DOI: https://doi.org/10.15407/techned2025.03.073

IMPACT OF SEASONALITY OF GENERATION AND LOAD ON THE OPTIMAL CAPACITY OF THE ENERGY STORAGE SYSTEM OF THE PROSUMER'S MICROGRID

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Due to the instability of renewable energy sources, maintaining the stable operation of microgrids becomes an urgent and difficult task. energy storage systems can provide uninterrupted power for such Microgrids, but their integration is accompanied by challenges related to determining the optimal storage parameters. This study presents a method that allows optimizing the capacity of the energy storage system, taking into account various controller algorithms of the operation of the prosumer's microgrid. Purpose. Development of a method for determining the optimal capacity of an energy storage system to maximize profit from interaction prosumer's microgrid with the power grid. Two radically different controller algorithms of microgrid operation are considered: the first is focused on the maximum use of solar generation, and the second is on the balanced use of all elements of the prosumer's microgrid system, including storage and energy consumption. A microgrid was studied using the example of a prosumer, which includes a solar photovoltaic system, a load profile, an energy storage system and connection to the power grid at a three-zone time-to-use tariff. In order to evaluate the effectiveness of the selected strategies, an analysis of indicators for winter and summer days was carried out, which made it possible to reveal the effect of seasonality on the operation of the microgrid. The proposed method allows to determine the capacity of the energy storage system when designing individual solar photovoltaic system. References 15, table 2, figures 10.
Key words: microgrid, load modelling, prosumer, energy storage, renewable energy sources, optimization.

Introduction. Microgrids (MGs) are self-contained low-voltage energy systems that are predominantly used in modern power grids to generate energy from renewable energy sources. microgrids include Distributed Energy Resources (DERs) based on renewable energy sources such as wind and solar generation systems, forecasted and stochastic consumers (their Load Profiles), and Energy Storage Systems (ESS) [1–5]. Prosumer is an active consumer who has a two-way connection with the Power Grid [6, 7].

In turn, the MGs of the prosumer should include a generation system, a load profile, an energy storage system, a control system and be able to transmit electricity to the power grid in two ways. Also, such systems, in the case of disconnection from the Power Grid, should be able to operate autonomously for some time.

Due to the inconsistency of the generation of renewable energy sources (RES), the operation of MGs becomes unreliable, which necessitates the use of Battery energy storage systems that can instantly supply energy if necessary [6–8]. Unreliability is also driven by demand due to fluctuating loads on the consumer side and variations in electricity prices [9, 10]. This leads to voltage and frequency fluctuations, and also affects the stable operation of the system. Such problems can be solved with the help of ESS [1, 2, 4, 8, 11, 12].

In recent years, many researchers have been presenting control algorithms for Microgrids based on advanced electronic devices [7, 13]. These strategies formulate a complex objective function that takes into account the costs of operating and maintaining generating plants, the cost of exchanging with the grid, as well as greenhouse gas emissions. However, they are not sufficiently focused on determining the optimal capacity of the energy storage system. In progress [7, 8, 12, 14, 15] Consumer load management strategies are developed that include demand-response programs such as incentive or dynamic pricing and direct load management. While these strategies optimize energy costs, their demand-response programs are mainly aimed at reducing the

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ratio of peak to average demand, i.e., load equalization. However, in the case of MGs, these demand-responds programs do not significantly improve the cost-effectiveness and reliability of the system.

Therefore, in order to make the Prosumer's Microgrid cost-effective and efficient, it is needed to develop a strategy for determining the optimal ESS capacity based on the prosumer's load profile, which focuses on: 1) maximizing the prosumer's profit from interacting with the grid and 2) efficient use of the Battery Energy Storage System (BESS) taking into account the load that is not provided by renewable energy. In contrast to existing approaches, the proposed ESS capacity determination algorithm is aimed at maximizing battery utilization and interaction with the power grid. This is achieved by using a three-zone time-of-use tariff plan for electricity and developed strategies for the operation of energy storage.

