Optimisation of Battery Energy Storage Systems Capacity for Purpose to Reduce Energy Cost

Paweł Parczyk[1[0009-0004-3287-9520]], Robert Burduk[1[0000-0002-3506-6611]]

Wrocław University of Science and Technology Department of Systems and Computer Networks, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland,
pawel.parczyk@pwr.edu.pl, robert.burduk@pwr.edu.pl

Abstract. High energy prices are a pressing problem for both developed and developing societies. They deepen social inequalities by causing energy poverty. Therefore, in this article, we propose a method for optimizing the capacity of Battery Energy Storage Systems, which operate in residential billed by a time-of-use tariff. It can reduce the cost of electricity and counteract energy poverty. We propose a control algorithm that minimizes energy costs and an optimization algorithm based on an objective function reflecting profitability. Simulations carried out on half a year of data showed the possibility of achieving savings of 23% for a tariff divided into two zones (on-peak and off-peak) and 21% for a three-zone tariff. An appropriately selected energy storage facility would pay off in 4.5 years and 5 years for subsequent scenarios, compared to 4.7 years and 5.1 years for the reference selection.

Keywords: Energy usage management, Energy Cost Optimisation, Battery Energy Storage Systems, Battery Optimisation

1 Introduction

Living in the times of the fourth industrial revolution, society uses various energy sources on a large scale for many purposes. Nowadays, it's hard to imagine life without lighting at night, without access to radio, television, and the Internet.

It makes us think, where are we now? How much does the access to energy impact us? What could happen if we lost this access or if it was limited? Access to the Internet, and therefore to information, offers enormous opportunities to those who can use it.

Considering the above issues, the inevitable question becomes: will we run out of energy? The answer is not simple. A well-managed power system has many safeguards against blackouts, but even the best safeguards can sometimes fail. The consequences of such a phenomenon can be very tangible. The review [3] describes the potential health risks associated with the occurrence of a blackout. The authors highlight the high risk and far-reaching consequences of lack of power for patients dependent on electricity, especially those connected to medical equipment.

However, in addition to a complete blackout, we face the challenge of eliminating energy poverty, which, due to the constant increase in the costs of generating electricity, may affect a significant part of society, eliminating their chances of participating in modern society. Researchers indicate the seriousness of this problem for both developed and developing countries. The [5] study analyzing the period from 2004 to 2019 in 28 European countries showed a decline in the importance of this problem over the years, but it is still significant and affects about 10% of the population.

In [7], the authors point out the potential causes of energy poverty. These are high energy costs, low income, and low energy efficiency, directly contributing to increasing energy demand, which translates into increased costs of already expensive electricity. The electricity market is a unique commodity market. Unlike other markets where goods are traded, there is no direct and high-volume storage and warehousing of goods. Energy must be produced and consumed at the same time. Therefore, the impact of supply and demand on prices is significant. Considering the periodic nature of changes in electricity prices, electricity suppliers in different countries provide various billing methods for the consumed electricity. The most popular settlement methods include fixed (static) tariffs, dynamic tariffs, and time-of-use (ToU) tariffs.

Based on the [6] study, in which researchers conducted a survey on a sample of 1405 respondents, it was found that the most popular method of settling accounts with the energy supplier is the fixed tariff (about 78.2%), where the energy price is independent of the hour. The fixed tariffs limit the consumer's risk related to price fluctuations and transfer it to the supplier, who takes this risk into account in the sales price. Therefore, it is the most convenient form of settlement for the consumer, but it is not the most profitable from a price point of view. On the other hand, switching to ToU tariffs relieves the energy supplier and transfers part of the risk related to price distribution to the consumer. Due to this variable billing, this kind is less convenient for the consumer, which decreases consumers' utility. Conversely, variable prices encourage customers to change the way they use energy and shift demand from more expensive periods to those when energy is cheaper [1], which leads to financial benefits. In [9], based on a survey conducted on a group of 1398 respondents, research has shown that about 70% are potential ToU purchasers.

An interesting and relatively simple solution may be the peak and off-peak tariffs, in which we distinguish two time and price zones. In this case, the off-peak price is usually lower, and the peak price is higher compared to the price in the fixed tariff. When using such billing, the consumer pays attention to the hours of electricity use. It limits energy-intensive processes such as using a stove, washing machine, or dishwasher during peak hours and transfers them to off-peak hours. In this way, the consumer achieves an average energy price ranging between peak and off-peak prices. Depending on the tariff and energy management method, the final energy cost may be lower compared to a fixed tariff.

