

Analysis of the impact of the capacity and control algorithm of energy storage bank on the effectiveness of photovoltaic installations

Antoni Artur Kurkarewicz^{1*}, Tomasz Bakoń¹

¹ Institute of Mechanical Engineering, Warsaw University of Life Sciences – SGGW, ul. Nowoursynowska 166, 02-787 Warsaw, Poland

* Corresponding author's e-mail: antoniarturkurkarewicz@gmail.com

ABSTRACT

The capacity and algorithm of the energy storage system play a key role in the effective use of energy produced by a photovoltaic installation. By comparing different energy storage operation algorithms, presented as block diagrams, two distinct algorithms were proposed. These differ in the order of energy transmission between the facility powered by the photovoltaic installation and the energy storage. The purpose of this article was to simulate the course of charging and discharging an energy storage using the measured values of insolation, temperature and power consumption of a certain object implemented into an Excel spreadsheet together with the equations describing the photovoltaic installation and the energy storage. On the basis of the simulation results, conclusions were drawn regarding the effective use of photovoltaic energy, the optimal capacity of the energy storage in relation to the power consumed by the facility and determining which energy storage algorithm provided the best efficiency in the use of energy from the photovoltaic installation.

Keywords: energy storage capacity, photovoltaic installation, energy storage algorithm.

INTRODUCTION

The essence of the problem in energy storage is the appropriate selection of the capacity of the energy storage (ES) to the individual needs of a given facility (e.g., house, factory, household, etc.), in such a way as to achieve the optimal self-consumption coefficient without unnecessary over sizing. Referring to the results contained in the articles [1, 2], it can be stated that the use of energy storage increases the efficiency in the use of energy from PV installations. The innovation in this article will consist of the application and comparison of results for two energy storage algorithms (ESAs) using the measured values of insolation, temperature, and power consumption. The a1 and a2 algorithms proposed in this article have a different approach when it comes to the sequence of energy transmission from the PV installation, and the ES and the energy receiver.

The selection of ES with too small a capacity may lead to too high energy transmission to the power grid, which may lead to problems with planning electricity demand. This problem has been presented in articles [3, 4]. The reasons for this are the stochastic nature of solar energy, where predicting the amount of energy produced is difficult due to for example, cloudiness and temperature and due to the method used to calculate maximum power point tracking, abbreviated as MPPT. An example method is described in detail in the article [5]. In the case of chemical energy storage, the problem is important due to the excessive cost of the batteries themselves and problems in their operation, e.g. (inability to deeply discharge them). Therefore, an important aspect when selecting an energy storage is the type of batteries because each has certain limitations and specific properties (e.g., self-discharge, memory effect, etc.). However, if the storage is operated

in accordance with its characteristics, then there are no such threats. A LiFePO₄ battery was chosen, the nominal voltage and capacity values for this battery are (12 V; 250 Ah), while the degrees of safe charge and discharge are as follows 100 and 30%. By using series-parallel connections, different voltages and capacities can be obtained. SOC(t) % (state of charge) contains the information about the percentage state of charge of the ES and with its help, one can monitor parameters such as the amount of stored energy. By taking its value as a time-dependent function, the duration of discharge or charge can be predicted, given the charge or discharge current Eq. (1). Another essential element of the energy storage operation is the algorithm under which the energy storage charging and discharging processes are conducted. There are many possible approaches to the subject, and each is characterized by different advantages and disadvantages. The energy storage algorithm also serves to protect the ES, and depending on the battery type, it is designed to prevent a decrease in ES capacity due to excessive discharge or damage caused by overcharging. Therefore, ESA is a key element of the entire system's operation because it controls the cooperation among PV installations, the ES, and the power grid. Thus, from the point of view of this article, ESA is an essential element to consider. The installation accepted for analysis is of a hybrid type, using an inverter that allows the PV installation to operate together with the ES system while being able to consume and send energy to the grid. An example diagram of such an installation can be found in Figure 1. Hybrid inverters play a key role in this type of installation.

Devices of this type can be divided into two subtypes: one is adapted to work with the PV

system together with the ES and does not require the installation of additional devices. An example of a device of this type can be found in article [6]. The other, however, requires a separate battery charging controller, information on these devices can be found in article [7]. Such an installation is recommended due to its positive effects on the functioning of PV installations, which are described in article [8]. Installations of this type have enormous potential regarding the combination of technologies used. For example, articles [9, 10] describe a case of PV installations equipped with ES, where a fuel cell or a wind turbine was installed. This further increases the potential of PV installations to operate neutrally with the grid.

ENERGY STORAGE ALGORITHMS USED FOR SIMULATION

ESA diagrams can be found in the articles devoted to the subject of modeling the cooperation of energy storage facilities with RES installations, they take the form of block diagrams. Algorithms for the operation of an energy storage can be found in almost all articles devoted to modeling the cooperation of an energy storage with renewable energy installations, an example of a block diagram can be found in the article [11]. A characteristic feature of all algorithms controlling the ES charging process is that they must have the measurement data about the system in order to control the charging and discharging process. On the other hand, in article [12] one can find a block diagram of the algorithm performing a similar function to the one contained in article [11], with the difference that the information that is used to make decisions about whether the energy storage

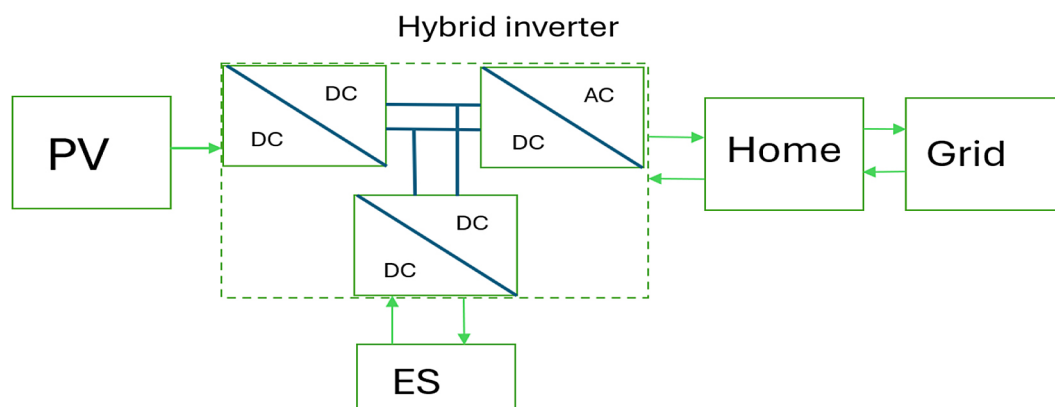


Figure 1. Simplified diagram of hybrid PV installation

is charged or not is the SOC(t) value. The flow-chart from article [12] is based on the inequalities saying that when the SOC(t) is not in the range of 85 to 15%, the energy storage is disconnected, and when the inequalities are met, then either the energy storage is charged or discharged. The third algorithm used to control the charging process is contained in the article [13] and, similarly to the previous two, it contains irregularities the task of which is to control the discharge and charging of the energy storage. In this particular algorithm, the information that controls charging or discharging is the values of voltage change and power change over time.