The goal of the paper is development of a method for determining the optimal capacity of the energy storage system to maximize the profit of the prosumer's microgrid from interaction with the electric power grid due to different seasons as winter and summer.

Subject of investigations. The developed model of the prosumer includes a rooftop solar photovoltaic system with a capacity of 8 *kW*, the Load Profile described in the paper [6], ESS with a smart controller and connection to the power grid. Mathematical model makes at Matlab. The Single-line diagram of the developed Prosumer's Microgrid is shown in Figure 1.

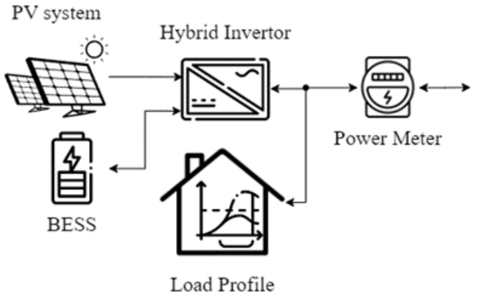
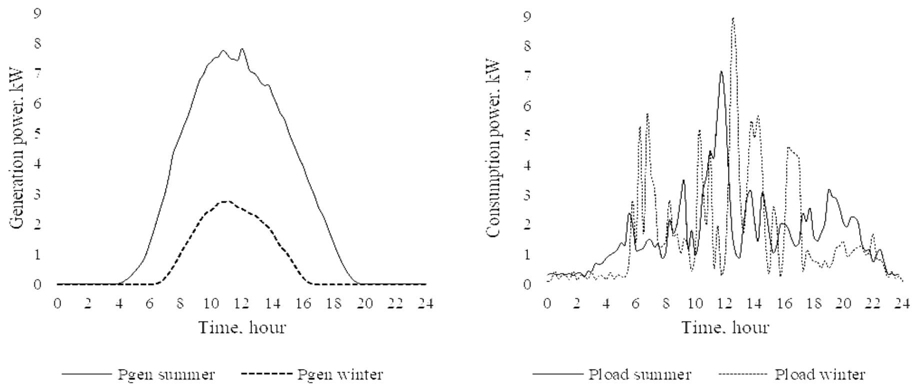


Fig. 1

At Figure 2, *a* shows a profile of generation for the summer and winter seasons obtaining from the SoDa [3], as well as the Load Profiles of a family shown at Figure 2, *b*. The load profile is average in the profiles for the summer and winter seasons of the typical family's working day, generated by LPG [6]. The family consists of two adults working remotely and two children. The house is equipped with a standard set of equipment for a comfortable stay and has a gas heating system.



a ***b***

Fig. 2

Basic calculation relationships and assumptions.

Objective function: The objective function presented at formulae (1) is aimed at maximizing the profit received from the sale of electricity to the power grid. It consists of the sale of electricity to the power grid (3), the cost of purchasing electricity from the power grid (4) and the cost of using a unit of capacity of the energy storage system (5).

$$\max_{C} \sum_{i=0}^{N} \left(C_{sell}(t_i) - C_{buy}(t_i) - C_{main}(t_i) \right), \quad (1)$$

$$N = T/\Delta T, \quad (2)$$

where T is the total duration of the test period of system operation; i is the number of the time period into which the test period is separeted; N is the number of time periods; $\Delta T = 0,25$ is time period, *hour*; $t_i = i \cdot \Delta T$ is the moment of the beginning of the *i*-th time period; $C_{sell}(t_i)$ is the total cost of power sold to the grid for the period t_i, *$*; $C_{buy}(t_i)$ is the total cost of power purchased from the grid for the period t_i, *$*; $C_{main}(t_i)$ is the total cost of operating the ESS for the period t_i, *$*

$$C_{sell}(t) = P_{sell}(t) \cdot K_{encost}(t) \cdot E_{tariff} \cdot \Delta T \text{ ,} \tag{3}$$

where $P_{sell}(t)$ is power sold to the Power Grid in a period of time *t*, *kW*; $K_{encost}(t)$ is electricity cost factor as a function of time *t*; E_{tariff} is electricity tariff, *$/kWh*.

