutions. Luwen Pan and Jiajia Chen [7] tackled the topic of virtual power plants. The research aimed to establish an acceptable pricing strategy to encourage prosumers to participate in demand response. Attention was also paid to the response and arrangement of energy storage configurations in improving sustainable development. Jingang Han et al. [8] proposed a new energy management algorithm from various energy sources. The research aimed to increase the utilization rate of power generation from photovoltaics and extend battery life, thus reducing the operating costs of the base station. The results supported by experimental data indicate a reduction in daily costs from 9.49% to 14.64% depending on the scenario. Ameer A. Kareim Al-Sahlawi et al. [9] conducted simulations for optimizing a hybrid energy system consisting of photovoltaic/wind/battery with an electric vehicle charging station using V2G technology in a grid-connected system. The strategy proposed by the authors for energy management based on rules serves to control and observe the proposed power flow in the system. Jinchao Li et al. [10] proposed shared energy storage as a new form of energy storage. The idea is characterized by flexibility of use and high speed utilization. The article focused on the configuration, operation, and economic benefits of shared storage with photovoltaic installations. The results show that the cost of electricity decreased by 17.16% compared to systems without storage.

The review presented indicates that electric energy storage systems are becoming an essential component of Renewable Energy Source (RES) systems both in Europe and worldwide. They help partially solve issues with the unstable operation of the power grid and enable increasing the profitability of RES exploitation by shifting the time of energy consumption or introducing it into the power grid. The current regulations in Poland allow for the resale of produced electric energy, including under a tariff dedicated to prosumers. Prosumers are entities that produce and consume electric energy for their own needs (individuals, schools, churches, cooperatives, and housing communities). The current form of settlements known as net-billing applies to all prosumer RES installations with an installed capacity not exceeding 50 kW, which were connected to the grid after 31 March 2022. The implementation of the existing rules stems from the provisions of Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019, on common rules for the internal market in electricity and amending Directive 2012/27/EU. Additionally, the provisions of Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018, on the promotion of the use of energy from renewable sources (RED II) oblige member states to allow prosumers to sell the energy they produce at rates corresponding to the market price of electric energy. All EU member states are obligated to implement these regulations, aiming to harmonize the European market and enable end consumers to directly participate in the energy market, as well as to benefit financially from selling the electric energy they produce.

Net-billing is a system of valuable prosumer settlements (Figure 1). It is based on selling electric energy at market rates derived from the Day-Ahead Market (DAM). The profit from selling electric energy is transferred to the prosumer's account, called the "prosumer deposit", from which the bill for the energy consumed (purchased) from the grid is then paid (without the possibility of settling distribution costs and fixed costs). Funds can be settled for a maximum of 12 months from the moment they are credited to the prosumer's account. Money that is not used within the 12-month period will be returned to the prosumer, with the condition that it will not exceed 20% of the value of the electric energy sold in a given calendar month.

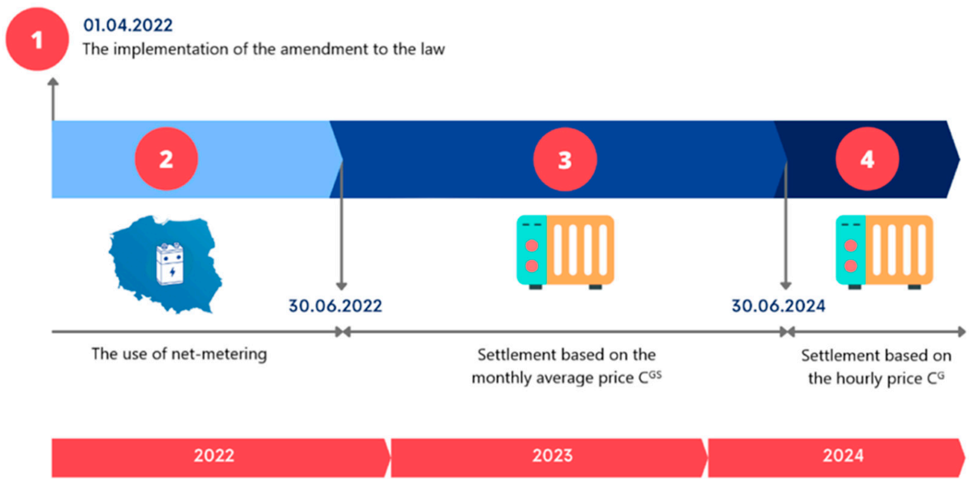


Figure 1. Stages of introducing the net-billing system in Poland [11].

Excluding the transitional period (from 1 April 2022, to 30 June 2022), which aimed to practically implement solutions enabling the use of the net-billing tariff, it can be stated that in Poland, this form of settlement has been mandatory since 1 July 2022. Until mid-2024, the rate at which the prosumer sells electricity in a given month is determined as the averaged value of the market prices applicable in the previous month. This means that the timing of introducing energy into the power grid does not affect the profit from sales. Therefore, the use of an energy storage system during this period will not translate into increased profit from selling electricity.

From 1 July 2024 onward, the settlement system will take the form of dynamic tariffs and the sale of electricity at hourly rates. The energy taken from and fed into the grid will be balanced for each hour using the vector method. The difference between the energy consumed and supplied will be determined for each hour, indicating how much energy has been ultimately sold (or bought) without distribution charges.

