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Developing an energy storage systems selection methodology for peak shaving purposes in photovoltaic micro-installations

Anna Pirogowicz[1]
Piotr Olczak[2+]

[1,2]*Mineral and Energy Economy Research Institute, Polish Academy of Sciences, 7A Wybickiego St., 31-261, Cracow, Poland.*
[1]*Email: olczak@min-pan.krakow.pl*
[2]*Email: annapir@student.agh.edu.pl*

(+ Corresponding author)

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ABSTRACT

This study investigates the selection methodology for peak shaving purposes in photovoltaic micro-installations. Due to the increasing share of photovoltaic micro-installations in the national electricity production and the consequent changes in the country's energy policy, the need for energy storage is becoming increasingly apparent. Therefore, based on data collected throughout the study of a photovoltaic installation conducted in years 2020-2024 and data on market electricity prices, the correlation between production, market electricity prices, and energy value was analyzed. The analysis established interconnections between these values and identified factors influencing their changes. It was observed that the market price of electricity is relatively low during hours of increased photovoltaic energy production. By comparing the correlations between energy production and electricity prices over different years, an increasing impact of the increasing share of photovoltaic energy production in national electricity production on the market price of electricity was noted, highlighting the importance of energy storage. For the described household, an energy storage system was selected with a view to meeting the energy demand during hours of higher market electricity prices. The selected model was Lithium-Iron-Phosphate battery with a capacity of 5 kWh. Furthermore, the cost effectiveness of household-scale energy storage systems was examined. Implementing the proposed solutions could result in increased auto-consumption and presumably improve cost-effectiveness of photovoltaic installations in the future.

Contribution/Originality: The research assessed the validity of implementing energy storage systems for household photovoltaics through analysing the influence of various factors.

1. INTRODUCTION

Both in Poland and in other countries, an increasing number of households are opting to install residential renewable energy systems. In the case of grid-connected on-grid photovoltaic (PV) systems, it involves local transmission systems as well as energy settlement.

There are variety of energy settlement methods. The first analyzed criterion used for dividing these methods is the compensation time. If the existing mechanisms compensate for energy production and consumption in real-time (or up to 15 minutes), we refer to it as "self-consumption," whereby all the energy produced by the consumer is immediately consumed by them. If compensation occurs over a longer period, such system is called "net-metering." This system treats the grid as a sort of energy storage, allowing the prosumer to retrieve 0.8 kWh from the grid for every 1 kWh they send to the grid if their installation is up to 10 kW or 0.7 kWh if their installation is between 10 kW and 50 kW (Trela & Dubel, 2021).

The profitability of self-consumption varies by country. For instance, in France, self-consumption is not profitable due to low market electricity prices. Low electricity prices make both the production of energy for personal use and its sale unprofitable. In Germany, photovoltaic installations operate on a guaranteed tariff and self-consumption basis. Selling energy to other users is not possible (Ciocia, Ahmad, Chicco, Di Leo, & Spertino, 2016).

Another method is energy settling based on energy monetary value, known as "net billing." Energy value equals the value of energy production multiplied by electricity price.

The shift in energy settlement method from net-metering to net-billing aimed to encourage prosumers to store produced energy independently (Dzikuć et al., 2021; Mirowski & Sornek, 2015; Rokicki et al., 2022; Trela & Dubel, 2021). Therefore, it is essential to consider the profitability of implementing this solution in micro-photovoltaic installations, taking into account various factors such as the cost of purchasing and installing storage, the wear and tear of energy storage, the optimization of its use (discharging to a certain depth to extend the battery set's lifespan (Lis, Szul, Krilek, Melicherčík, & Kuvik, 2022), market electricity prices, and energy consumption.

Unfortunately, the profitability of energy storage is greater for large-scale solutions than for small-scale ones, such as individual households. For this reason, the benefits derived from energy storage may turn out to be less than the investment cost (Berrada, Loudiyi, & Zorkani, 2017).

2. OBJECT OF RESEARCH

The object of research is a PV micro-installation studied in the articles by Kazanecka and Olczak (2023) and Olczak and Komorowska (2021) located in the village of Łęki in southern Poland. The installation consists of 14 monocrystalline Longhi HPH360 panels, whose total capacity equals 5.04 kWp, mounted on the roof of a residential building with a southeast orientation.