$$C_{buy}(t) = P_{buy}(t) \cdot K_{encost}(t) \cdot E_{tariff} \cdot \Delta T \text{ ,} \tag{4}$$

where $P_{buy}(t)$ is power purchased from the Power Grid over a period of time *t, kW*.

$$C_{main}\left(t\right) = BC \cdot K_{BC} \cdot \Delta T \text{ ,} \tag{5}$$

where BC is ESS capacity, *kWh*; K_{BC} is the cost of using a unit of ESS, $/(kWh·h).

$$K_{BC} = \frac{Cost_{batt} \cdot 10^3}{U_b \cdot I_b \cdot h_b} \text{,} \tag{6}$$

where $Cost_{batt}$ is the cost of one battery, *$*; h_b is estimated battery life-time 10 year, corresponding to 3500 cycles of charge/discharge, *hour*; U_b is battery voltage, *V*; I_b is battery capacity, *Ah*.

Prosumer's Microgrid power balance equation: The installed MGs satisfies the load of the domestic building and exports electricity to the power grid. The power balance equation at each time *t* is given by the formula (7).

$$P_{grid}(t) = P_{gen}(t) - P_{load}(t) + P_{BESS}(t) \text{,} \tag{7}$$

where $P_{gen}(t)$ is generation capacity in time period *t, kW*; $P_{load}(t)$ is load power in time period *t*, *kW*; $P_{BESS}(t)$ is the charge or discharge power of the ESS in the time period *t*, *kW*.

$$P_{BESS}(t) = P_{discharge}(t) - P_{charge}(t) \text{,} \tag{8}$$

where $P_{discharge}(t)$ is the power of the ESS discharge in the time period *t*, *kW*; $P_{charge}(t)$ is the power of the ESS charge in the time period *t*, *kW*.

All types of power at equations (7), (8) takes as constant for a period of time ΔT, that is, taken as average power during this period.

Technical limitations of the Prosumer's Microgrid: When modeling MGs, it is necessary to take into account the limitations of the ESS operation. The system must not exceed the limit values of the battery's charge or discharge power to ensure a guaranteed period of operation of the energy storage system. In this study, for simplicity, the charging/discharging process is considered linear depending on the SOC parameter.

The maximum charging power of the battery is found by equation (9)

$$P_{charge.max} = 0.8 \cdot BC \cdot 1\left[h^{-1}\right], \tag{9}$$

$$0 \le P_{charge} \le P_{charge.max} \text{.} \tag{10}$$

The maximum discharging power of the battery is according to equation (11)