The aim of the study is to analyze the profitability of implementing an energy storage system within the framework of the hourly settlement-based net-billing tariff. Taking into account the intended form of the settlement system, the extent to which the use of energy storage can increase profits from energy sales during hours when the PV installation is not operating is verified. Knowledge of the continuous changes in energy values will help prosumers manage their energy production consciously and enable increased profits from operating a hybrid installation (photovoltaic installation with energy storage operating in on-grid mode). An additional goal of the study is to determine the optimal capacity of the storage system based on the daily energy production from the PV installation.

2. Description of the Research Position

The research was conducted at an installation located at the Wrocław University of Science and Technology on the roof of building L1, belonging to the Laboratory of

Renewable Energy. The installation consists of 16 different photovoltaic modules with a total capacity of 5 kWp connected to power optimizers, and then to a 5 kW hybrid inverter and a 15 kWh energy storage system. Figure 2 illustrates the climatic conditions prevailing in Wrocław using meteorological data for a Typical Meteorological Year for the local weather station. The chart was prepared based on ministerial data used for energy calculations of buildings [12].

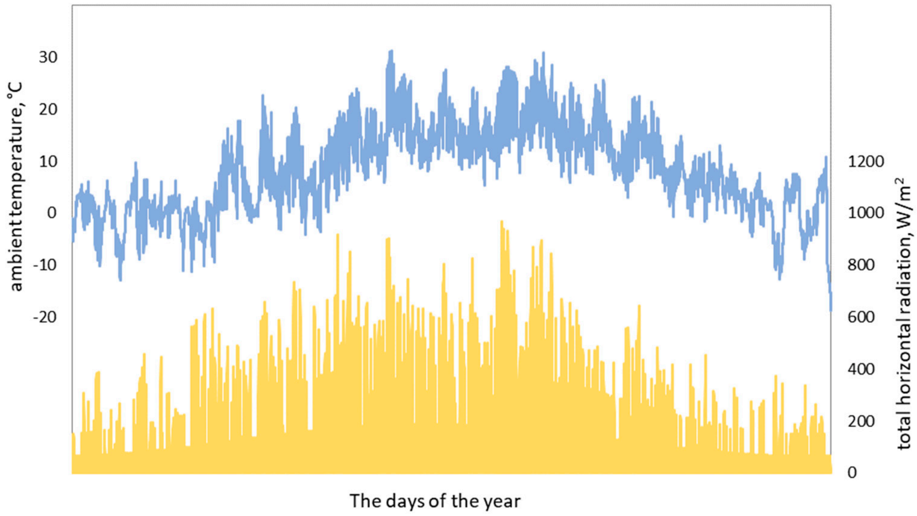


Figure 2. Adopted meteorological conditions TMY Wrocław, Poland (based on [12]).

The analyzed photovoltaic modules are mounted on a concrete structure on a flat roof (Figure 3). The azimuth of the installation is southwest at 210°, and the tilt angle is 15°.

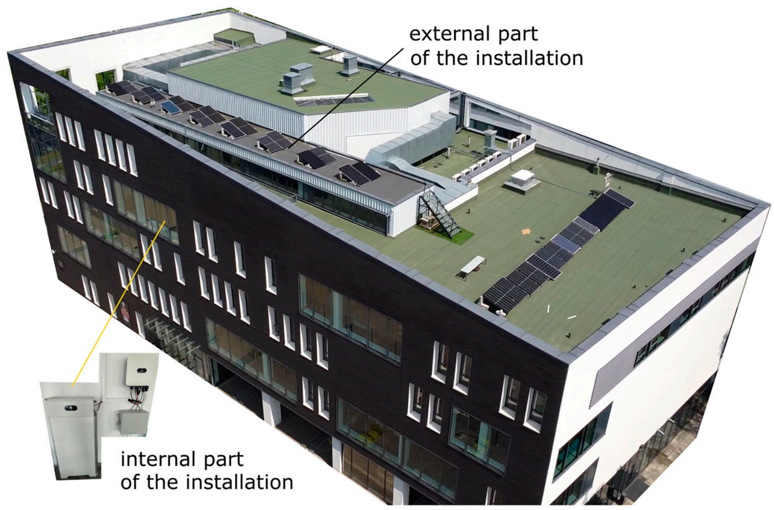


Figure 3. Analyzed photovoltaic installation in Renewable Energy Laboratory.

In Figure 4, the schematic of the research setup is presented, including electrical connections, communication cables, and data transmission via Wi-Fi network.

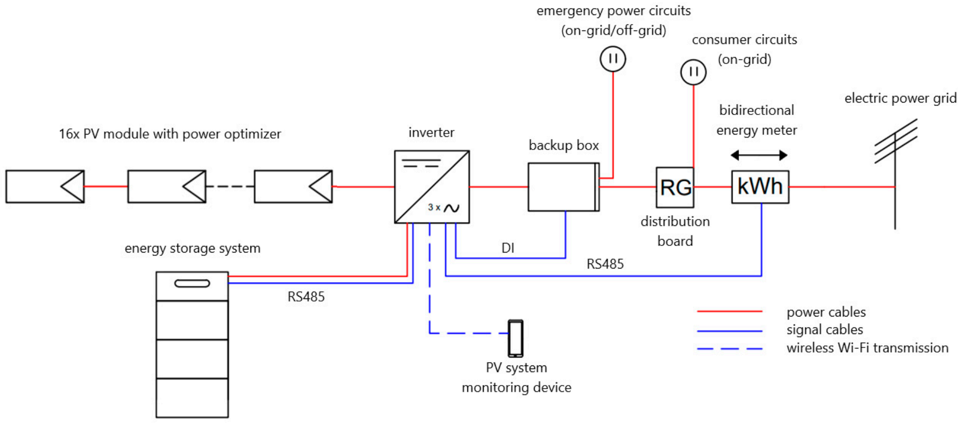


Figure 4. Schematic of the research setup.