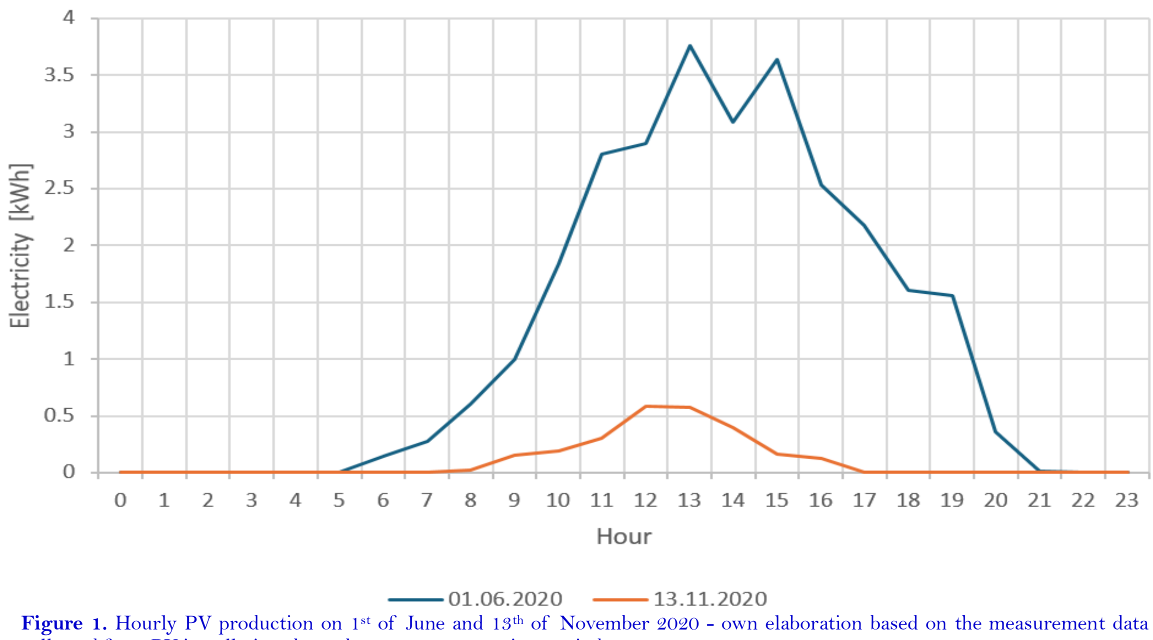

Figure 1. Hourly PV production on 1st of June and 13th of November 2020 - own elaboration based on the measurement data collected from PV installation throughout 2020 – 2024 time period.

3. MATERIALS AND METHODS

3.1. PV Energy Production

Figure 1, suggests that afternoon hours produce the highest amounts of energy due to increased sunlight and the southeast orientation pf the photovoltaic panel. Sunlight intensity varies depending on the month, being highest in the summer months and lowest in the winter months. This results in lower energy production in November compared to June.

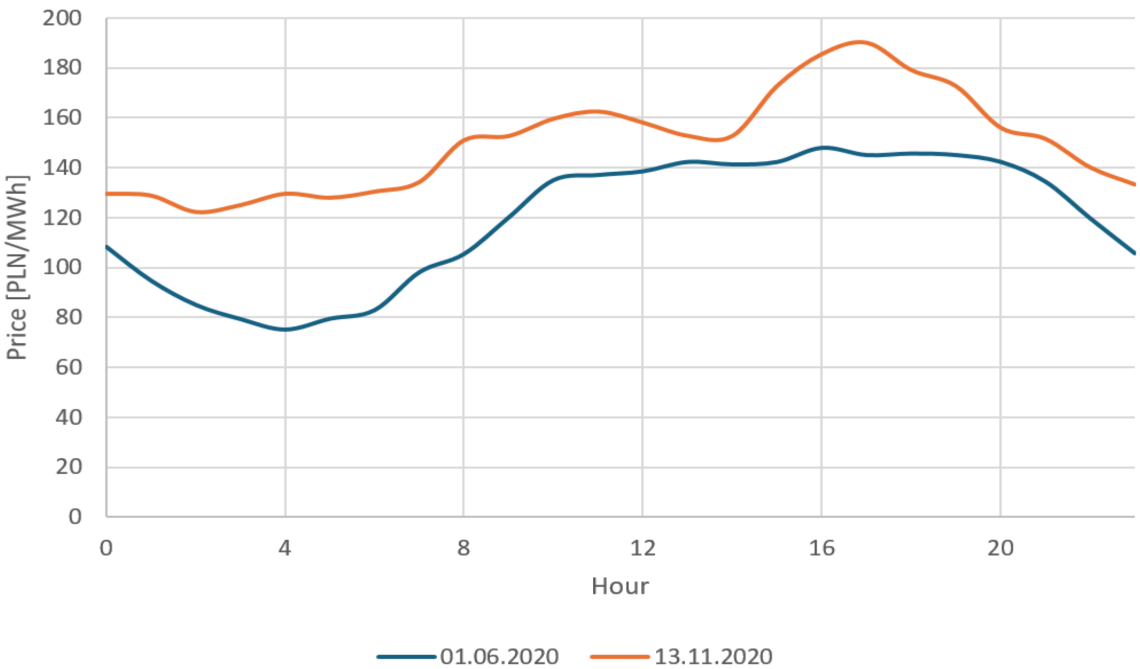

Figure 2. Market electricity prices on 1st of June (Friday) and 13th of November (Friday) 2020 - own elaboration based on market electricity prices data in 2020.