$$P_{discharge.max} = 0.8 \cdot BC \cdot 1\left[h^{-1}\right], \tag{11}$$

$$0 \le P_{discharge} \le P_{discharge.max} \text{.} \tag{12}$$

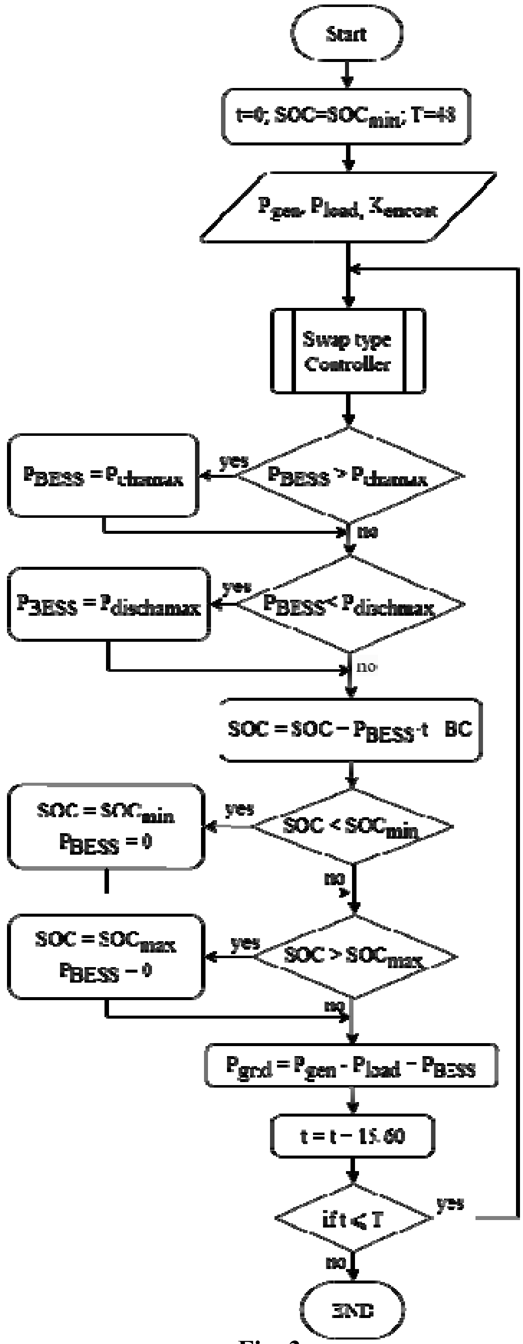


Fig. 3

Limitations on the state of charge of the battery must also be taken into account

$$SOC_{\min} \le SOC \le SOC_{\max} \text{ ,} \tag{13}$$

where SOC is the state of charge of the ESS battery in relative units; SOC_{min} is the minimum permissible state of charge of the ESS battery; SOC_{max} is the maximum permissible state of charge of the ESS battery.

Prosumer's Microgrid Modeling and Management Algorithms. In the work, the limit values of the state of charge of the battery are taken as $SOC_{\min} = 0.2$ and $SOC_{\max} = 1$. At Figure 3 shown working algorithm of Prosumer's Microgrid showed. The simulation covers two days, 15 minutes increments, all balance equations are calculated for 192 intermediate points. Only the second day data is involved in the analysis, the first is used as "calibrated day" due to the inability to determine the initial conditions for the first day.

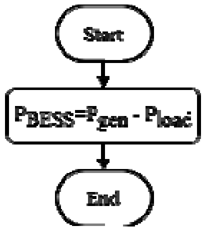


Fig. 4

Direct controller algorthm (DirC): The "direct" controller algorithm is focused on preserving peak generation with the help of ESS and transferring it to the evening and night hours. The controller algorithm is implemented by changing modes as shown in Figure 4.

Case 1. The load power exceeds the output power of the Solar Photovoltaic System. There are two options for this mode:

– 1a. The battery is not completely discharged. The load is partially provided by its own generation, the deficit is covered by the battery.

– 1b. The battery is completely discharged. The load is partially provided by its own generation, the deficit is covered by the power grid.

Case 2. The output power of generation exceeds the load capacity. There are two options for this mode:

– 2a. The battery is not fully charged. The load is provided by its own generation, the exceeds goes to charge the battery.

– 2b. The battery is fully charged. The load is provided by its own generation, the exceeds is sold to the grid.

Smart controller algorithm (SmC): The "smart" controller algorithm is aimed at maximizing profits from the sale of electricity at peak times at a three-zone time-of-use tariff. The controller algorithm is implemented by series changing modes during the day, as shown in Figure 5. Here h is hour number in the current conditions.

Case 1. Dawn from 7:00 a.m. to 8:00 p.m. There is no own generation, we cover our own load from the power grid.

Case 2. Morning from 8:00 a.m. to 11:00 a.m. Tariff coefficient K_{encost}= 1.5. We cover our own load with the energy accumulated in the battery and sell all our own generation to the power grid. Provided that the battery charge has dropped to a minimum value, we use our own generation and purchase energy from the power grid. We do not charge the battery (we use it only for discharge).