On the basis of the measured values, simulations can be conducted to determine the theoretical work cycle of the energy storage for a given algorithm. This will then allow for the calculation of values such as energy sent to the grid and energy taken from the grid, based on the ESA, and subsequently to determine which capacity variant is optimal. For the model, it was assumed that any amount of energy could be sent to the grid. These measurements were obtained from a measuring station at the Faculty of Production Engineering, Warsaw University of Life Sciences. The diagrams shown in Figures 2, 3, and 4 were generated using data measured as of 31.07.2024. The shapes of the curves presented in Figures 2 and 4 coincide with the daily time series load demand curve and daily time series PV output curves presented in article [14].

Formulas to calculate charge and discharge currents

The equations describing the charge and discharge current are a crucial element of the

algorithms because the values calculated on the basis of these equations are part of the model describing the SOC(t) function. This function describes the amount of energy stored in the ES and is a value compared to the safe degrees of discharge and charge in the unevenness contained in the energy storage algorithms.

Discharge current on a given day:

$$Ad(t) = \frac{P(t)}{U_{dis}} [A] \quad (1)$$

where: $P(t)$ – power consumed by installations from the kW network,
 U_{dis} – discharge voltage ES V.

Charging current on a given day:

$$Ac(T) = \eta_{pv} \cdot A_{pv} \cdot L_{pv} \cdot \frac{Is(t)}{U_c} \cdot (1 + t_{pv} \cdot T(t)) [A] \quad (2)$$

where: A_{pv} – PV panel area m^2 , U_c – charging voltage ES V, η_{pv} – PV panel efficiency %, $Is(t)$ – insolation function Wm^{-2} , $T(t)$ – temperature function $^{\circ}C$, t_{pv} – PV panel temperature coefficient $\% ^{\circ}C^{-1}$, U_c – charging voltage ES V, L_{pv} – number of PV panels pieces.

Description of the a1 algorithm

For the a1 algorithm, the priority is to charge ES. The capacity is selected so that the ES can store all the energy produced during the day, and only when charging is completed is the energy transferred to the facility (Figure 5).

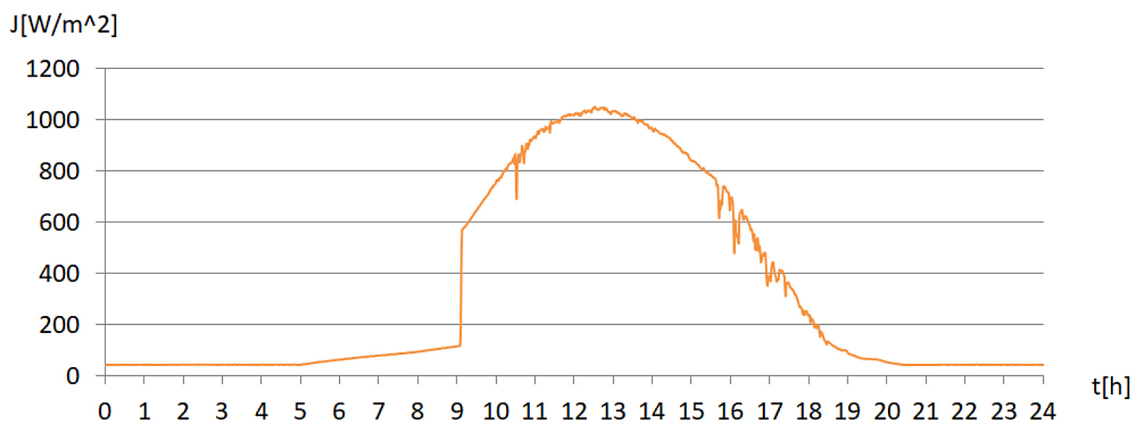


Figure 2. Example of an insolation graph

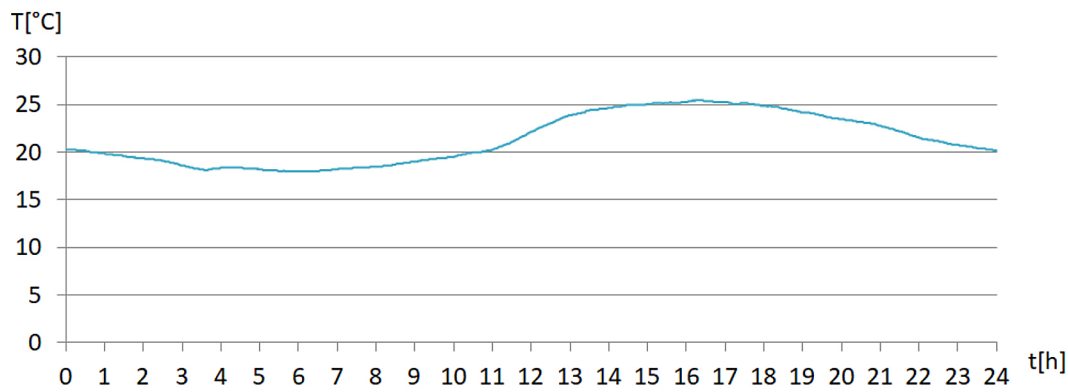


Figure 3. Example of a temperature graph

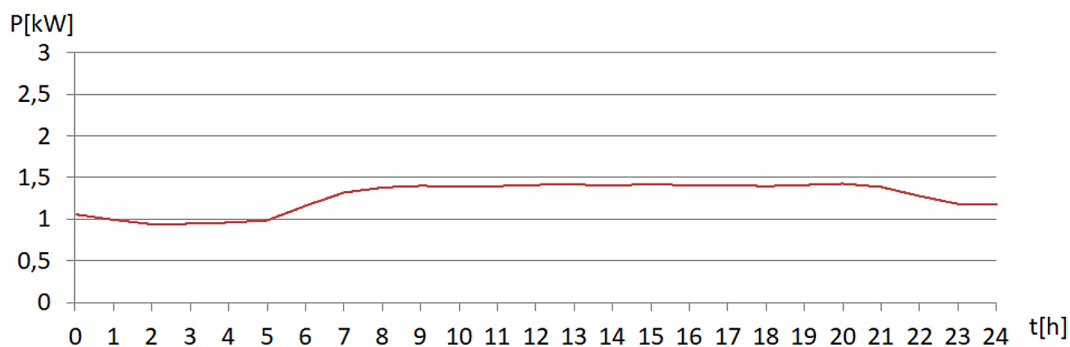


Figure 4. Example of a power consumption graph

Description of the a2 algorithm

For the a2 algorithm, the priority is to meet the energy needs of the household, and only when there is an overproduction of energy is it stored in ES. This reduces the overall energy consumption of the national energy system (Figure 6).

The a2 algorithm is a bit more complicated compared to the a1 algorithm. The greatest change concerns the ES charging current, where it is no longer related to the energy produced from PV Equation 2), as in the case of a1, but it is the difference between the power of the PV installation and the power that is necessary to power the facility. Thus, when ΔP is greater than zero, then there is an overproduction of energy, which can be stored if ES has not reached full charge.

PARAMETERS DESCRIBING THE PV AND ES INSTALLATIONS

The optimal number of PV panels is an important aspect of this type of installation functioning, because too few panels will prevent

the ES from charging effectively, and too many panels will cause excessive energy to be sent to the grid.