3.2. Market Electricity Prices

As shown in Figure 2, the price of electricity changes throughout the day. On days with higher photovoltaic energy production, the market electricity price is highest during the hours of the highest energy production (desirable for PV installation owners'). Hourly prices differ depending on the day. On days with lower photovoltaic energy production, the price of electricity increases with the increase in average consumer demand.

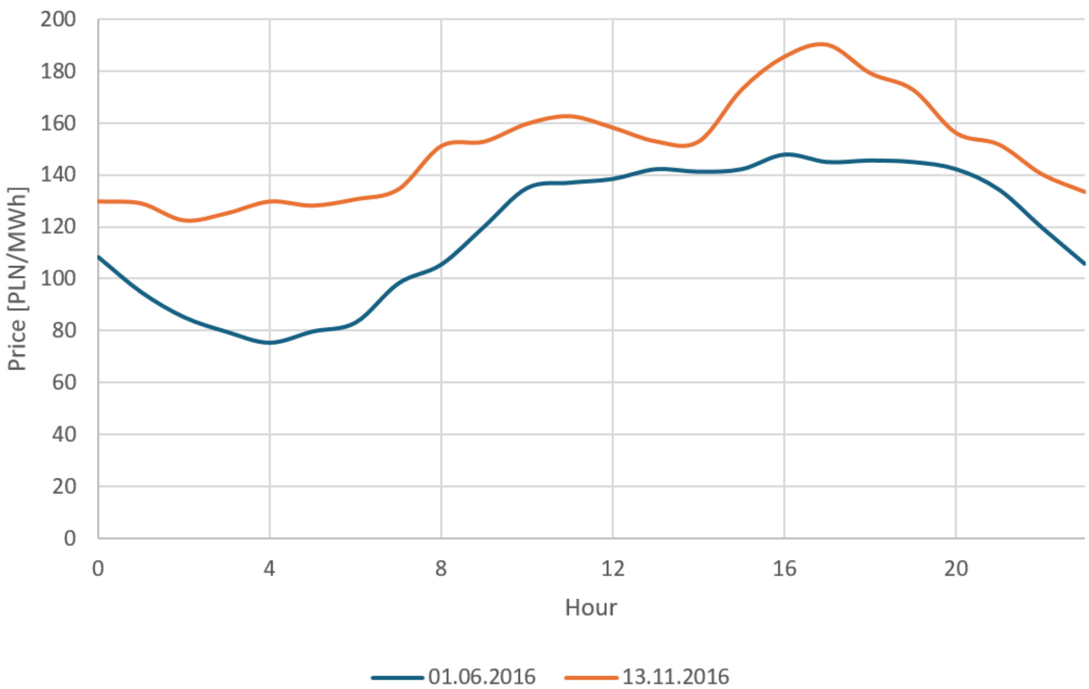

Figure 3. Market electricity prices on 1st of June (Wednesday) and 13th of November (Sunday) 2016 - own elaboration based on market electricity prices data in 2016.

Comparing Figures 2 and 3, it can be observed that the hourly price profiles differ. Recent years have seen an increase in the share of energy production from photovoltaic installations in the national energy mix. Due to these changes, the profitability of photovoltaics has increased (also due to the decrease in Levelized Cost of Electricity (LCOE) value (Nieto-Diaz, 2022) leading to the decision to invest in a PV installation for the described household in 2020.