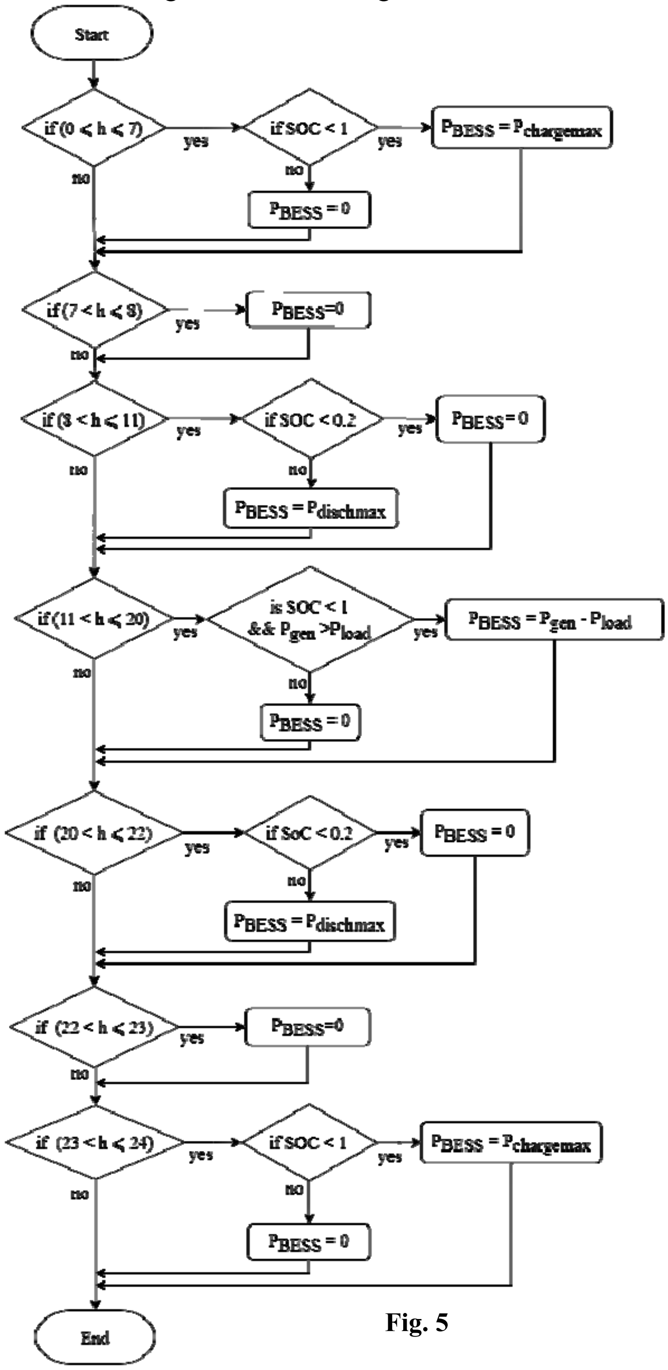


Fig. 5

Case 3. Lunch from 11:00 a.m. to 8:00 p.m. Tariff coefficient K_{encost}= 1. We use batteries only to charge from our own generation. Provided that our own load exceeds our own generation, we additionally use energy from the grid to cover the deficit. Provided that we cover our own load at the expense of our own generation, then we use the exceeds energy to charge the battery. If the battery charge has reached its maximum value, then we sell the excess energy to the power grid.

Case 4. Evening from 20:00 to 22:00. We cover our own load with the energy accumulated in the battery. Provided that the battery charge has dropped to the minimum value, we use our own generation and purchase energy from the power grid. We do not charge the battery (we use it only for discharge).

Case 5. Dusk from 10:00 p.m. to 11:00 p.m. There is no own generation, we cover our own load from the battery and from the power grid. We do not charge the battery (we use it only for discharge).

Case 6. Night from 11:00 p.m. to 7:00 a.m. Tariff coefficient K_{encost} = 0.4. We charge the battery to the maximum value and cover our own load from the power grid. We use the battery only for charging from the mains.

Optimization method. To solve the optimization problem, the Hook-Jeeves direct search method was chosen. The search starts at the starting point x0, called the old basis, and is carried out along the coordinate directions. In each direction, in turn, with steps $+t_0$ and $–t_0$, the conditions for finding a local solution are checked, after which the new base point is x_1 with the coordinates obtained as a result of successful steps.