SOC(t) function

In energy storage operation, the most important parameter is the SOC(t) function, which describes how the amount of energy stored within the ES changes over time. While it can be presented in various forms, based on information in article [15], the integral form Equation 3 has been used for the simulation. The initial charge state for each day is assumed to be the previous day's SOC value at 12:00 PM. On the other hand, for the first day of each analyzed month, it was assumed that the ES is discharged to the lower limit of safe discharge, i.e. 30%, which means that the energy storage is empty. The batteries were configured with 6 cells connected in series, and three such series strings were then connected in parallel (3×6 configuration) and taking into account the limit degree of discharge of 30% and the nominal parameters of the batteries included in the energy storage, the value of the capacity can be

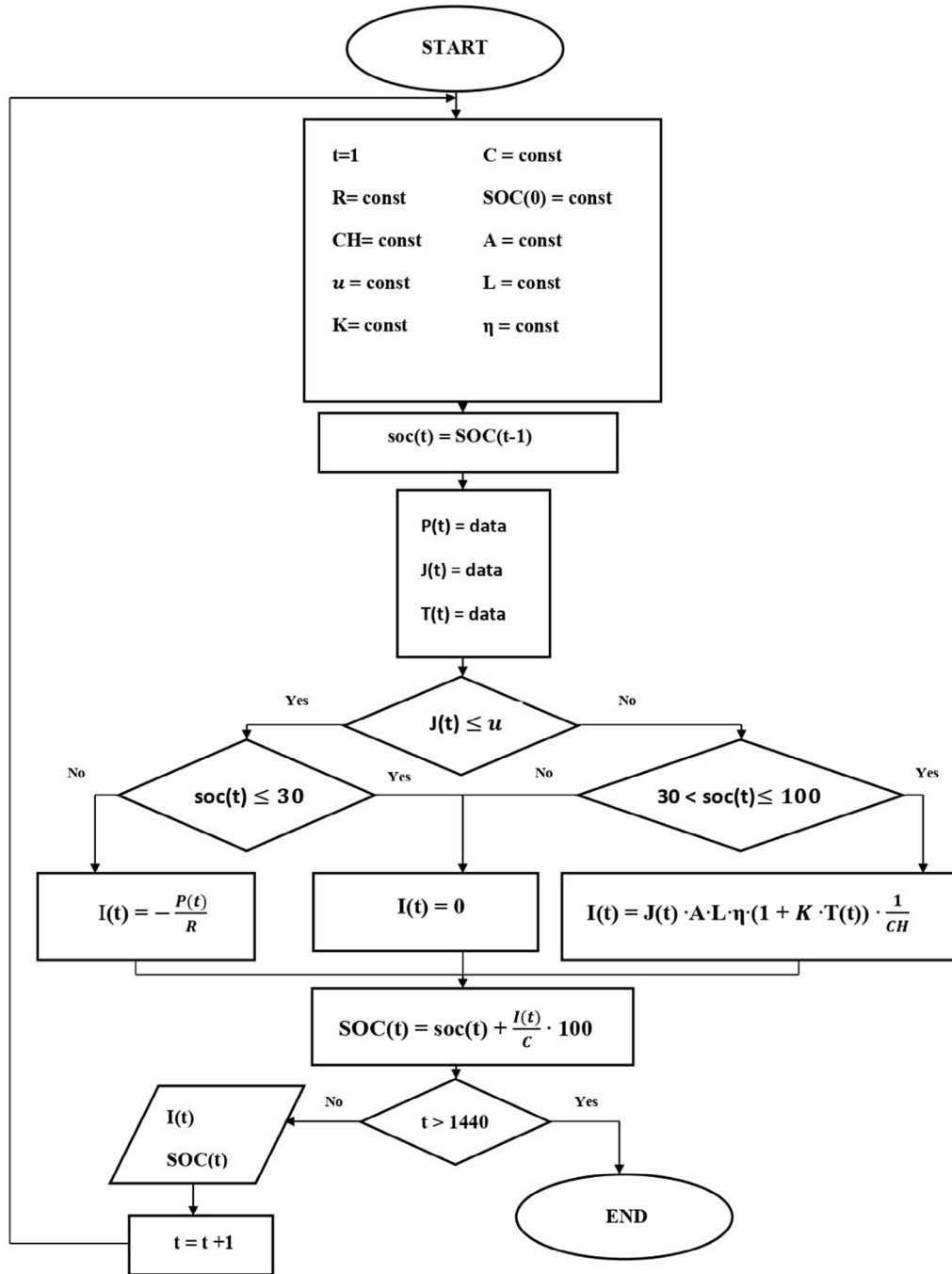


Figure 5. Algorithm 1 diagram

calculated, which is 37.8 kWh. On the other hand, values such as SOCmax, SOC24:00 and SOCmin mean the maximum SOC value, SOC at 24:00 and the minimum SOC value for the day.

$$SOC(a) = \frac{100}{60} \cdot \int_0^a \frac{A(t)}{C} dt + soc \text{ [%]} \quad (3)$$

where: $A(t)$ – function of charge or discharge current in time (t) for a given day A ,
 C – energy storage capacity Ah,

soc – the state of the initial charge of the energy storage on a given day %.

Formulas for calculating the energy taken from the grid and produced by PV installations

Energy taken from the national energy system on a given day:

$$E_{grid} = \frac{1}{60} \cdot \int_0^{1440} P(t) dt \text{ [kWh]} \quad (4)$$

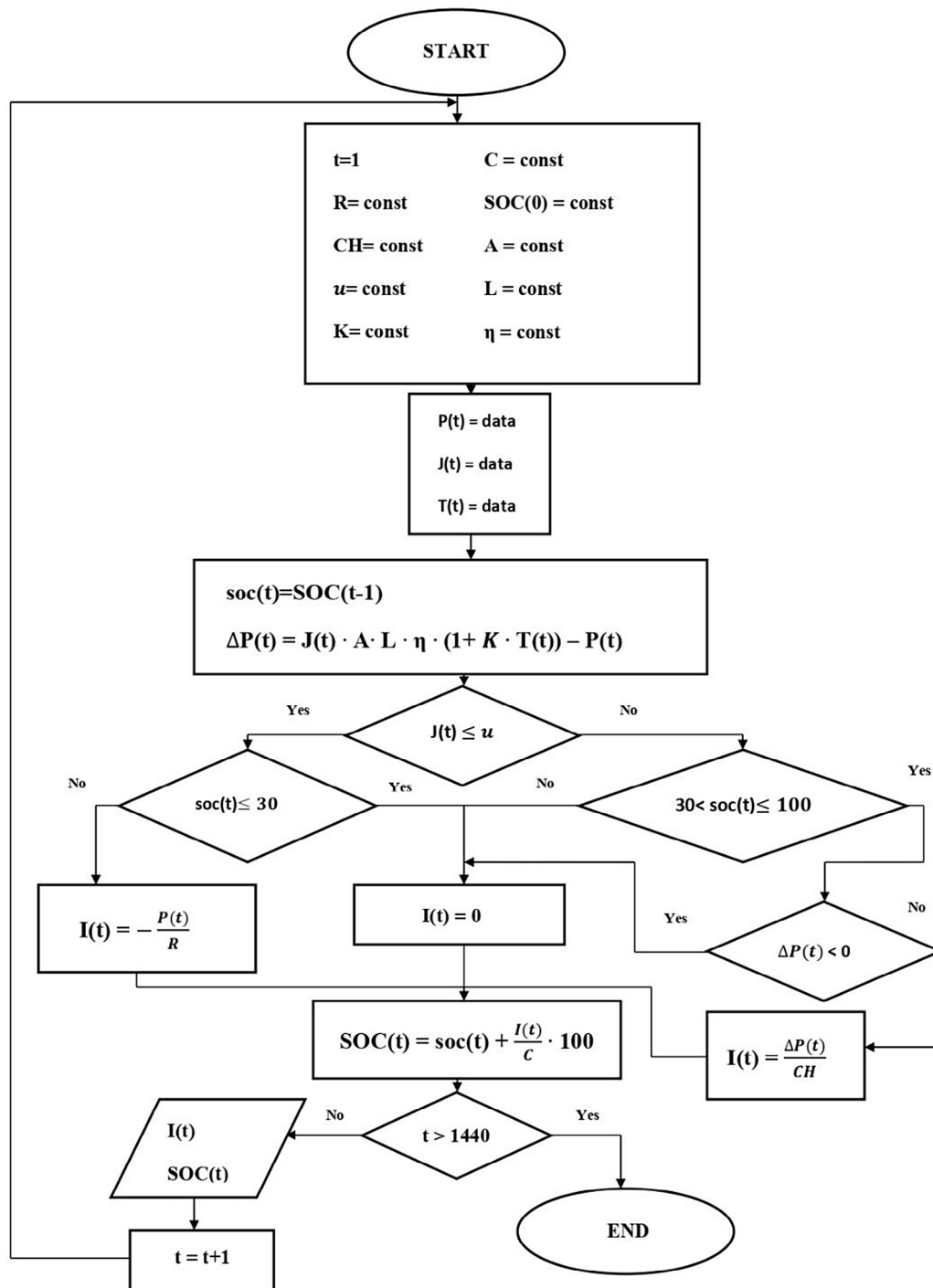


Figure 6. Algorithm 2 diagram, R – discharge voltage ES V, CH – charging voltage ES V, K – temperature coefficient PV %°C⁻¹, C – energy storage capacity Ah, A – area of one PV panel m², L – number of PV panels, η – efficiency of the PV panel %, P(t) – power consumption during kW, J(t) – insolation function during Wm⁻², T(t) – temperature function over time °C, soc – initial charge state ES %, u – inverter starting value Wm⁻²

Energy produced by PV installations on a given day:

$$E_{pv} = \frac{\eta \cdot A \cdot L}{1000 \cdot 60} \cdot \int_0^{1440} I_s(t) \cdot (1 + K \cdot T(t)) dt \text{ [kWh]} \quad (5)$$

The integral is calculated in the range from 0 to 1440 due to the fact that the measurements were taken every minute during the entire day, based on insolation measurements and the technical data of the PV installation located in Table 1. The above charts in Figure 7 show that

Table 1. Numerical value of parameters to simulate the operation of PV and ES installations

Symbol	Unit	Numerical value
u	Wm ⁻²	100
t _{pv}	%°C ⁻¹	0,0035
A	m ²	1.98
L	-	17
η	%	0,15

Note: The number of panels is assumed to be seventeen panels, the other parameters are examples of parameters for a PV panel.

for the number of 17 panels, the graph of energy produced from PV in the period when energy production is highest coincides more or less with the graph of energy taken from the grid, i.e. about 35 kWh, which allows assuming that an energy storage with a capacity of 37.8 kWh will be suitable for operation for a facility with such energy demands.

Percentage of energy sent to the grid on a given day:

$$PE_{wys} = E_{wys} \cdot E_{grid}^{-1} \cdot 100 [\%] \quad (6)$$

where: E_{wys} – energy sent to the grid on a given day taking into account the algorithm a1 and a2 kWh, E_{grid} – Equation 4 energy taken from the grid without considering the PV installation on a given day kWh.

Percentage of energy consumed by the system after considering the energy produced by PV installations:

$$PE_{pob} = E_{pob} \cdot E_{grid}^{-1} \cdot 100 [\%] \quad (7)$$

where: E_{pob} – energy consumed by the system, taking into account the energy produced by PV Equation 5 on a given day kWh, E_{grid} – energy taken from the grid by the system without taking into account the PV installation on a given day kWh.

Percentage of energy saved due to the use of PV and energy storage:

$$PE_{zao} = (E_{grid} - E_{pob}) \cdot E_{grid}^{-1} \cdot 100 [\%] \quad (8)$$

Thus, in a situation where Equation 8 is close to 100 %, the system must have drawn minimal or zero energy from the power grid on a given day. This implies that the energy taken from the grid without considering PV generation Equation 7 is also zero.

ANALYSIS OF THE IMPACT OF ENERGY STORAGE CAPACITY ON THE EFFICIENT USE OF ENERGY PRODUCED BY PV INSTALLATIONS

The analysis of the impact of capacity on the energy efficiency of the PV installation was first carried out for the capacity of 37.8 kWh, because on the basis of Figure 7 it can be stated that the energy produced at the time when the insolation conditions during the year are the best was about 35 kWh. Then the capacity was reduced to 31.5 kWh in order to check how the installation would behave in the situation of reduced capacity.

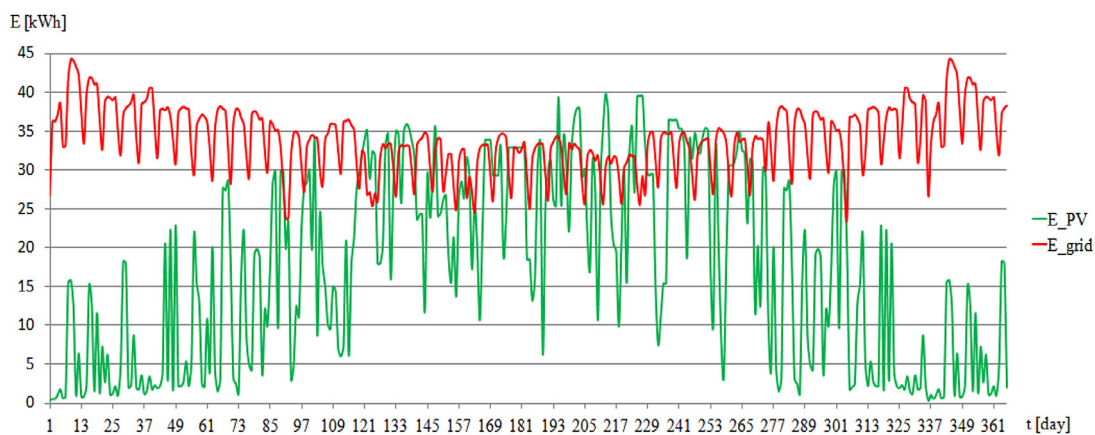


Figure 7. Energy charts

Table 2. Average values of parameters for individual months a1, capacity of 37.8 kWh

Average values	SOCmin	SOC24:00	SOCmax	E _{pv}	E _{grid}	PE _{wys}	PE _{pob}	PE
Month	%	%	%	kWh	kWh	%	%	%
January	29.97	30.55	40.02	5.37	37.96	0.00	86.40	13.60
February	30.20	33.28	43.27	6.21	36.42	0.00	82.56	17.44
March	39.12	49.75	66.17	14.66	34.27	2.08	60.73	39.27
April	55.79	68.08	81.95	18.00	32.81	8.25	51.31	48.70
May	78.85	89.39	99.98	27.88	30.94	31.43	38.09	61.91
June	80.99	90.93	100.06	26.73	30.93	29.24	40.23	59.78
July	52.61	76.16	98.04	27.12	30.95	20.24	30.40	69.60
August	64.26	79.61	94.29	27.17	31.47	21.28	32.55	67.45
September	58.99	75.82	93.13	26.45	32.16	15.57	31.45	68.55
October	40.69	51.32	68.42	14.66	34.27	2.08	57.80	42.20
November	30.58	33.55	45.41	6.07	36.43	0.00	79.81	20.19
December	29.97	30.55	40.06	5.38	37.87	0.00	86.35	13.65

Note: A large number of months with an average SOC_{max} above 90%.