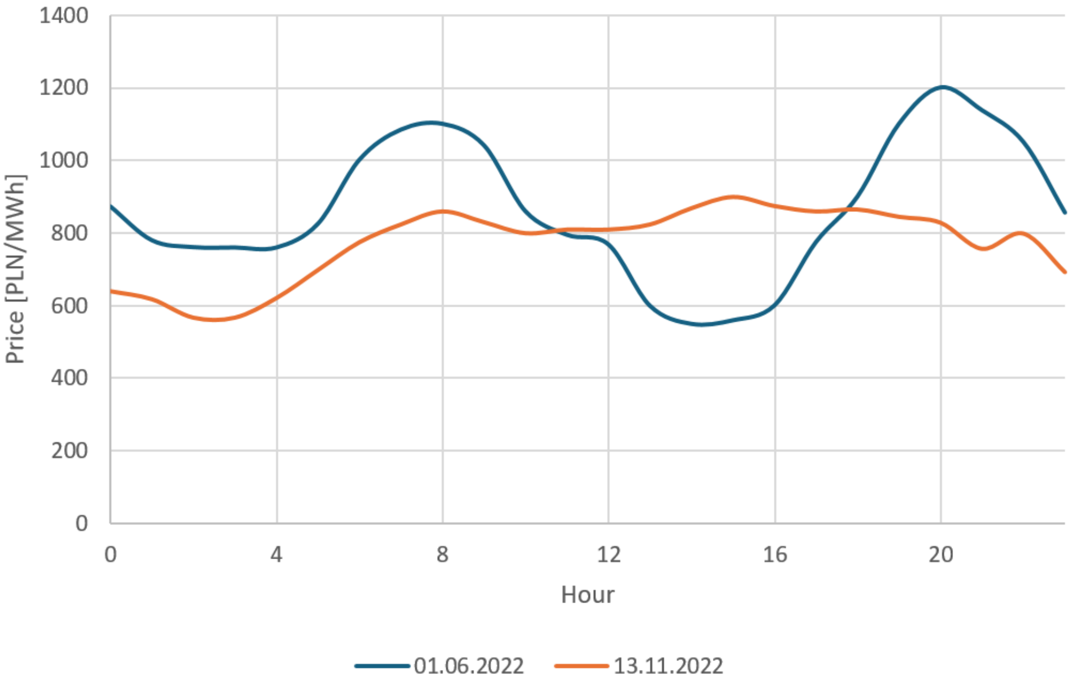

Figure 4. Market electricity prices on 1st of June (Wednesday) and 13th of November (Sunday) 2022 - own elaboration based on market electricity prices data in 2022.

Figure 4 illustrates the real impact of PV energy production on market electricity prices. Energy storage during days of higher photovoltaic energy production has become more profitable due to higher prices during hours of lower (or non-zero) photovoltaic energy production. It is linked to the increased share of photovoltaics' production in the country's energy mix.

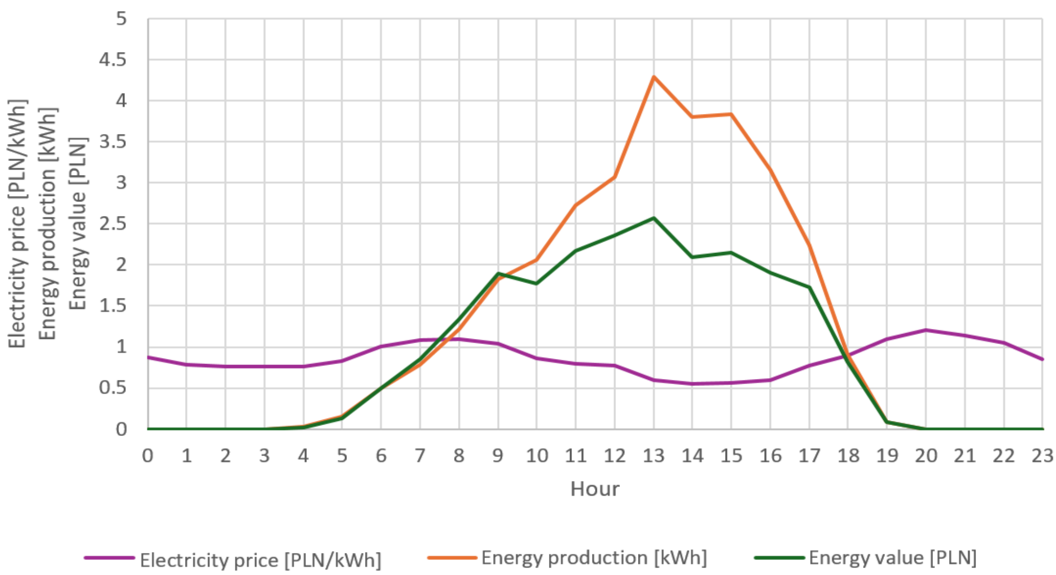

Figure 5. Market electricity prices, energy production and energy value on 01.06.2022 – own elaboration based on the measurement data collected from PV installation throughout 2020 – 2024 time period and market electricity prices in 2022.