Due to the incomplete year of operation of the photovoltaic installation, data from the PV SOL Premium 2023 R3 software package were used for analysis. Presented below are the monthly production from the installation and the simulation results (Table 1 and Figure 5).

Table 1. Monthly energy production—measured and projected data.

Month	PV SOL, kWh	Measurement Data, kWh	Deviation, %
1	155	-	-
2	223	-	-
3	425	-	-
4	685	645	5.79
5	732	720	1.69
6	755	764	1.13
7	761	756	0.66
8	625	639	2.31
9	494	560	13.48
10	310	287	7.36
11	173	159	8.30
12	101	98	3.05
Yearly	5439	-	-
Total (Months 4–12 excluding 9)	4142	4068	1.80

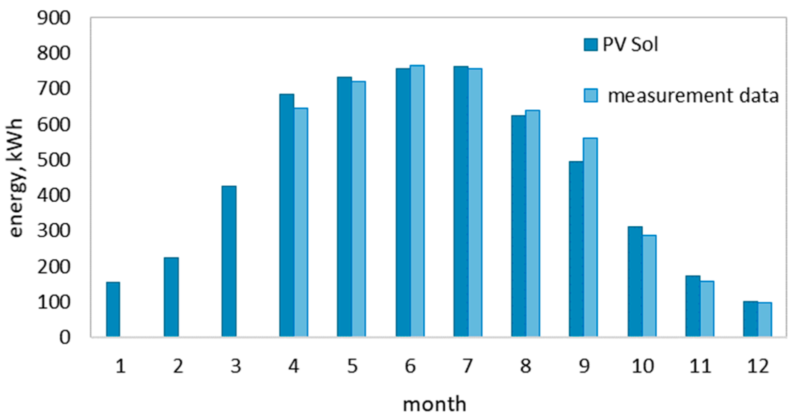


Figure 5. Graph depicting energy production from the 5 kWp photovoltaic installation for actual and theoretical data.

Analyzing the data reveals discrepancies between actual and projected values. Therefore, to validate the results, Equation (1) was used, which describes the deviation of energy production values obtained from the software in relation to the values obtained in the experiments:

$$\delta x = \frac{|x - x_0|}{x} \cdot 100\%, \quad (1)$$

where the following are defined:

δx—deviation of energy production, %;
x—calculated value (from PV SOL Premium), kWh;
x_0—experimental data from PV installations, kWh.

The largest discrepancies are observed in months with low production, where the deviation varies by several percent in favor of the projected values (Figure 6). However, particular attention should be paid to the month of September, where the deviation is the greatest, reaching 13% in favor of actual production. This is due to a weather anomaly. As reported by the State Research Institute—Institute of Meteorology and Water Management—the average air temperature in September 2023 in Poland was 17.7 °C, which was 3.9 degrees higher than the long-term average (1991–2020) for this month. This month was extremely warm in terms of temperature in every region of the country [13]. Therefore, it was omitted from comprehensive analyses. After summing up the energy from production and calculated data, a deviation below 2% was found. With such a small difference, it was concluded that the use of theoretical data in further analysis is justified and accurately reflects the actual operation of the installation.

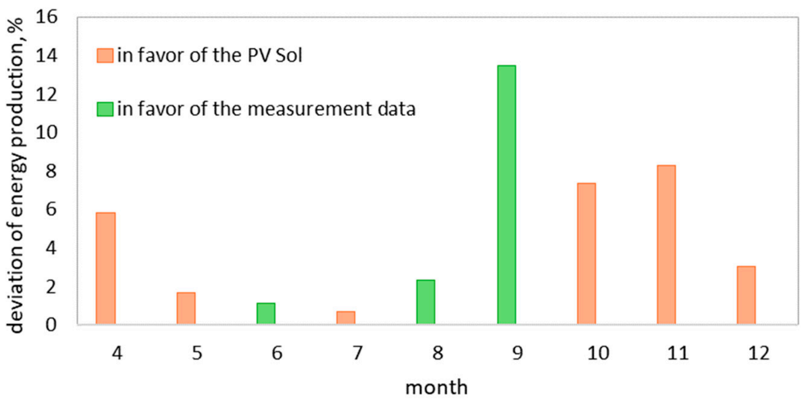


Figure 6. Percentage deviation between actual energy production and calculated.

3. Results

Electricity production from the PV installation was compared hour by hour with the market electricity prices (MEP) [14]. In the first scenario, the installation operated without an energy storage system, feeding all produced energy into the power grid and selling it at current hourly rates. In the second scenario, the photovoltaic inverter cooperated with an energy storage system, allowing the sale of energy to be shifted to the evening hours. During this part of the day, energy prices are highest for most of the year. Figure 7 presents the averaged energy prices throughout a day for September and October 2023, based on the monthly report from the Commodity Energy Exchange. The charts show a significant disparity in prices, especially when comparing afternoon hours with morning and evening hours. Based on data from the National Bank of Poland (NBP), all amounts were converted to Euros using an exchange rate of 1 EUR = 4.3191 PLN [15].