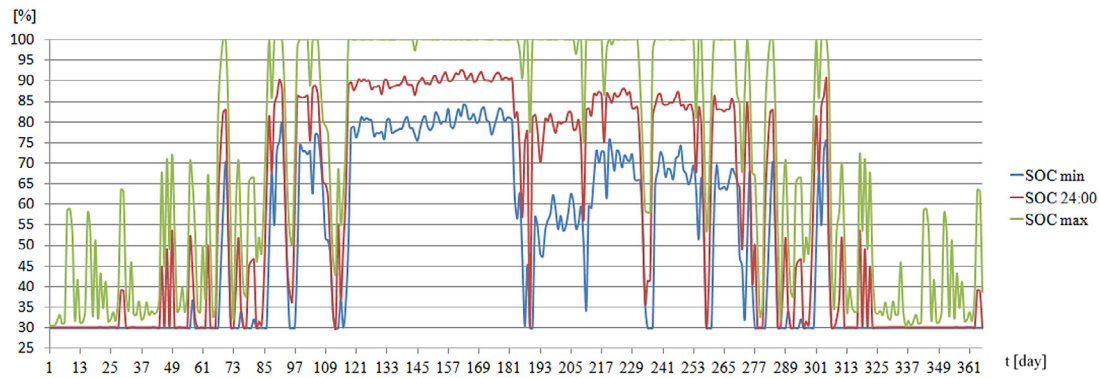


Figure 8. SOC chart (minimum, maximum, end of day) algorithm 1

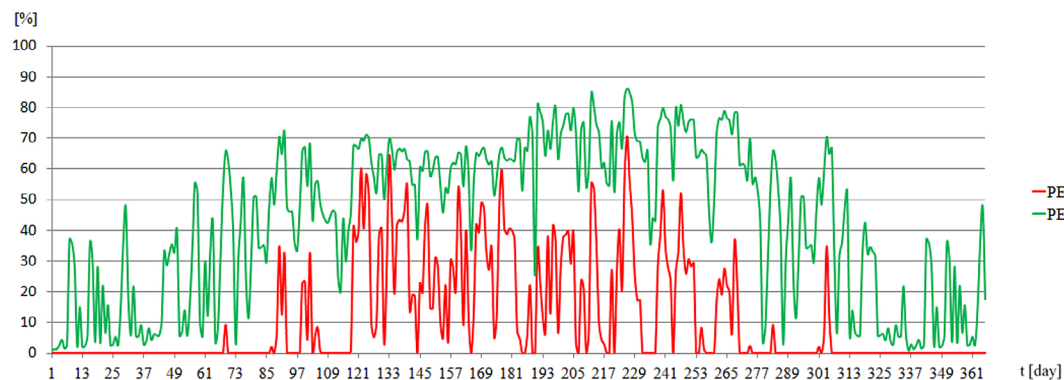


Figure 9. Graph of energy sent and saved for algorithm 1

On the basis of the results of calculations and charts, it can be concluded that algorithm 2 compared to algorithm 1 gave much better results in terms of efficiency in the use of PV energy throughout the year. For both the 37.8 and 31.5kWh capacity, it is clear that the amount of

energy sent to the power grid was higher for a1 than for a2. The averaged values in Tables 2 and 3 for the capacity of 37.8 kWh clearly indicate that for a1 a large amount of energy was sent to the power grid in the months when production from PV installations was the highest, while for

Table 3. Mean values of parameters for individual months a2, capacity of 37.8 kWh

Average values	SOCmin	SOC24:00	SOCmax	Epv	Egrid	PEwys	PEpob	PE
Month	%	%	%	kWh	kWh	%	%	%
January	29.90	29.92	31.91	5.37	37.96	0.00	86.48	13.52
February	29.98	30.15	33.25	6.21	36.42	0.00	82.26	17.74
March	30.14	32.39	41.93	14.66	34.27	0.00	56.38	43.62
April	30.11	35.18	44.70	18.00	32.81	0.00	44.46	55.54
May	39.83	52.63	68.06	27.88	30.94	0.49	9.29	90.71
June	35.65	46.74	60.25	26.73	30.93	0.00	15.19	84.81
July	36.13	54.68	76.77	27.12	30.95	2.35	15.15	84.85
August	44.55	57.22	71.58	27.17	31.47	3.26	15.13	84.87
September	36.74	49.89	65.79	26.45	32.16	0.00	16.98	83.02
October	30.13	32.39	42.44	14.66	34.27	0.00	55.52	44.48
November	29.98	30.15	33.61	6.07	36.43	0.00	82.08	17.92
December	29.97	29.98	31.97	5.38	37.87	0.00	86.42	13.58

Note: Low average amount of energy sent to the grid and large amount of energy saved.

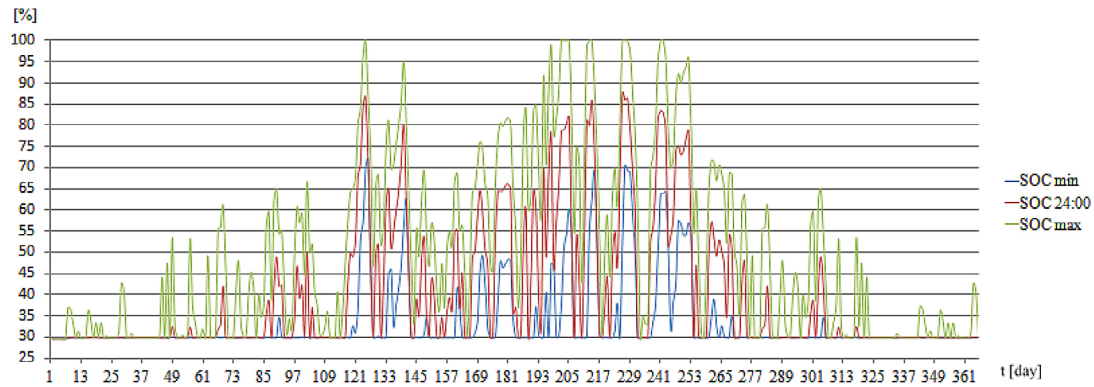


Figure 10. SOC chart (minimum, maximum, end of day) algorithm 2

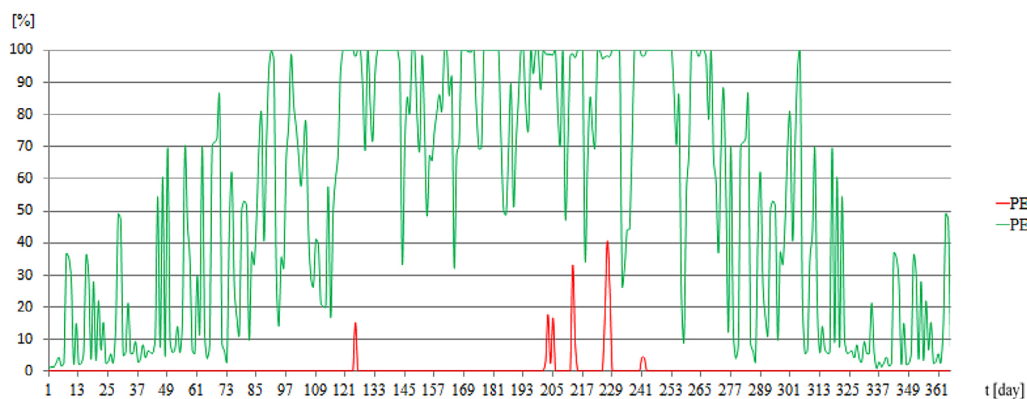


Figure 11. Graph of energy sent and saved for algorithm 2

a2 these amounts were noticeably lower. The results for a1 contained in Figure 8 show that for algorithm 1 between days 110 and 193 the energy storage did not discharge below the level of 75%, similarly for the capacity of 31.5 kWh, where in