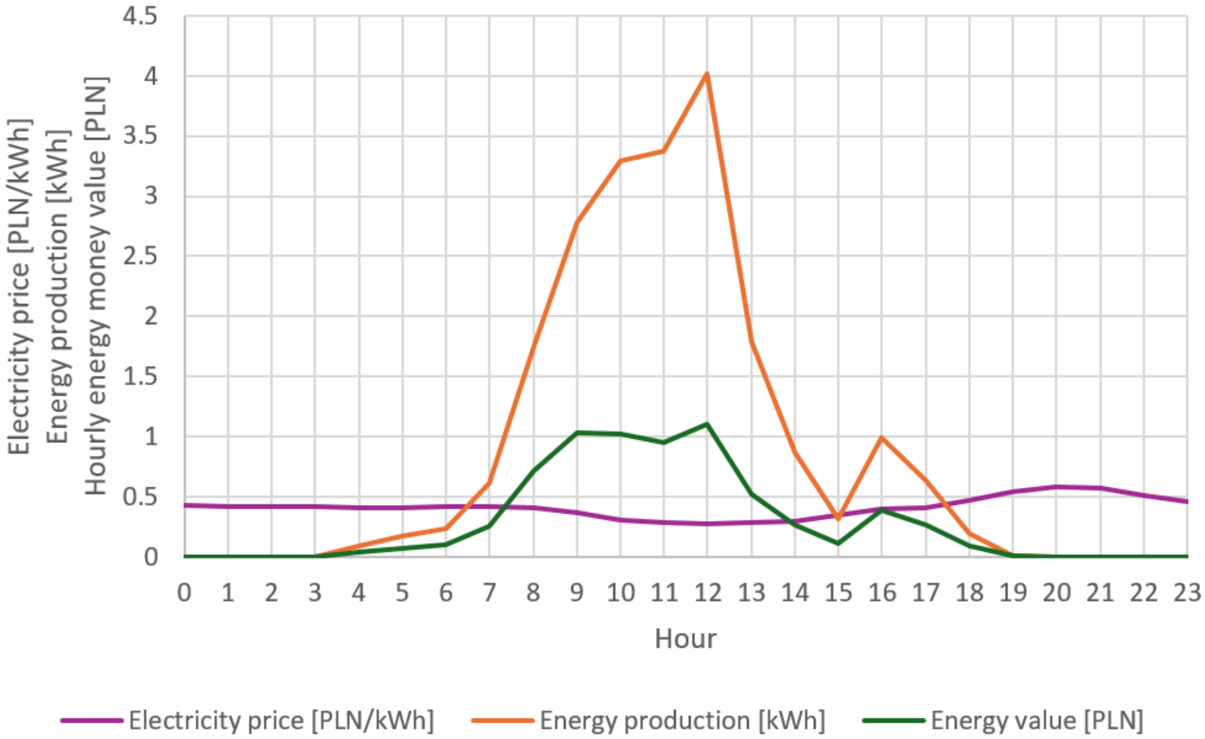

Figure 6. market electricity prices, energy production and energy value on 29.05.2024 – own elaboration based on the measurement data collected from PV installation throughout 2020 – 2024 time period and market electricity prices in 2024.

3.3. Correlations Between Energy Value, Market Electricity Prices and Energy Production

Figures 5 and 6 show the distribution of energy prices, photovoltaic energy production, and value throughout the day. The price and the production of energy strictly determines its monetary value. In both charts, the lines representing energy value and energy production coincide at the beginning of the day. As production increases, these lines begin to diverge. The greatest difference between energy value and energy production occurs at noon, when photovoltaic production is at its peak. This occurs due to the decrease in market energy prices as national photovoltaic energy production increases.