Manual energy management described above may be a good solution. However, there remains the problem of other electrical devices whose operation cannot be influenced, or changing the nature of their use will significantly reduce usage comfort. For example, the refrigerator runs all the time. The electric water heater works when there is a demand for domestic hot water. In the case of home installations, hot water is most often needed in the morning and evening. Likewise, the light is mainly used in the evening or at night. The existence of such devices operating at specific hours or all the time may significantly limit the efficiency of manual transfer of consumption. Which, in consequence, may make fixed tariffs more profitable than others.

Meeting the above issues, in this article, we present an approach that reduces electricity costs by using a Battery Energy Storage System `BESS` in a residential electrical installation using tariff settlement. The study was carried out in a simulation on half-yearly energy consumption data in a single-family house located near Wrocław. Electricity prices and distribution costs come from two other customers using the services of the same energy supplier company. The main contributions of this work are as follows:

1. Proposing an energy storage operation method that reduces the average cost of electricity for consumers settled according to `ToU` tariffs.
2. Creating an optimization method for selecting the `BESS` capacity and power for a home installation to minimize the average cost of electricity.
3. Conducting a simulation on real data obtained from a single-family house located near Wrocław using a smart meter.
4. Conducting an analysis of the profitability of investments in energy storage, taking into account market prices of `BESS` based on solutions provided by Pylontech and Hypontech and taking into account the efficiency of the energy conversion process during its accumulation and distribution.

Research is currently underway on energy storage management systems and their optimization. Researchers have different approaches to the topic and define different goals of their research. In some articles, the main goal is to reduce the cost of electricity [8] or [2]. Compared to the article [4], in which a group of researchers draws attention to the problem of prematurely aging battery cells.

The remainder of this article is organized as follows. Section 1 introduces the problem at hand. Considered scenarios are defined in Section 2. Section 3 presents the proposed method. Section 4 is devoted to presenting and discussing the results of the conducted experiments, which are summarized in Section 5.

2 Scenarios

This work verifies the possibility of using the `BESS` system to reduce cost of energy, which is one of the factors affecting energy poverty. The use of energy storage in a system using `ToU` tariff billing can significantly reduce energy costs by shifting demand from peak hours to off-peak hours.

Due to the multitude of methods available for billing consumers' with energy suppliers, the study took into account three scenarios, which are described below:

1. Scenario 1 - The consumer household does not use any of the available `ToU` tariffs. It uses a fixed tariff. This is the basic (reference) case compared to the others and, therefore, constitutes a reference point.
2. Scenario 2 - The consumer household uses a tariff consisting of 2 time zones: Two peaks, during which the price is equal, and an off-peak period, during which the price is lowest.
3. Scenario 3 - A consumer household uses a tariff consisting of 3 time zones divided into two peaks with different prices: the morning peak (cheaper) and the afternoon peak (more expensive), as well as the off-peak period.

Table 1. Energy prices in individual time zones for the analyzed scenarios.

	Tariff price [PLN/kWh]		
	peak 1	peak 2	off-peak
Scenario 1	1.30		
Scenario 2	1.65		0.67
Scenario 3	1.34	2.13	0.74

Energy prices in the analyzed ToU tariffs are presented in Figure 1. The prices are also given in numerical format in Table 1. It is worth noting that not all tariffs are fixed throughout the year. Some tariffs also take into account the absence of peak periods on weekends and holidays. However, the impact of such exceptions only confuses this analysis and is therefore omitted. In the analyzed period, prices and hours of subsequent zones in ToU tariffs are constant throughout the analyzed period.

The values of energy price rates in individual time zones consist of two components. The first is a fixed price for energy, taken from the price list of one of the Polish electricity suppliers. The second component is the price of energy supply (distribution price), which is a variable factor and is calculated on the basis of other dependencies. In order to obtain objective conditions, the distribution price was taken from real energy bills.

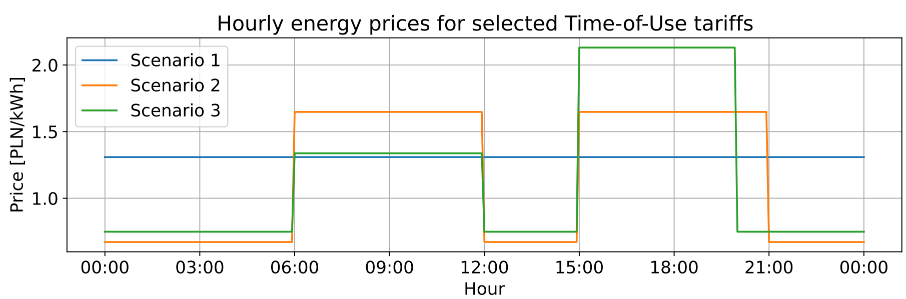

Fig. 1. Comparison of hourly energy prices of the analyzed ToU tariffs. The selection of time zones in ToU tariffs is modeled on real tariffs offered in Poland by one of the electricity suppliers.