Figure 12 the mentioned period when the energy storage did not discharge completely was extended, while decreasing from 75% to about 60%. Where for algorithm 2, the difference between the two graphs shown in Figures 10 and 14

Table 4. Mean values of parameters for individual months a1, capacity 31.5 kWh

Average values	SOCmin	SOC24:00	SOCmax	E _{pv}	E _{grid}	PE _{wys}	PE _{pob}	PE
Month	%	%	%	kWh	kWh	%	%	%
January	29.95	30.66	42.06	5.38	37.87	0.00	86.35	13.65
February	30.24	33.92	45.92	6.21	36.42	0.00	82.57	17.43
March	38.00	49.85	69.11	14.66	34.27	2.66	60.69	39.31
April	50.32	64.81	81.35	18.00	32.81	8.47	52.53	47.47
May	59.24	79.89	98.59	26.65	30.94	16.53	27.47	72.53
June	57.83	78.86	96.28	25.25	30.93	13.15	29.58	70.42
July	60.84	80.46	97.98	27.12	30.95	19.57	30.18	69.82
August	59.00	76.76	94.29	27.17	31.47	21.63	32.74	67.26
September	53.44	72.78	93.09	26.45	32.16	16.39	32.23	67.77
October	36.95	48.20	67.57	13.85	34.27	2.19	60.39	39.61
November	30.22	33.78	47.54	6.07	36.43	0.00	80.38	19.62
December	29.95	30.66	42.06	5.38	37.87	0.00	86.35	13.65

Note: Increase in energy sent to the grid compared to Table 2.

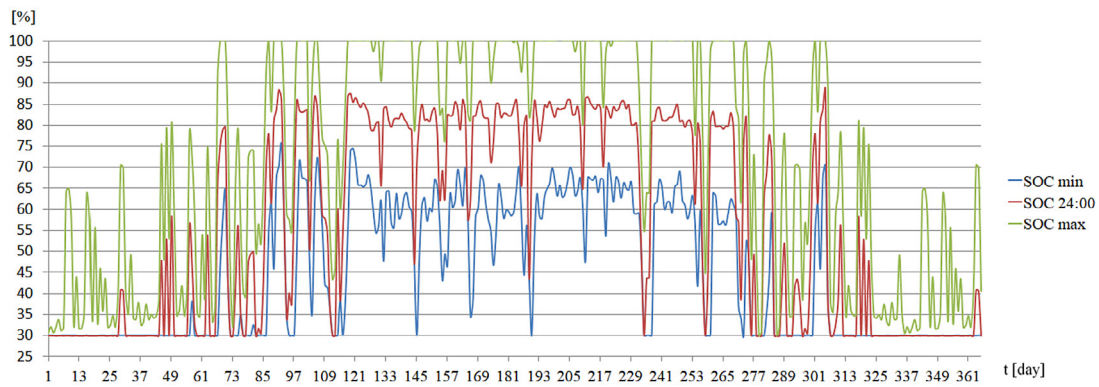


Figure 12. SOC chart (minimum, maximum, end of day) algorithm 1

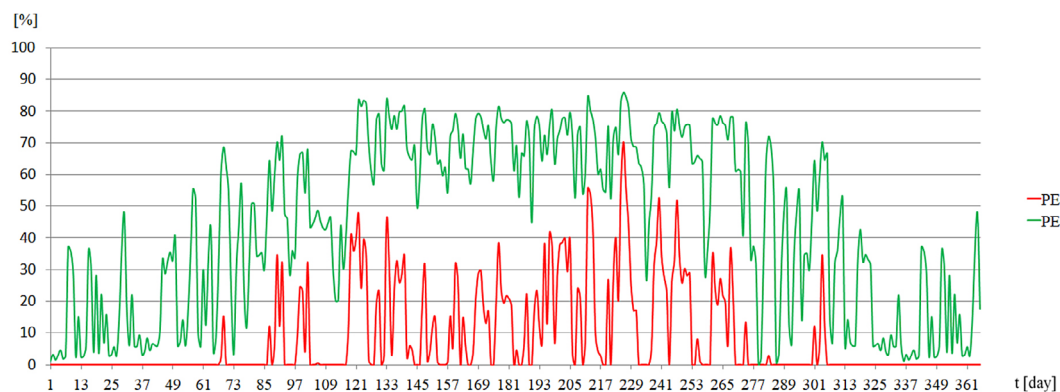


Figure 13. Graph of energy sent and saved for algorithm 1

was minimal. Tables 4 and 5 containing averaged results of the simulation for ES capacity of 31.5 kWh were similar to those for the capacity of 37.8 kWh, where the values of energy sent to the grid increased, due to the decrease in the capacity

of ES. This was due to the fact that when fully charged, the energy storage during the night discharge did not reach full discharge, so a large amount of energy was still stored when charging started the next day, which was not the case for

Table 5. Mean values of parameters for individual months a2, capacity 31.5 kWh

Average values	SOCmin	SOC24:00	SOCmax	E _{pv}	E _{grid}	PE _{wys}	PE _{pob}	PE
Month	%	%	%	kWh	kWh	%	%	%
January	29.96	29.97	32.37	5.38	37.87	0.00	86.42	13.58
February	29.97	30.18	33.90	6.21	36.42	0.00	82.26	17.74
March	30.16	32.87	44.31	14.66	34.27	0.00	56.38	43.62
April	30.13	36.21	47.64	18.00	32.81	0.00	44.46	55.54
May	37.13	51.75	71.00	26.65	30.94	0.76	13.26	86.74
June	32.72	45.24	62.19	25.25	30.93	0.00	19.00	81.00
July	36.16	51.90	69.89	27.12	30.95	1.00	14.88	85.12
August	42.46	56.50	72.85	27.17	31.47	5.11	16.43	83.57
September	36.79	52.35	71.12	26.45	32.16	0.50	18.22	81.78
October	30.16	32.85	44.92	13.85	34.27	0.00	57.80	42.20
November	29.96	30.17	34.32	6.07	36.43	0.00	82.08	17.92
December	29.98	29.98	32.37	5.38	37.87	0.00	86.42	13.58

Note: More energy saved compared to Table 3.