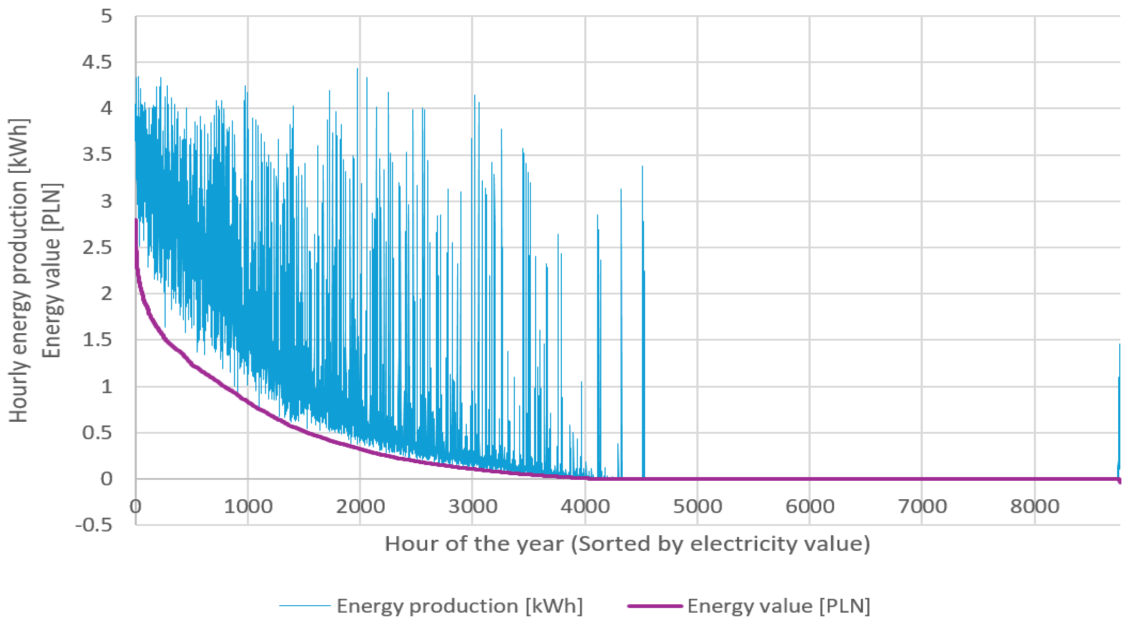

Figure 7. Correlations between energy production, energy value and hour of the year 2023 sorted by energy value – own elaboration based on the measurement data collected from PV installation throughout 2020 – 2024 time period and market electricity prices in 2023.

The maximal hourly energy value in 2023 equaled approximately 2.8 Polish zlotys (PLN), while the minimum value amounted to 0 PLN. These values were calculated as the multiplication of energy production and its price at a given hour. As shown in Figure 7, high energy values do not coincide with low energy production values. There are hours when the energy value equals zero, despite non-zero energy production. It occurs due to low electricity prices. During such hours, energy production is unprofitable. Energy production during periods of negative electricity prices results in negative energy values.

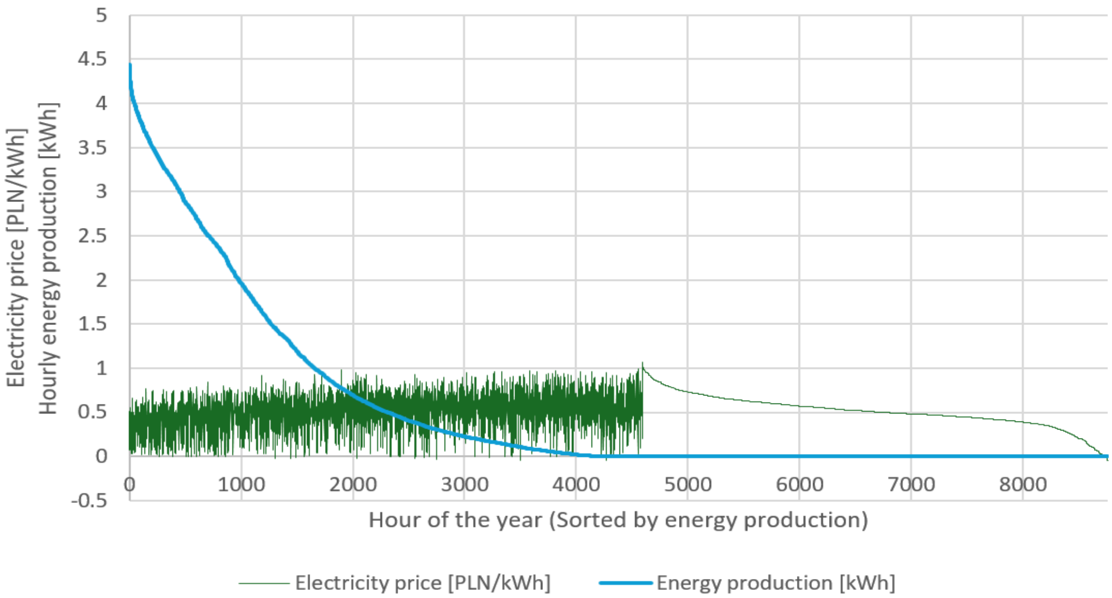

Figure 8. Correlations between market electricity prices, energy production and hour of the year 2023 sorted by energy production – own elaboration based on the measurement data collected from PV installation throughout 2020 – 2024 time period and market electricity prices in 2023.