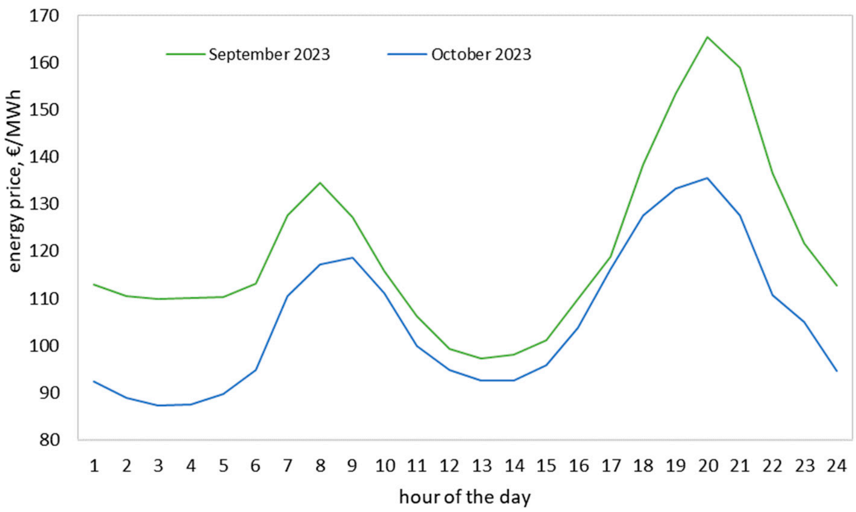


Figure 7. The average daily energy prices for September and October 2023 "Weighted average prices for particular hours" [16].

The main parameters that affect the amount of energy sold are the capacity and power of the energy storage system, as well as the power of the inverter. Too low power limits the ability to charge the storage system during peak PV system operation and to discharge stored energy during peak electricity prices. In this study, both the inverter and the energy storage system were assumed to have a power level of 5 kW. During evening sales, it was possible to send a maximum of 5 kWh of energy to the grid every hour.

In practice, the parameters of the power grid are equally important. The rapid development of the photovoltaic sector in Poland in recent years has led to the connection of systems with high peak power to the grid. There are currently over 1.3 million micro-installations (installed capacity up to 50 kWp). Depending on the region, sunny days may lead to problems with available transmission capacity and increased voltage in the grid, which is a result of introducing energy from many connected RESs at the same time. Problems most commonly occur in the hours before noon and in the afternoon when a large amount of generated energy enters the electrical installation of the facility, and there is a lack of sufficient self-consumption. The use of an energy storage system reduces losses resulting from inappropriate grid parameters for the operation of the inverter.

In the following charts (Figure 8), monthly energy prices at each hour of the day are presented. In all months, significant dynamics of changes within individual hours can be observed.