The Battery Energy Storage System consists of two components. It is a battery that stores energy in Lithium Iron Phosphate cells. Additionally, to ensure control and safety of the behavior, the battery is equipped with a Battery Management System (BMS). The last element of the system is an inverter, i.e., a device that converts direct current (DC) stored by the battery into alternating current (AC) used in electrical installations. It is worth noting that transforming energy is a process with a limited efficiency defined at the level of 95%. Throughout the market research done, the solution based on the Pylontech Force H2 battery and the Hypontech HHT inverter was selected. When selecting the technology, the battery life was also taken into account, which is one of the most important parameters determining the profitability of the investment. In the datasheet, the energy storage manufacturer declares a lifetime of approximately 5,000 cycles - Assuming one cycle per day, the lifetime is about 13.7 years. It is worth mentioning that during use, the battery will lose only part of its capacity, and therefore, after 5,000 cycles, it will still be usable. Then, based on the offers received, investment prices for energy storage facilities with capacities ranging from 7.10 to 14.20 kWh were determined (7.1 was a reference capacity). The obtained results are presented in table 2. Based on tabular data on investment prices of energy storage facilities, the relationship

Table 2. List of parameters and prices of energy storage facilities.

Capacity (C) [kWh]	Maximum power [kW]	Investment cost (IC) [PLN]
7.10	3.552	22 042
10.65	5.328	28 757
14.20	7.104	35 427

between capacity and price was estimated. This is a linear relationship expressed by the formula 1. Investment cost (IC) is a linear function of capacity (C).

$$IC = 1891.56 \cdot C + 8612.70 \tag{1}$$

Additionally, the function expressed by the equation was presented in Figure 2. The blue dashed line presents an approximated cost while blue dots present the real prices from the table 2. Approximation was made in the range from 0 to 14.20 kWh. Estimating the cost of storage and knowing energy prices in individual `ToU` tariffs allows to perform a step-by-step simulation and obtain the alternate cost of using other tariffs with or without energy storage.

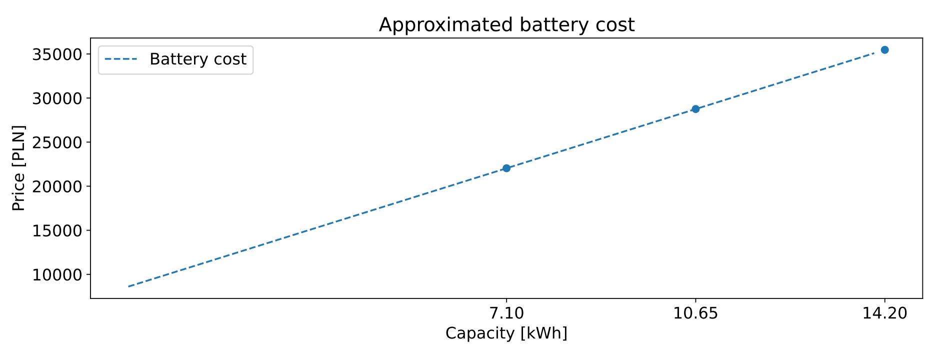

Fig. 2. Approximated battery price for batteries ranging from 0 to 14.20 kWh.

3 Proposed methods

In this article, we propose a method of using BESS in a residential electrical installation billed at ToU tariff. This system is based on the assumption that it is possible to shift demand from periods when energy costs are the highest, i.e. from peaks. To the periods when energy is cheaper - to the off-peaks. To achieve this effect, in the first subsection of this section, we propose an algorithm for scheduling charging and discharging the battery that also meets the limitations imposed by hardware devices. The next subsection presents the method of selecting the optimal capacity of the battery storage system using a simulation approach.

3.1 Scheduling method for Battery Energy Storage System

Using the known electricity price schedule in ToU tariffs, the system's task is to ensure the maximum possible battery charge level at the end of the period of cheaper energy (off-peak) so that this energy is available for use and thus allows to reduce peak consumption. When there is the off-peak zone, and the battery charge level called the

Algorithm 1 BESS charge and discharge policy algorithm

```
if is_peak(timestamp) then
    if SoC > 0% then
        if demand > max battery power then
            discharge battery with power = max battery power
        else
            discharge battery with power = demand power
        end if
    end if
else
    if SoC < 100% then
        charge battery with power = max battery power
    end if
end if
```

State of Charge (SoC) is lower than the maximum level, the battery is charged with the maximum battery power. Since the battery is fully charged, the battery goes into standby. When the peak zone is reached, the battery begins to discharge. With each passing moment, the power of the battery discharging is adjusted to current demand, but at the same time, exporting energy to the grid is avoided. If the energy demand of the installation exceeds the maximum power of the storage facility, then power equal to the maximum power is taken from the BESS , and the utility grid covers the rest of the demand (algorithm 1).