As shown in Figure 8, the smaller the share of photovoltaics in energy production, the higher the prices. It can also be observed that with zero energy production, electricity prices can vary, depending on factors such as energy production from other energy sources and the price of electricity imported from neighboring countries. Lower electricity prices typically occur during nighttime hours from 1 AM to 4 AM (Komorowska & Olczak, 2024; Olczak & Komorowska, 2021).

3.4. Energy Demand

Energy demand varies throughout the day, week, and year. It is typically highest during evening and morning hours, weekends, and winter months due to factors such as lifestyle patterns and increased need for heating and lighting (Andersen, Baldini, Hansen, & Jensen, 2017). Due to increased electricity consumption and insufficient PV energy production during certain hours, there is a need for energy storage or drawing energy from the grid.

3.5. Selecting an Energy Storage System for Micro PV Installations

Batteries are the traditional energy storage systems used in photovoltaic micro-installations. Batteries can be categorized as follows:

3.5.1. Lithium-Ion Nickel Manganese Cobalt (NMC)

Main advantages: availability of many suppliers, very high energy density, and long lifespan. According to a study by Li et al. (2020), NMC batteries have an energy density of approximately 800 Wh/kg. Due to their light weight, aviation and transportation commonly use these batteries.

3.5.2. Lithium-Iron-Phosphate (Lithium Ferrophosphate) (LFP)

Characterized by their relatively low cost (Rafał & Grabowski, 2021) lifespan of up to 20 years, and up to 7000 charge-discharge cycles. However, the operation of lithium-iron energy storage requires precise programming of the cooperating device, as exceeding critical operating parameters can damage the storage and potentially cause fire due to lithium leakage. (Figura, Chochlewicz, & Wroński, 2016).

3.5.3. Lithium-Titanium-Oxide (LTO)

Characterized by a wide range of discharge depths and long lifespan due to the number of cycles (Rafał & Grabowski, 2021). Zhang et al. (2022) research demonstrates the high safety of LTO batteries, despite their low energy density.

3.5.4. Lead-Acid (LA)

Characterized by availability of many suppliers (Rafał & Grabowski, 2021). However, their low energy density and limited number of cycles make them unattractive for household energy storage (Xu et al., 2023).

Due to the safety and low cost of lithium-iron-phosphate batteries, they are recommended for use in photovoltaic micro-installations. Estimates place their average number of cycles to be around 7,000, with a lifespan of up to 20 years and an efficiency of nearly 100%. In comparison, lead-acid batteries' efficiency comes to 70-90% (Berrada et al., 2017).

Another important aspect of selecting an energy storage system is its size. The most commonly used batteries have capacities of 5 or 10 kWh.

The prices of 5-kWh batteries vary by model and range from approximately 11,000 to 18,000 PLN, while 10-kWh batteries cost between 25,000 and 40,000 PLN.