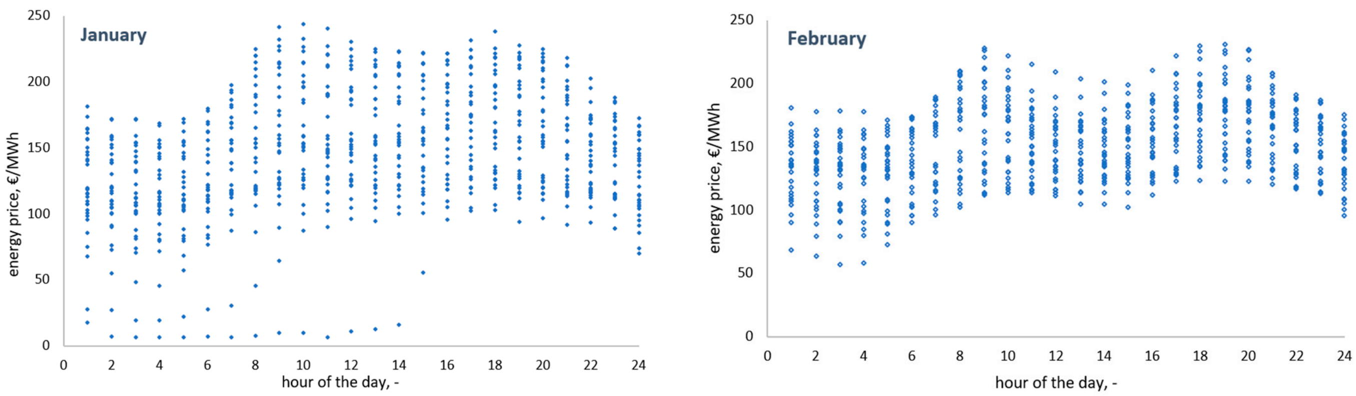
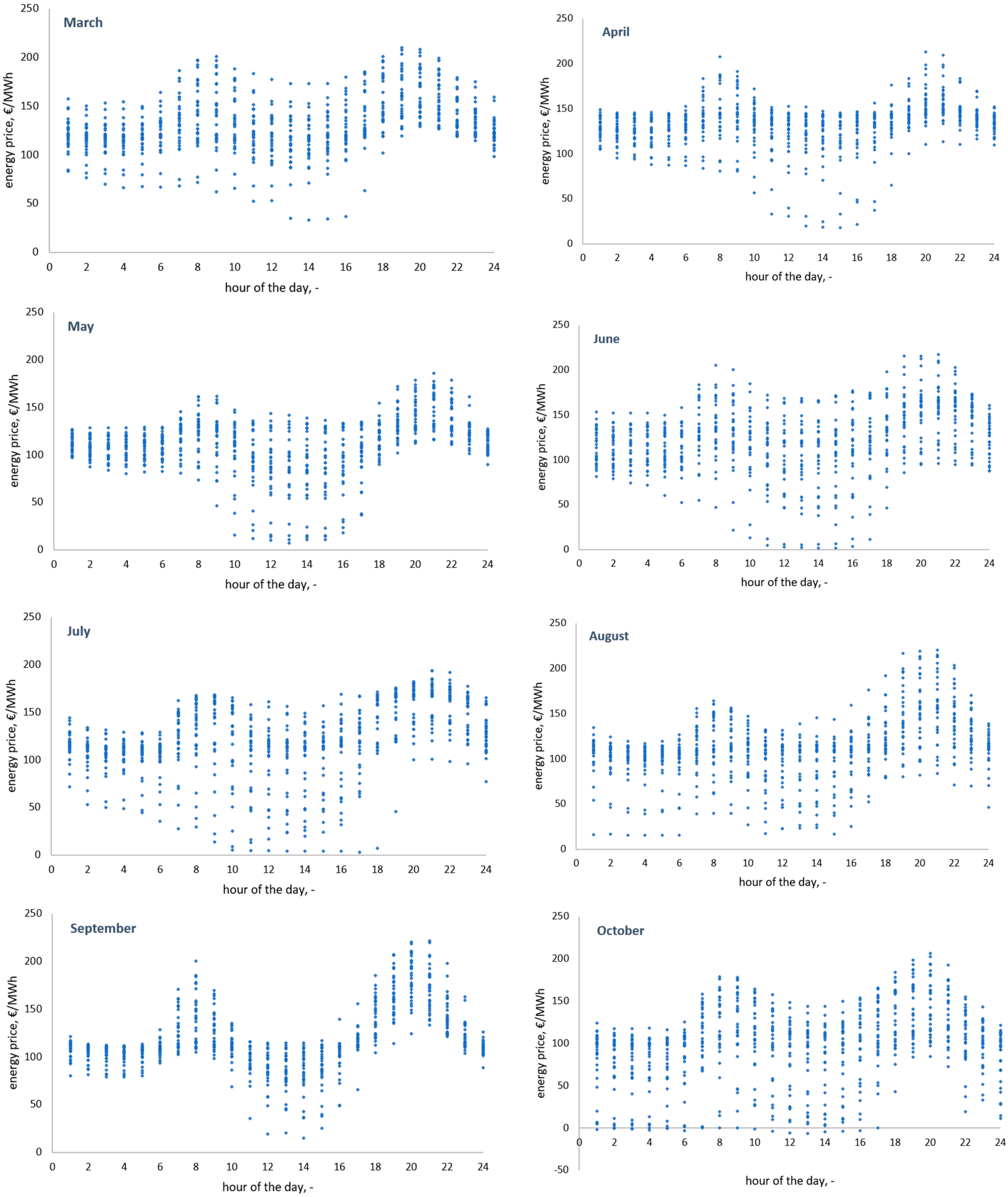


Figure 8. *Cont.*



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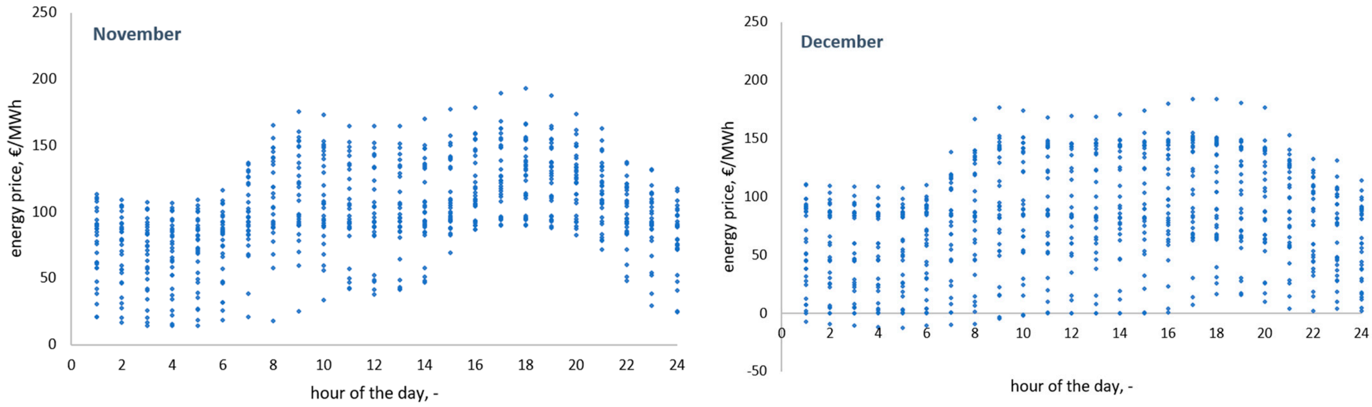

Figure 8. Hourly changes in energy prices over the course of the year (based on [17]).