The direction from the old basis to the new one determines the direction of the search acceleration, and as the next point of the minimizing series is checked $y_1 = x_0 + \lambda(x_1 - x_0)$. Here, λ is the accelerating multiplier, which is determined automatically in Matlab. If point y1 is successful, it becomes the next point to explore, otherwise the search continues from point x1. The search ends when the accuracy of the coordinates reaches less than 10^{-6}.

This study looked at one type of Prosumer and its load model in winter and summer, as described in [11]. The installed load capacity of the Prosumer is 10 *kW*, and the daily consumption throughout the year varies from 12 to 24 *kWh*. Simulation of the prosumer's microgrid was carried out for the rated power of the Rooftop Solar Photovoltaic System of 8 *kW*, separately for the winter and summer periods of the year. The duration of the test period of operation of the system *T* at equation (1) was 48 hours, that is, one day. Numerical simulation and optimization were performed using Matlab.

Given the local nature of the chosen optimization method, the complexity of equation (1) and the changing simulation conditions, the choice of starting point x0 can significantly affect the results. Therefore, for verification, the algorithm was run from the starting points x_0 = 0, x_0 = 30, x_0 = 60. These x_0 values correspond to the edges and medium of the desired ESS battery capacity range. The results showed that running from all starting points resulted in the same solution, although the number of iterations differed but did not exceed 50.

Simulation results. In this model, the cost of electricity is taken as $E_{tariff} = 0.1 \cdot K$ [*$*]. Figure 6 shows the hourly profile of the zonal pricing coefficient *K* for a prosumer at a three-zone time-of-use tariff.

To assess the effectiveness of the proposed algorithms for controlling the Prosumer's Microgrid, it is considered on the example of the winter and summer seasons. A day ($T = 24$) is simulated to assess the effectiveness of the ESS, the modeling step is selected in 15 minutes. The work did not take into account the limitations of connecting the MGs to the Power Grid.

The following are profiles of the MGs example for the "direct" and "smart" controller algorithm. Figure 7 shows the *SOC* parameters of the optimal ESS capacity of smart and direct controller algorithms. Figure 8 shows the charging / discharging power of the ESS. Figure 9 shows the MGs power that is transmitted to the power grid.

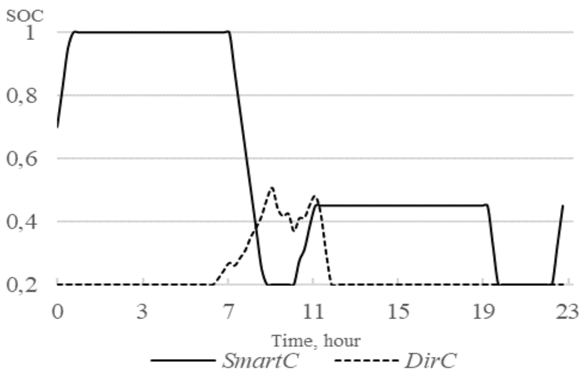


Fig. 6

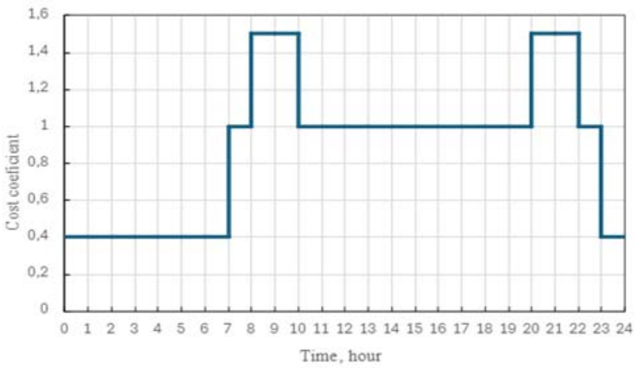


Fig. 7

Table 1 and Table 2 shows the generalized results obtained for the summer and winter seasons under different controller algorithms of MGs operation. For each of the controller algorithms, simulations were carried out at different values of the ESS capacitance. Figure 10 shows the dependence of profit on the capacity of the ESS for the summer (*a*) and winter (*b*) seasons. In economic calculations, the issue of RES taxation was not taken into account.