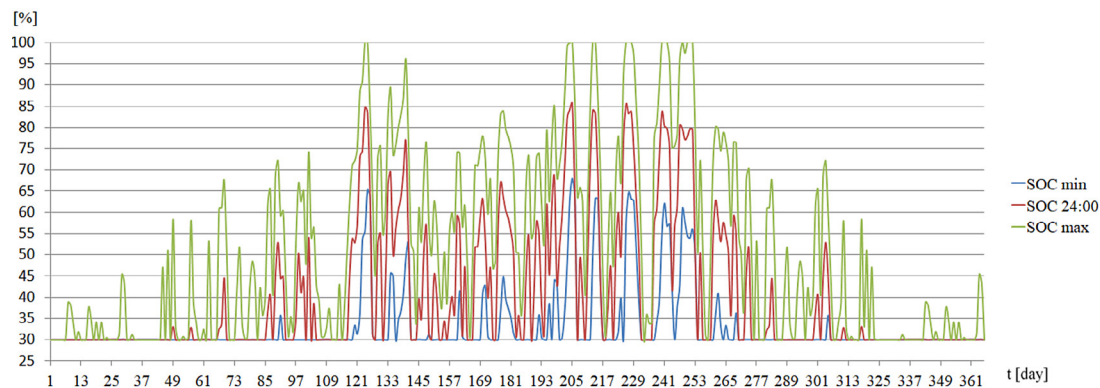


Figure 14. SOC chart (minimum, maximum, end of day) algorithm 2

a2. For Figures 9 and 13, it is difficult to see an improvement in energy efficiency. In turn for a2 the results contained in Figures 11 and 15 show that for this algorithm the best energy efficiency was obtained, because the PE_{zao} for this algorithm was almost always equal to zero both in terms of the capacity of 37.8 and 31.5 kWh. On the other hand, comparing the results contained in Figures 10 and 14, it can be concluded that despite the reduction in capacity, full charging of the energy storage was rare.

ANALYSIS OF THE OPERATION OF A PHOTOVOLTAIC INSTALLATION WITH AN ENERGY STORAGE

For the calculation of the payback time of the installation, it was assumed that the price

for one kilowatt hour is $0.357 \text{ PLN} \cdot \text{kWh}^{-1}$ because this is the lowest energy price recorded in 2024 in Poland, which allows concluding that the installation with the use of a specific algorithm and the number of batteries will certainly not pay for itself until the estimated moment. It was also assumed that the energy sent to the grid is not taken into account in the calculation of the payback time of the installation, because for the simulation it was assumed that the power grid is always able to receive it, but it might not be possible for the national energy system due to the frequent need to disconnect such installations due to overproduction of energy. It can be added that the PV installations with energy storage are designed precisely to prevent energy transmission to the grid, as transmission of energy to the power grid has many adverse consequences for the grid itself and other photovoltaic

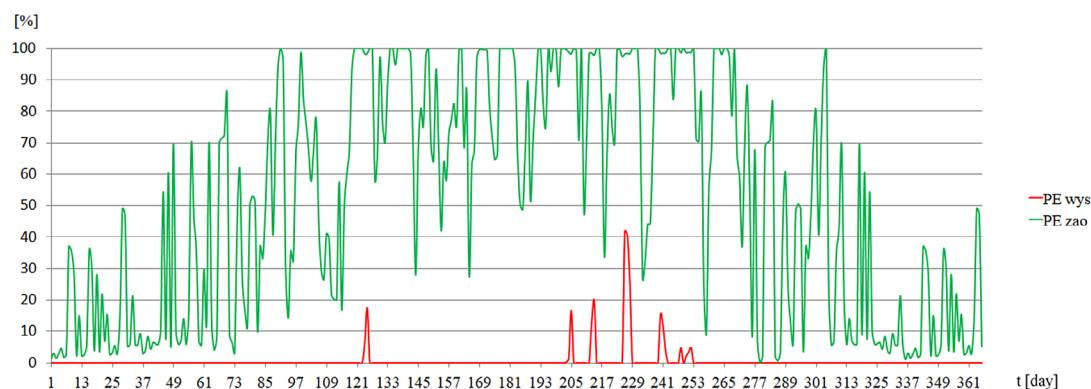


Figure 15. Graph of energy sent and saved for algorithm 2

Table 6. Cost estimates of a PV installation with energy storage

Item name	Quantity	Price [PLN]	Cost [PLN]
PV panels	17	500	8500
Hybrid inverter	1	6000	6000
Batteries	18 or 15	355	6390 or 5325
Mounting system	1	2500	2500
Wiring, electrical protection	-	2000	2000
Labor	-	6000	6000
		sum	31390 or 30325

Note: The two numbers in the battery row refer to the two capacity variants due to the different number of batteries installed 3×6 or 3×5 .

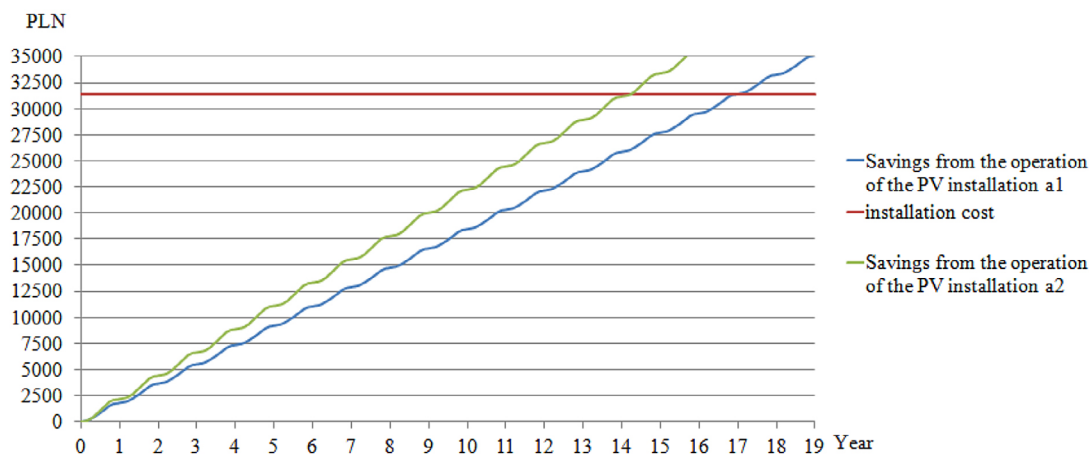


Figure 16. Payback time of an installation with an energy storage capacity of 37.8 kWh

installations located in the immediate vicinity of such an installation.