The comparison of hourly prices shows that the value of energy changes throughout the day by even several hundred percent, sometimes reaching prices around PLN 0. In the case of negative prices in the settlement of sales, PLN 0 was adopted in accordance with the RESs Act (Article 4b, point 7).

The lowest prices usually occur during nighttime and afternoon hours, while the highest values are observed in the morning and evening hours. This is particularly noticeable during the summer months. This period also corresponds to the highest efficiency of the PV installation. Statistically, production from April to September accounts for up to 70–75% of the annual yield. Figure 9 shows the share of energy yields from the research installation in individual months compared to the annual yield.

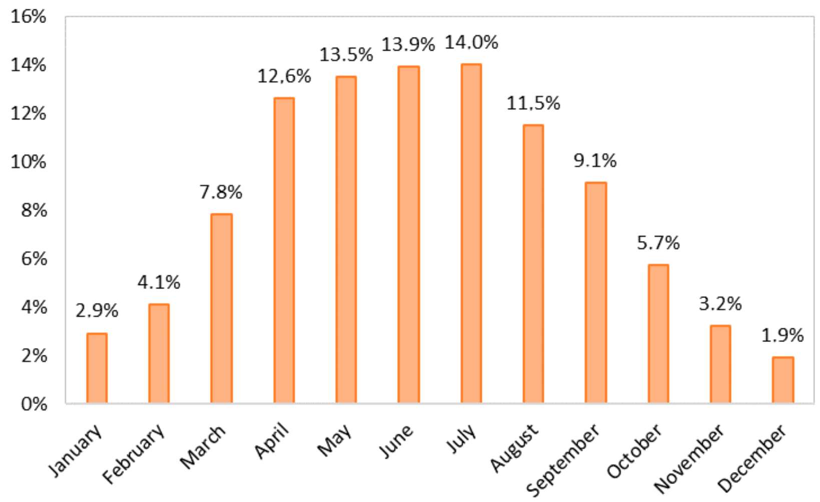

Figure 9. Share of monthly yield in annual production—research installation.

In the discussed case, during the period from March to October (8 months), 88% of the annual energy production was achieved. This disproportion shows that energy prices during the summer period will have a significant impact on the profits from sales.

Figure 10 presents a comparison of hourly energy prices with the production profile from the research installation. The maximum production achieved during the afternoon hours coincides with the time when energy prices are among the lowest during the day.

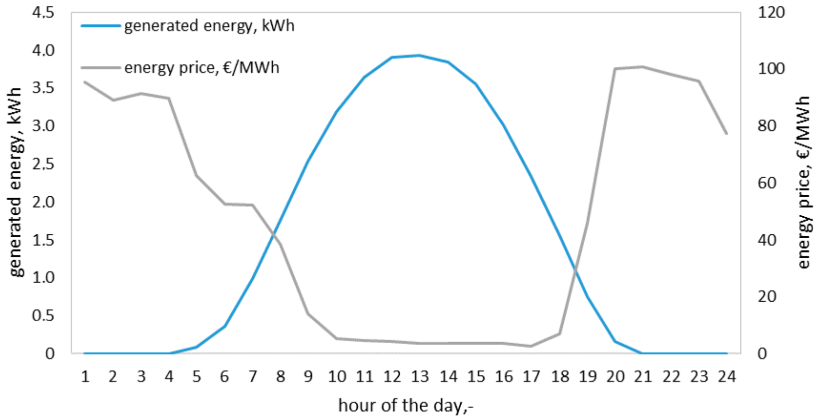

Figure 10. Hourly energy price comparison with production from the research installation for 2 July 2023.

The chart presents an example for a Sunday in July (Figure 10), where two factors influence the energy price. Of course, energy prices do not always reach such low values as those shown in Figure 10. Firstly, during weekends, the demand for energy across the country is lower than on weekdays. Secondly, in the summer period, there is an increased production from RES installations, resulting in a decrease in electricity prices on the exchanges. Despite this, the trend of increasing prices in the evening hours is noticeable for most of the year.

In Table 2, the profit from selling energy directly during the operation of the research installation is compared with the profit generated by shifting sales to the evening hours. It can be noticed that such a scheme of energy storage operation will bring benefits each month. A graphical interpretation is shown in Figure 11.

Table 2. Comparison of profit from energy sales for both scenarios of the research installation operation.

	Profit without Energy Storage, EUR	**Profit with Energy Storage, EUR**	**Profit Increase, EUR**	**Profit Increase, %**
January	27.80	29.14	1.35	4.86
February	34.03	39.78	5.74	16.87
March	50.29	66.16	15.87	31.56
April	85.01	102.39	17.39	20.46
May	73.69	101.25	27.56	37.40
June	86.56	113.90	27.34	31.59
July	79.92	115.76	35.85	44.86
August	63.34	90.63	27.29	43.08
September	47.70	80.06	32.36	67.84
October	30.28	45.28	15.00	49.54
November	17.83	22.58	4.74	26.58
December	10.37	11.33	0.96	9.26
Total	606.82	818.27	211.45	34.85

On an annual scale, the profit from direct sales amounted to EUR 606.82, while after shifting sales to the evening hours, it increased by EUR 211.45 (34.85%), reaching a total of EUR 818.27. The highest percentage increase was recorded in September (67.84%), while the lowest was in January (4.86%). By way of financial comparison, July performed the best, with an increase of EUR 35.85, while December performed the worst, with an increase of only EUR 0.96.