The operation of the proposed algorithm is presented in the figure 3, which shows the selected two-day period. The drawing is divided into two sections: the upper and the lower. In the upper section, the energy demand without using BESS . The lower section of the figure shows the same period with the use of an energy storage system.

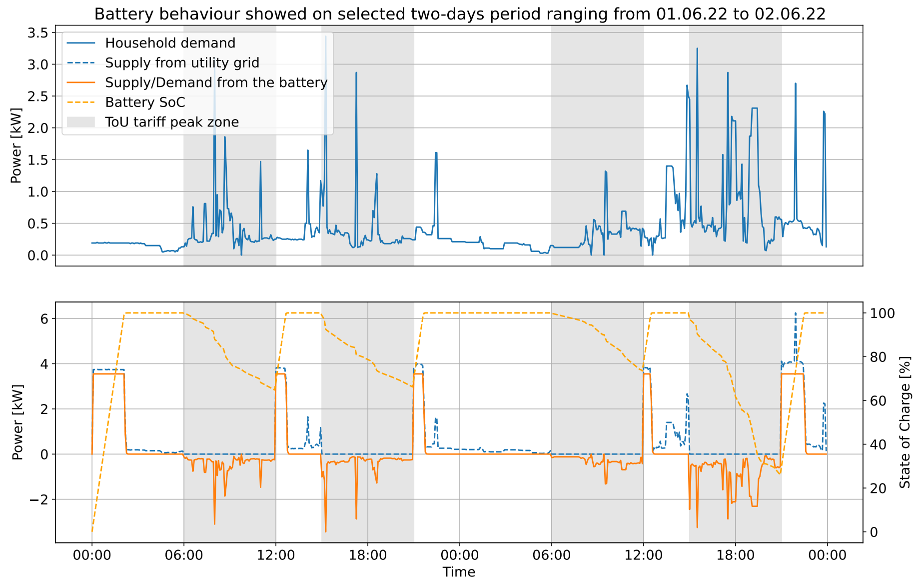

Fig. 3. An example of a selected two-day period of battery charging and discharging scheduling algorithms. The upper graph shows the measured energy requirements without using storage. The lower graph shows the same period when using energy storage.

Two types of areas are marked on the charts: white and gray. White areas represent off-peak periods, and gray areas represent peak periods according to the `ToU` tariff. The example uses a peak and off-peak zone layout as shown in Scenario 2 (Section 2). The measured energy demand of the building is presented with a solid blue line. As expected, the greatest intensity of electricity use occurs during peak periods. The orange dashed line shows the energy storage `SoC` level. It is expressed as a percentage value. The power at which the storage system is charged or discharged is presented with a solid orange line. Positive values mean that the battery is charged by the grid load, while negative values mean that the battery is discharged, thus reducing grid demand. The last characteristic presented in the figure is the energy taken from the distribution network, which is marked with a dashed blue line. It is created as the sum of demand (solid blue line) and power from storage (solid orange line).

The presented curves show the behavior of the presented method over time. Analyzing the graphs according to the X axis, at the beginning at midnight, the battery level `SoC` was 0%. Therefore, the battery charging procedure has begun. The battery power graph was set to a fixed value of a little less than 2kW. The grid demand graph (dashed blue) shows a value slightly higher than the battery charging power value. Then, between 2:00 a.m. and 3:00 a.m., the battery `SoC` value has achieved 100%. So until 6:00 a.m., when the first peak began, the battery was idle. At 6:00 a.m., the battery storage system discharging procedure began to meet demand. We can observe negative values on the battery power graph (solid orange line) and a lowering `SoC` value. At the same time, almost all the time, except for one moment, the grid demand graph is 0 kW. Only at the moment of the highest consumption of over 3 kW was the maximum battery power exceeded, and the excess power had to be covered by the grid supply. Then, from 12:00, the battery was recharged again to provide power during the second peak. The entire second day looked similar to the first one, except for the occurrence of a full battery discharge when SoC met 0% after 6:00 p.m.