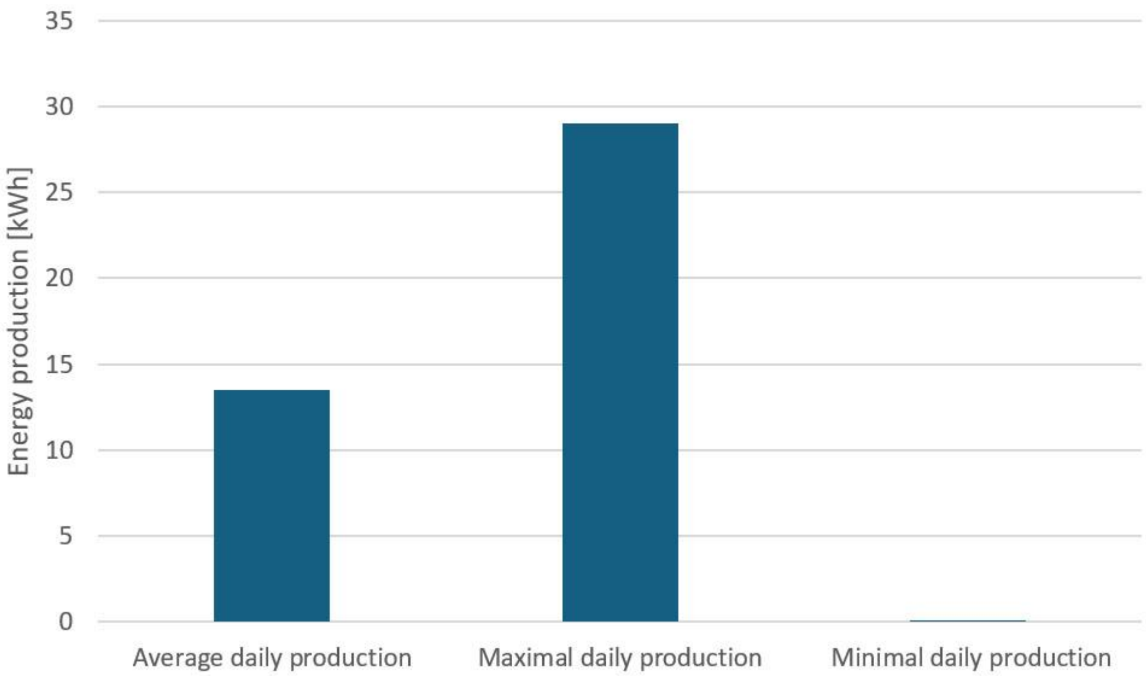

Figure 9. Average, maximal and minimal daily energy production in 2020-2024 time period - own elaboration based on the measurement data collected from PV installation throughout 2020 – 2024 time period.

Figure 9 illustrates the central tendency and dispersion of daily energy production in 2020-2024 time period. The average daily PV production reached approximately 13 kWh, with a maximal total daily production of about 29 kWh and a minimal total daily production of 0 kWh (which occurred on 31 days during these years).

Considering daily energy production, a 5 kWh energy storage system would be sufficient for a household with an average daily consumption of 15 kWh (Olczak & Komorowska, 2021). However, it is important to determine the depth of discharge for the battery in order to prolong its lifespan. Batteries with a 100% discharge depth are becoming increasingly available.

3.6. Profitability of Energy Storage Systems

The article Lis et al. (2022) presents the Cost of Conserved Energy (CCE) formula for calculating the profitability of investing in an energy storage system:

$$CCE = \frac{(NI + Ke,o \cdot n) \cdot \frac{i}{1-(1+i)^{-n}}}{\Delta E}$$

Where:

NI – Initial costs (purchase and installation costs) [PLN].

Ke,o – Annual operational costs (maintenance, insurance, and depreciation) [PLN].

i – Discount rate (3%) (Chmielniak, 2019; Kryzia, Kopacz, & Kryzia, 2020).

n – Assumed lifespan of the energy storage in years.

ΔE – Annual energy savings [kWh].

The investment is profitable if the formula calculates the cost of the saved energy to be lower or equal to the price of energy. The cost of saved energy calculated in the article (Lis et al., 2022) was higher than its price, making the investment unprofitable.

For the analysis of a household in Łęki, an LFP battery with a capacity of 5 kWh and a depth of discharge of 100% was selected. The cost of the chosen energy storage, including installation, equals approximately 19,000 PLN. The number of cycles (charging and discharging) totals approximately 7,000; therefore, the estimated lifespan of the battery comes up to 20 years. Due to the lifespan, linear depreciation must be considered in the annual costs, amounting to 850 PLN per year. The connection fee for the energy storage can be omitted, as it is not applicable for storage units up to 2 MW (Adamska, 2022). In profitability calculations, it is also necessary to consider fixed costs included in the contract with TAURON Distribution Sp. z o.o. and other fixed costs such as operational costs and insurance costs, as well as variable costs, which include the costs of purchasing and selling energy depending on the amount of energy bought or sold (Lis et al., 2022). Assuming that the household consumes an average of 15 kWh per day (noting that daily demand is difficult to estimate and varies throughout the year), and production exceeds demand typically only from May to September, allowing for energy storage or transferring energy to the grid, the investment in energy storage is rather unprofitable.

4. SUMMARY AND CONCLUSIONS

Due to the significant development of household photovoltaics, there is a need for energy storage. Therefore, one installation was selected for analysis in this context.

The analysis does not definitively determine how much energy should be stored concerning the day-night scale (storing energy so that the energy collected during the day proves to be sufficient for the night, particularly considering evening hours when energy consumption is usually the highest) and the annual scale (storing energy considering the varying production and consumption of energy throughout the year) and which approach is more economically profitable. However, it can be stated that a small energy storage system is generally more profitable than a large one. For this reason, an LFP storage system with a capacity of 5 kWh and an estimated lifespan of about 20 years, was selected for the analyzed household. Given that a household that uses an average of 15 kWh per day, such a storage size would cover energy consumption during the evening hours (around 7 PM to 10 PM) when electricity prices are highest.

The studied household uses a net-metering system, but due to the economic profitability of the energy storage system, it is recommended to consider the net-billing system introduced for new photovoltaic installations in Poland. However, even with a change in the energy settlement system, such an investment on a household scale is often unprofitable, primarily due to the insufficient energy production from photovoltaics throughout the year and the high costs associated with purchasing energy storage.

Directions for further research: investigation of other energy storage capacities; in-depth analysis of the economic aspects of energy storage.

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