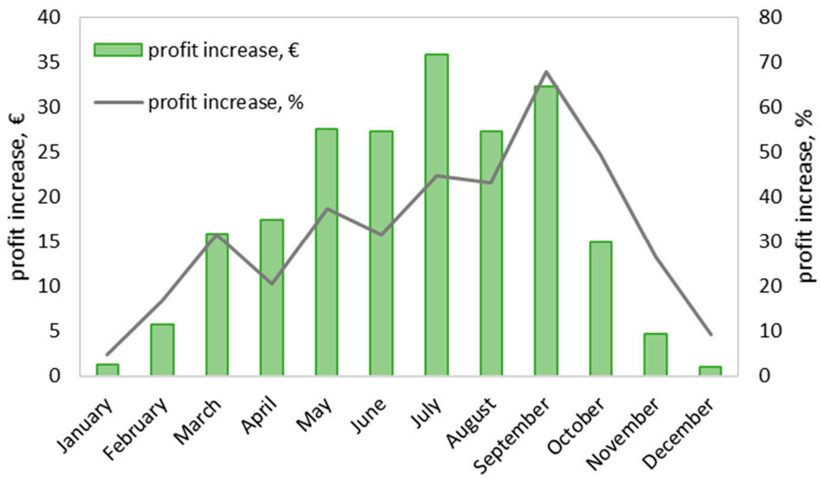

Figure 11. Increase in profit expressed in PLN and as a percentage for each month.

It is also worth analyzing the eight best months (from March to October—88% of annual production). During this period, the profit in the first scenario amounted to EUR 516.79, and in the second scenario EUR 715.43. The use of the energy storage system will increase the profit by EUR 198.64 (38.44%). This represents 93.95% of the total annual profit increase resulting from shifting sales to the evening hours. In the case of the four weakest months, due to minimal energy production and smaller price differentials throughout the day, the use of energy storage will bring only symbolic benefits amounting to EUR 12.79 (14.21%).

In the summer months, the possibility of transferring daily production to the evening hours will require having a large energy storage system. On the most sunny days, energy production from the research installation reached values in the range of 35–40 kWh. Such significant over-sizing of the energy storage capacity does not find financial reflection. Expanding the energy storage system involves a fixed cost (dependent on the price of the battery module), but each additional capacity will be needed for an increasingly smaller part of the year. In order to select the most optimal energy storage capacity for a 5 kWp installation, the daily production was classified. Table 3 presents the frequency of daily production occurrences with a division every 5 kWh. On no day did the daily energy production exceed 40 kWh.

Table 3. Frequency of daily energy production occurrences in a given range.

Daily Production	Number of Days in a Year
<5 kWh	73
5–10 kWh	72
10–15 kWh	58
15–20 kWh	43
20–25 kWh	39
25–30 kWh	40
30–35 kWh	27
35–40 kWh	13

Table 4 shows how increasing the energy storage capacity increases the number of days on which it was possible to store daily production. Choosing a capacity ranging from 5 kWh to 15 kWh allows a level of coverage ranging from 20% to 55.6% of days in the year.

Table 4. Energy storage capacity enabling the accumulation of daily production.

Energy Storage Capacity, kWh	Part of the Year When It Was Possible to Accumulate Daily Production, %	Increase, %
5 kWh	20.0%	-
10 kWh	39.7%	98.6%
15 kWh	55.6%	40.0%
20 kWh	67.4%	21.2%
25 kWh	78.1%	15.9%
30 kWh	89.0%	14.0%
35 kWh	96.4%	8.3%
40 kWh	100.0%	3.7%

In order to verify the payback period, the profit from energy sales was compared with the prices of energy storage systems. Four price variants were adopted based on the current average prices of sets (BMS + energy storage) from various manufacturers available on the Polish market. The prices are presented in Table 5.

Table 5. Average prices of energy storage sets (BMS + energy storage).

Price Range	Price PLN/EUR
High Price	3000/694.59
Average Price	1800/416.75
Low Price	1000/231.53
Low Price with 50% Subsidy	500/115.76

Given the development of the energy storage market in recent years, subsidy programs have been launched in Poland, which can significantly reduce the payback period of investments. Therefore, as the fourth variant, the price of the energy storage set with a 50% subsidy was adopted. The payback periods of the investment are shown in Figure 12.

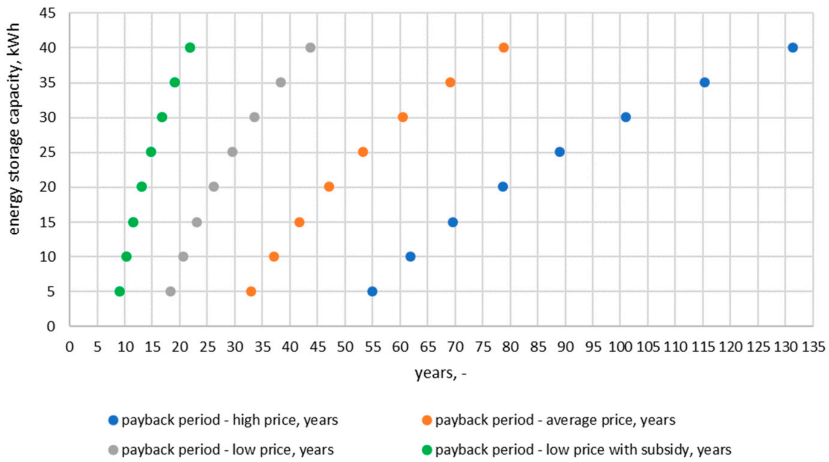

Figure 12. Payback period of energy storage investments depending on their price.