On the basis of Figures 16 and 17, it can be indicated that for a PV installation operating under the a2 algorithm with a 3×5 energy storage, the shortest payback time of about 14 years was obtained. This is the lowest result among all those included in Table 6. The difference between the price of 37.8 kWh and 31.5 kWh energy storage

was PLN 1065. The aforementioned difference translated into a reduction in the payback time by about 1 year for both algorithms. For the variant with reduced capacity and with algorithm 2 used, a result was obtained that turned out to be lower than the operating time of the batteries used in the energy storage. Taking into account the fact that the batteries contained in the energy storage must be replaced after about 15 years. As the

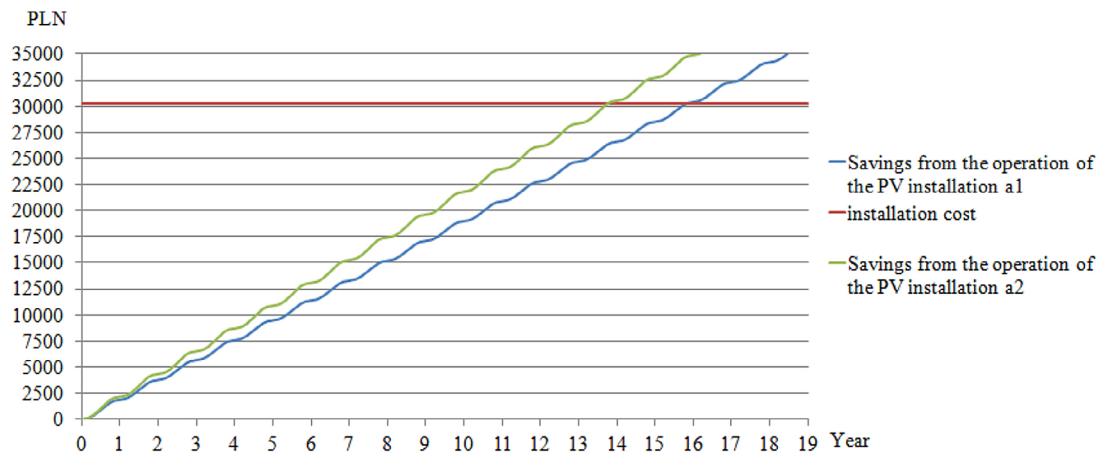


Figure 17. Payback time of the installation with an energy storage capacity of 31.5 kWh

Table 7. Installation payback time depending on the algorithm and capacity

Return time of the installation expressed in years	Energy storage 3 × 6	Energy storage 3 × 5
a1	17	16
a2	15	14

Note: The combination for which the shortest payback time was obtained is an installation with the a2 algorithm and a capacity of 31.5 kWh.

batteries for a2 were often charged to less than 90%, it can be assumed that the battery life operating under such conditions could be even longer than 15 years. Therefore, on the basis of the results, it can be concluded that the cost of such an installation will pay off, provided that there is no reduction in electricity prices and no fees for the transmission of excess energy to the national energy system are charged.

CONCLUSIONS

On the basis of the results of the analysis of the impact of capacity on the effective use of the energy from PV installations and the economic analysis of PV installations with energy storage, it can be concluded that the a2 algorithm for the capacity of 31.5 kWh gave the best efficiency results among all modeled variants. This efficiency applies to both logistical energy management and the return on installation costs. Better results of a2 are due to the sequence of energy transmission, where it is first used in the household, and only later, if there is a surplus of energy, it can be stored. While for a1, the energy was first directed to the energy storage

and only then to the household after reaching full charge, which in the summer meant that the energy storage was not able to discharge, hence the worse results in terms of energy efficiency. On the other hand, from the economic point of view, an energy storage system with a reduced value from 37.8 kWh to 31.5 kWh turned out to be a better solution based on the information in Table 7. The energy storage with a capacity of 31.5 kWh was cheaper by PLN 1065 and this difference for both a1 and a2 resulted in a shorter payback time of the installation costs by about a year, which, with a difference in energy efficiency and battery life of 15 years, allows concluding that the use of a2 with a capacity of 31.5 kWh is the best solution, because the life of the batteries will be longer than the payback time.

REFERENCES

1. Ross, K.; Matuszewska, D.; Olczak, P. Analysis of using hybrid 1 MWp PV-farm with energy storage in Poland. *Energies* 2023, 16, 7654. <https://doi.org/10.3390/en16227654>
2. Mansor, M.A.; Hasan, K.; Othman, M.M.; Noor, S.Z.B.M.; Musirin, I. Construction and performance investigation of three-phase solar PV and battery energy storage system integrated UPQC. *IEEE Access* 2020, 8, 103511–103538. <https://doi.org/10.1109/ACCESS.2020.2997056>
3. Badiei, Y.; Campos do Prado, J. Analysing the impact of electricity rates on the feasibility of solar PV and energy storage systems in commercial buildings: financial vs. resilience perspective. *Energies* 2023, 16, 2421. <https://doi.org/10.3390/en16052421>
4. Ullah, I.; Rasheed, M.B.; Alquthami, T.; Tayyaba, S. A Residential load scheduling with the integration of on-site PV and energy storage systems in

- micro-grid. *Sustainability* 2020, 12, 184. <https://doi.org/10.3390/su12010184>
5. Wang, T.; Lin, C.; Zheng, K.; Zhao, W.; Wang, X. Research on grid-connected control strategy of photovoltaic (PV) energy storage based on constant power operation. *Energie* 2023, 16, 8056. <https://doi.org/10.3390/en16248056>
6. Coelho, S.; Monteiro, V.; Sousa, T.J.C.; Barros, L.A.M.; Pedrosa, D.; Couto, C.; Afonso, J.L. A unified power converter for solar PV and energy storage in dc microgrids. *Batteries* 2022, 8, 143. <https://doi.org/10.3390/batteries8100143>
7. Hasan M.; Serra Altinolu H. Current and future prospective for battery controllers of solar PV integrated battery energy storage systems. *Frontiers in Energy Research* 2023. <https://doi.org/10.3389/fenrg.2023.1139255>
8. Subramaniam, U.; Vavilapalli, S.; Padmanaban, S.; Blaabjerg, F.; Holm-Nielsen, J.B.; Almakhlles, D. A hybrid PV-battery system for ON-grid and OFF-grid applications – controller-in-loop simulation validation. *Energies* 2020, 13, 755. <https://doi.org/10.3390/en13030755>
9. Vasantharaj, S.; Indragandhi, V.; Subramaniaswamy, V.; Teekaraman, Y.; Kuppusamy, R.; Nikolovski, S. Efficient control of DC microgrid with hybrid PV – fuel cell and energy storage systems. *Energies* 2021, 14, 3234. <https://doi.org/10.3390/en14113234>
10. Liu, M.; Zhang, B.; Wang, J.; Liu, H.; Wang, J.; Liu, C.; Zhao, J.; Sun, Y.; Zhai, R.; Zhu, Y. Optimal configuration of wind-PV and energy storage in large clean energy bases. *Sustainability* 2023, 15, 12895. <https://doi.org/10.3390/su151712895>
11. Garip, S.; Ozdemir, S. Optimization of PV and battery energy storage size in grid-connected microgrid. *Appl. Sci.* 2022, 12, 8247. <https://doi.org/10.3390/app12168247>
12. Aranzabal, I.; Gomez-Cornejo, J.; López, I.; Zubiria, A.; Mazón, J.; Feijoo-Arostegui, A.; Gaztañaga, H. Optimal management of an energy community with PV and battery-energy-storage systems. *Energies* 2023, 16, 789. <https://doi.org/10.3390/en16020789>
13. Masenge, I.H.; Mwasilu, F. Modeling and control of solar PV with battery energy storage for rural electrification. *Tanzan. J. Eng. Technol.* 2020, 39, 47–58. <https://doi.org/10.52339/tjet.v39i1.518>
14. Liang, G.; Sun, B.; Zeng, Y.; Ge, L.; Li, Y.; Wang, Y. An optimal allocation method of distributed PV and energy storage considering moderate curtailment measure. *Energies* 2022, 15, 7690. <https://doi.org/10.3390/en15207690>
15. Degla, A.; Chikh, M.; Chouder, A.; Bouchafaa, F. Comparison study and parameter identification of three battery models for an off-grid photovoltaic system. *Int. J. Green Energy* 2019, 16, 299–308. <https://doi.org/10.1080/15435075.2019.1566134>