Summarizing the operation of the proposed method for scheduling the charging and discharging processes of battery storage systems, one can easily observe an effective shift in demand from peak to off-peak hours. Comparing the household demand (solid blue) and supply from the utility grid (dashed blue) curves shows the minimization of demand during peak hours at the expense of off-peak hours after using the warehouse. At the same time, limitations in battery operation are visible. The following two problems seem to be the most important:

1. Too low battery power, which results in the need to refill from the utility grid even during peak hour.
2. Insufficient battery capacity, which means that the warehouse is unable to meet the entire demand during peak hours lasting many hours.

One possible way to workaround both problems would be to use a larger BESS , but this involves increased overhead and may lead to suboptimal battery use. Therefore, it is necessary to determine what battery size would be optimal and allow the unit price of electricity to be reduced as much as possible.

3.2 Optimization of Battery Energy Storage System capacity

Knowing the mechanism for scheduling battery charging and discharging and all the consequences of using a battery with too low capacity or power, the mechanism for selecting the appropriate capacity can proceed. To define what capacity is optimal, the metrics according to which the assessment will be made between the two selected storage needs to be defined. The aim of the work is to reduce energy cost which is one of the factors shaping the level of energy poverty. The metric for assessing the quality of the BESS will be the weighted average energy price achieved in the analyzed period. However, installing an energy storage facility also requires financial outlays, so the price of the installed energy storage facility will be considered.

By reducing the average cost of electricity, it is possible to calculate the savings incurred by the household due to the use of BESS . Those savings are the product of a subtraction of reference cost (cost incurred in scenario 1) and the *Cost*, which is a product of the multiplication of the Supply from the utility (US) achieved using selected battery and selected ToU tariff according to the equation 2.

$$^{1}Cost(C) = \sum_{i=0}^{n} \frac{US(C)_i * ToU_i}{12} \tag{2}$$

[1] The factor 12 comes from the sampling rate of the dataset, which was described in Section 4.

By dividing the annual savings by the investment cost (IC), we will obtain the annual profit coefficient $P(C)$ dependent on the selected battery capacity, which should be as high as possible equation 3. Similarly, by calculating the reciprocal of profit, we will obtain the payback period of the investment (Return ($R(C)$)) equation 4, calculated in years, which should be as short as possible.

$$^{2}P(C) = 2 \cdot \frac{Ref - Cost(C)}{IC(C)} \tag{3}$$

$$R(C) = P(C)^{-1} = \frac{IC(C)}{2 \cdot (Ref - Cost(C))} \tag{4}$$

The optimization task is to find the value of the energy storage capacity C_{opt} that maximizes the obtained profit $P(C)$ in accordance with the equation 5.

$$\exists\, C_{opt} \in C\ \forall\, x \in C/C_{opt}\ P(x) < P(C_{opt}) \tag{5}$$

Due to the linear nature of the optimized equation, the Nelder-Mead Simplex algorithm will be used for optimization.

4 Results

In order to conduct this experiment, data spanning a half-year period ranging from 1^{st} June 2022 to 31^{st} December 2022 was collected. The data was sampled once every 5 minutes, which resulted in 53000 samples. The data comes from a residential installation located near Wrocław (Poland). The dataset was collected using a smart meter. Figure 4 portrays the first seven days of the collected dataset. The nature of the data is repeatable throughout the day. There are periods of increased activity during the day and periods of silence during the night. During the day, energy consumption is uneven, with large fluctuations.

The experiment's reference values are the operating costs of the installation that is not equipped with BESS. Those are presented in the table 3. In this case, using the fixed tariff (scenario 1) costs 8866 PLN, the ToU tariff costs 8128 PLN in scenario 2, and 8180 PLN in the last scenario. Energy consumption in all considered scenarios is the same. The average energy prices are as follows: a fixed tariff cost is 1.30 PLN/kWh, and for ToU tariffs it is 1.20 PLN/kWh and 1.21 PLN/kWh. It follows that, even without the BESS system, changing the billing method from a fixed tariff (scenario 1) to a peak and off-peak tariff with consumption consistent with the data would allow for benefits to be achieved.

Table 4 presents the calculated profit and the average price of electricity obtained during the operation of an installation equipped with BESS. The table shows nine basic results. For each of the three scenarios and for each of the three capacities defined in Table 2. As expected for the fixed tariff scenario, the energy cost does not depend on the battery used. Therefore, the profit is 0, and the average energy price is consistent

[2] The dataset covers half a year (Section 4). To calculate the annual indicators, you need to multiply the obtained results by 2.