The results indicate a significant disparity depending on the price and capacity of the energy storage system. Given the current prices of energy and storage sets, the application of the discussed solution to increase profit from sales is, in most cases, not economically justified. The payback periods significantly exceed the warranty periods of the devices, which are typically between 10 and 15 years or 5000–6000 charge/discharge cycles. Only in the case of the cheapest sets and with a 50% subsidy does the payback period approach the warranty period. It should be noted that the shortest payback periods are for storage systems with the smallest capacities. However, considering additional factors, the payback periods may be extended, further diminishing the feasibility of these investments. These factors include the Depth of Discharge (DoD), which is less than the total capacity of the energy storage system and typically amounts to a maximum of 80–90% of the total capacity. This means that the usable capacity is not equal to the total capacity. Another factor is the loss of capacity of the energy storage system due to natural processes resulting from the usage of the device. These factors contribute to a reduction in the volume of energy that can be sold.

Assuming that the increase in the price of the energy storage system is linear and that with each increase in capacity, the price rises by 100% of the base price, for the energy storage system in the considered configuration to be profitable, the profit from using a device with greater capacity should also increase by at least 100%. This is not possible due to the insufficient yields of the considered 5 kWp research installation. Depending on the capacity of the storage system, the increase in the amount of stored energy and the increase in profit from sales compared to an installation without energy storage are shown in Figure 13.

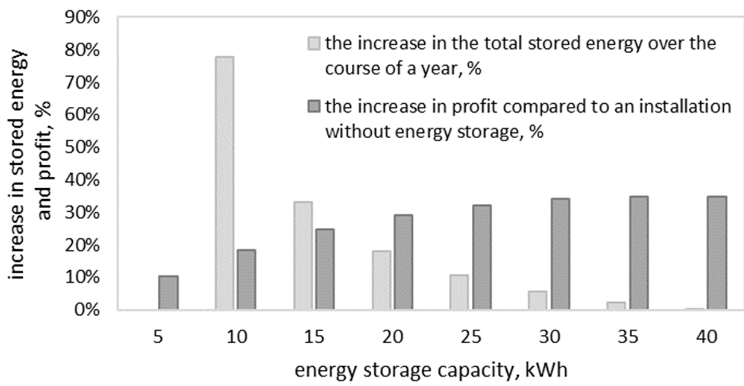

Figure 13. Percentage increase in the total storable energy and profit from energy sales depending on the capacity of the energy storage system.

As can be observed, the increases are far from values that would justify increasing the capacity of the devices.

4. Conclusions

The article analyzed the operation of a photovoltaic installation located in the Laboratory of Renewable Energy in Wrocław, Poland. The results obtained show that the use of energy storage as a means to shift energy sales undoubtedly translates into increased profit. This is evident in every month of the year. In the case of the four weakest months, due to minimal energy production and smaller price differentials throughout the day, the use of energy storage will bring only symbolic benefits amounting to EUR 12.79 (14.21%). To achieve maximum profit growth, the focus should mainly be on the warmer months, which are characterized by high availability of solar radiation energy.

Adapting the energy storage capacity to the 5 kWp research installation took into account the daily energy production. The results show that the greatest benefit will be brought by a capacity ranging from 5 to 15 kWh. Larger capacities often will not be utilized due to insufficient daily production.

It should be noted that the most profitable way to operate a PV system with energy storage is to maximize the consumption of electricity directly in the facility (self-consumption). The savings resulting from using the produced energy are greater than the profit from its sale, influenced by two factors: first, the amount at which the prosumer sells energy is lower than the purchase price; second, the cost of distribution is added to the purchase price of energy. In daily use, it is important for the prosumer to try to use the produced electricity for their own needs first, and only secondarily to direct it to the grid for sale.

After conducting an analysis that takes into account the costs of energy storage systems, a slight profitability of the discussed form of system operation (shifting the time of energy sales to the evening hours) can be observed. At present, this is only advantageous for the variant considering the smallest battery capacities and a financially supported system (subsidy). The main factor that can increase the profitability of the investment is the reduction in the cost of energy storage systems. This is quite possible in the coming years.

In their future work, the authors plan to conduct a broader analysis of energy storage operating modes that will include self-consumption. It is worth verifying the different energy consumption profiles occurring in facilities with varying energy demands. It will be important to compare the profits presented in the current analysis with the benefits derived from meeting energy demand both in real-time (PV installation without energy storage) and during periods when the PV system does not supply energy (PV installation with energy storage). Additionally, a significant factor will be the inclusion of dynamic energy purchase prices, which will come into effect in Poland in the coming months. As a result, the prices of energy drawn from the grid will change every 15 min. This will enable the recharging of energy storage with cheap energy, especially during the winter period when the PV installation generates negligible yields.

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