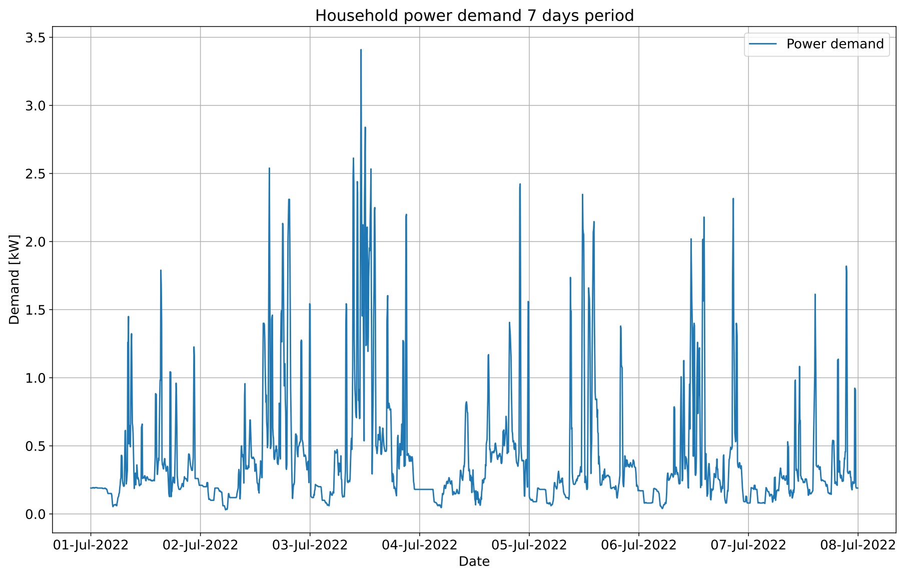

Fig. 4. The first seven days of the dataset. The plot presents recorded instantaneous power expressed in kW.

Table 3. List of operating costs for various `ToU` tariffs (scenarios) without using `BESS`.

`ToU` tariff	Cost [PLN]	Demand [kWh]	Average price [PLN/kWh]
Scenario 1	8866	6774.94	1.30
Scenario 2	8128	6774.94	**1.20**
Scenario 3	8180	6774.94	1.21

with the price shown in Table 3. For the remaining scenarios, the situation is different. As the battery capacity increases, the profit achieved also increases, and the average price of electricity decreases. The largest energy storage facility with a capacity of 14.2 kWh has the highest profits and the lowest prices. While the smallest energy storage facility achieves the lowest profits. A non-linearity can be noticed in the decrease in the average energy price, which is greater when switching from no battery (Scenario 2: PLN 1.2/kWh) to a battery with a capacity of 7.1kWh (Scenario 2: PLN 0.85/kWh) and it decreases of 29%. Compared to the decrease of average energy price after increasing the battery capacity to 14.2 kWh (Scenario 2: PLN 0.74/kWh), which is 12%. In the scenario 3, the situation is analogous, and the spathes are 26% and 10%.

To present this characteristic more clearly, the figure 5 shows the shape of the profit curve in the capacity range from 0 to 14.2 kWh. The graph shows the invariance of the relation for scenario 1 and the logarithmic shape for the remaining scenarios. Curves are ascending, but they cannot be unlimited. The maximum profit value is determined by the fact that the average electricity price in a given `ToU` tariff cannot be lower than the off-peak price in this tariff. However, the efficiency of the energy storage process must

Table 4. A summary showing the benefits of using BESS of various capacities in selected scenarios. The columns present data for a system with a specific capacity. In the rows, the data is arranged according to specific scenarios. The top row of cells shows the benefit of using the energy storage, i.e., the difference between the reference cost and the cost incurred when using BESS . The bottom row of the cell shows the average price of an energy unit obtained when using BESS .

	Capacity		
	7.1 kWh	10.6 kWh	14.2 kWh
Scenario 1	0 *PLN* 1.3 *PLN/kWh*	0 *PLN* 1.3 *PLN/kWh*	0 *PLN* 1.3 *PLN/kWh*
Scenario 2	2365 *PLN* 0.85 *PLN/kWh*	2842 *PLN* 0.75 *PLN/kWh*	3117 *PLN* 0.74 *PLN/kWh*
Scenario 3	2153 *PLN* 0.89 *PLN/kWh*	2548 *PLN* 0.83 *PLN/kWh*	2738 *PLN* 0.80 *PLN/kWh*

also be taken into account, which is not 100%; slightly more energy must be charged during off-peak than will be used during the peak. In the case of this work, the efficiency of the storage process was determined to be 95%.

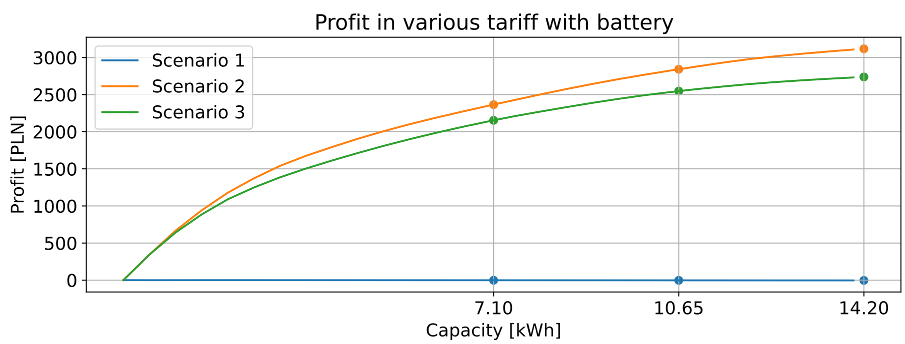

Fig. 5. Profit obtained for ToU tariffs with various BESS .

The next stage of the experiment is to compare the benefits obtained from using BESS with the financial outlay that would have to be incurred to install such a system. Two indicators were used for this purpose. The annual profit, which is the quotient of the profit and the investment price (Equation 3), indicates how much of the investment would be returned during the year. The second indicator was the payback time counted in years, which was the inverse of the first indicator (Equation 4). Figure 6 shows two graphs. The upper one shows the profit, and the lower shows the payback time. The charts only show scenarios 2 and 3 because for scenario 1, where the tariff is fixed, and the profit is 0. Therefore, the payback time is infinite, and the annual profit is zero. The graphs of both coefficients are symmetrical to each other. Due to the greater profits achieved in scenario 2, it is tilted more strongly. Both graphs have one global extreme, which determines the optimal size of energy storage.

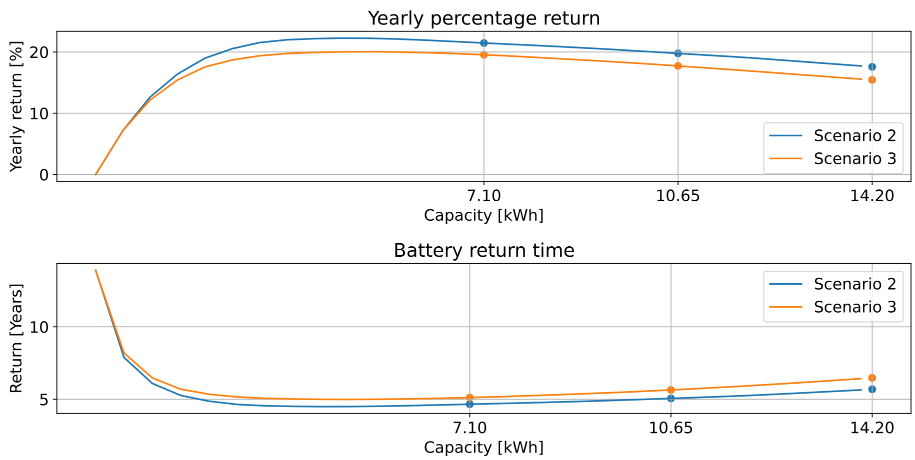

Fig. 6. A graph presenting the return time and annual profit from using BESS .

Using the Nelder-Mead Simplex algorithm, the optimal storage capacity value was determined. The optimal capacity was 4.625 kWh for scenario 2 and 4.812 kWh for scenario 3. The achieved profit was 1932 PLN and 1776 PLN, respectively. The annual profit was 22.2% and 20.1%, and the return time was 4.5 years and 5.0 years. The comparison of the obtained optimal and reference values is presented in Table 5.

Comparing the obtained results to other work, e.g., [10] it can be seen that similar results were obtained. Simulation studies have proven that the use of a battery in a residential installation contributes to cost reduction. Thanks to the possibility of shifting demand from the peak tariff to the off-peak period. However, calculating the investment payback time depends on many factors, including tariff system, battery cost, process efficiency, and household demand.

Table 5. Comparison of annual profits and return periods of reference and optimal BESS .

	Capacity				
	4.625 kWh	4.812 kWh	7.1 kWh	10.6 kWh	14.2 kWh
Scenario 2	1932 *PLN* 22.2% | 4.5Y 0.92 *PLN/kWh*	x	21.5% | 4.7Y	19.8% | 0.1Y	17.6% | 5.7Y
Scenario 3	x	1776 *PLN* 20.1% | 5Y 0.95 *PLN/kWh*	19.6% | 5.1Y	17.7% | 5.6Y	15.4% | 6.5Y

The presented algorithm allowed to achieve positive results in accordance with the presented metrics. Optimizing the size of `BESS` allowed us to maximize profits. The average energy price for scenario 2 decreased about 23% from PLN 1.2/kWh to PLN 0.92/kWh while achieving a payback time of 4.5 years. In the case of scenario 3, the average energy price decreased from PLN 1.21/kWh to PLN 0.95/kWh, which is 21%. The payback time was 5 years. The presented approach allows for a simulation estimation of the optimal energy storage. Allowing for a maximum reduction of energy poverty by reducing the average energy price that households must pay.

5 Conclusions and further works

In this article, we proposed a simulation method to select an appropriate Battery Energy Storage System `BESS` for residential that uses time-of-use (`ToU`) tariffs to account with the power supplier. This is intended to reduce energy costs, one of the causes of energy poverty.

In the article, we presented a method of energy storage management with the aim to minimize the energy costs incurred by the consumer. We defined metrics for assessing the effectiveness of individual storage systems and then presented an approach that allows for calculating the optimal battery capacity.

Experiments conducted over six months indicate the existence of potential benefits resulting from the use of the discussed solution. The optimal selection of `BESS` allows to maximize the benefits resulting from its use and minimize installation costs, thus minimizing the return time of the investment. In the scenarios discussed in the article, using `BESS` allowed for a reduction in the average energy price by as much as 23% or 21%. The analysis used market prices of `BESS` and took into account the efficiency of the energy storage process at the level of 95%.

The experiments that were conducted demonstrated the validity of the presented method. However, it is susceptible to further research. The next step will be to propose an extension of the battery control algorithm to also include production from renewable energy sources.

Disclosure of Interests The authors have no competing interests to declare that are relevant to the content of this article.

Data availability Data will be made available on request.

References

1. Albadi, M., El-Saadany, E.: A summary of demand response in electricity markets. Electric Power Systems Research **78**(11), 1989–1996 (2008). https://doi.org/https://doi.org/10.1016/j.epsr.2008.04.002, `https://www.sciencedirect.com/science/article/pii/S0378779608001272`
2. Azaroual, M., Maaroufi, M., Ouassaid, M.: An optimal energy management of grid-connected residential photovoltaic-wind-battery system under step-rate and time-of-use tariffs. International Journal of Renewable Energy Research **10** (10 2020)

3. Casey, J.A., Fukurai, M., Hernández, D., Balsari, S., Kiang, M.V.: Power outages and community health: a narrative review. Curr Environ Health Rep **7**(4), 371–383 (Nov 2020)
4. Galatsopoulos, C., Papadopoulou, S., Ziogou, C., Trigkas, D., Voutetakis, S.: Optimal operation of a residential battery energy storage system in a time-of-use pricing environment. Applied Sciences **10**(17) (2020). https://doi.org/10.3390/app10175997, https://www.mdpi.com/2076-3417/10/17/5997
5. Halkos, G.E., Gkampoura, E.C.: Evaluating the effect of economic crisis on energy poverty in europe. Renewable and Sustainable Energy Reviews **144**, 110981 (2021). https://doi.org/https://doi.org/10.1016/j.rser.2021.110981, https://www.sciencedirect.com/science/article/pii/S1364032121002732
6. Hoffmann-Burdzińska, K., Stolecka-Makowska, A., Flak, O., Lipowski, M., Łapczyński, M.: Consumers' social responsibility in the process of energy consumption—the case of poland. Energies **15**(14) (2022). https://doi.org/10.3390/en15145127, https://www.mdpi.com/1996-1073/15/14/5127
7. Kashour, M., Jaber, M.M.: Revisiting energy poverty measurement for the european union. Energy Research Social Science **109**, 103420 (2024). https://doi.org/https://doi.org/10.1016/j.erss.2024.103420, https://www.sciencedirect.com/science/article/pii/S2214629624000112
8. Merrington, S., Khezri, R., Mahmoudi, A.: Optimal planning of solar photovoltaic and battery storage for electric vehicle owner households with time-of-use tariff. IET Generation, Transmission & Distribution **16**(3), 535–547 (2022). https://doi.org/https://doi.org/10.1049/gtd2.12300, https://ietresearch.onlinelibrary.wiley.com/doi/abs/10.1049/gtd2.12300
9. Sundt, S., Rehdanz, K., Meyerhoff, J.: Consumers' willingness to accept time-of-use tariffs for shifting electricity demand. Energies **13**(8) (2020). https://doi.org/10.3390/en13081895, https://www.mdpi.com/1996-1073/13/8/1895
10. Villanueva, D., Cordeiro, M., Feijóo, A., Míguez, E., Fernández, A.: Effects of adding batteries in household installations: Savings, efficiency and emissions. Applied Sciences **10**(17) (2020). https://doi.org/10.3390/app10175891, https://www.mdpi.com/2076-3417/10/17/5891