Table 1

Controller algorithm	*DirC*			*SmartC*					
BC, kWh	0	10	20	11,15	30	55	70	94,5	100
$P_{\sum sell}$, *kWh*	36,224	28,269	22,546	44,801	68,512	103,188	124,953	160,395	168,167
$C_{\sum sell}$, *$*	4,373	3,363	2,480	5,975	9,868	15,363	18,759	24,271	25,518
$P_{\sum buy}$, *kWh*	12,352	4,488	1,855	21,495	48,234	86,609	110,234	148,554	160,859
$C_{\sum buy}$, *$*	1,206	0,214	0,076	1,403	3,135	5,732	7,352	9,987	10,940
K_{BC}, *$/(kWh·h)*	0,004	0,004	0,004	0,004	0,004	0,004	0,004	0,004	0,004
Profit, $	3,168	2,268	0,641	3,589	4,088	4,782	5,236	5,954	5,763

Table 2

Controller algorithm	*DirC*			*SmartC*					
BC, kWh	0	10	20	5	11,15	15	25	55	94,2
$P_{\sum sell}$, *kWh*	4,369	0,000	0,000	7,673	13,823	16,057	24,807	51,057	85,357
$C_{\sum sell}$, *$*	0,593	0,000	0,000	1,160	2,109	2,454	3,804	7,854	13,146
$P_{\sum buy}$, *kWh*	29,201	25,838	25,231	33,745	40,049	44,254	54,504	85,254	125,434
$C_{\sum buy}$, *$*	2,888	2,491	2,428	3,055	3,372	3,610	4,124	5,667	7,683
K_{BC}, *$/(kWh·h)*	0,004	0,004	0,004	0,004	0,004	0,004	0,004	0,004	0,004
Profit, $	-2,295	-3,372	-4,191	-2,336	-2,245	-2,478	-2,524	-2,661	-2,841

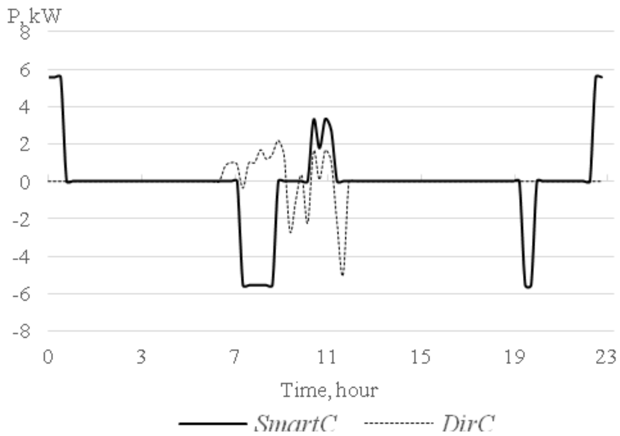


Fig. 8

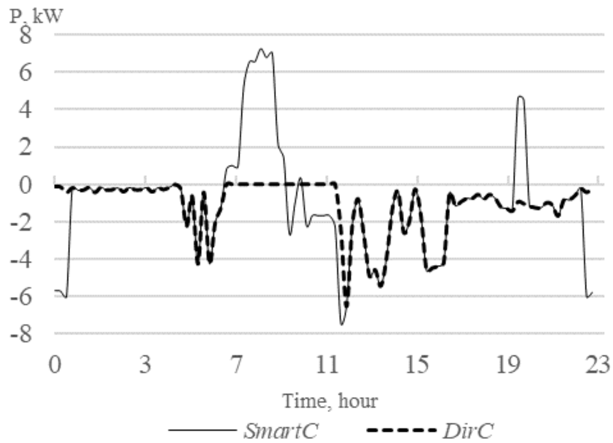
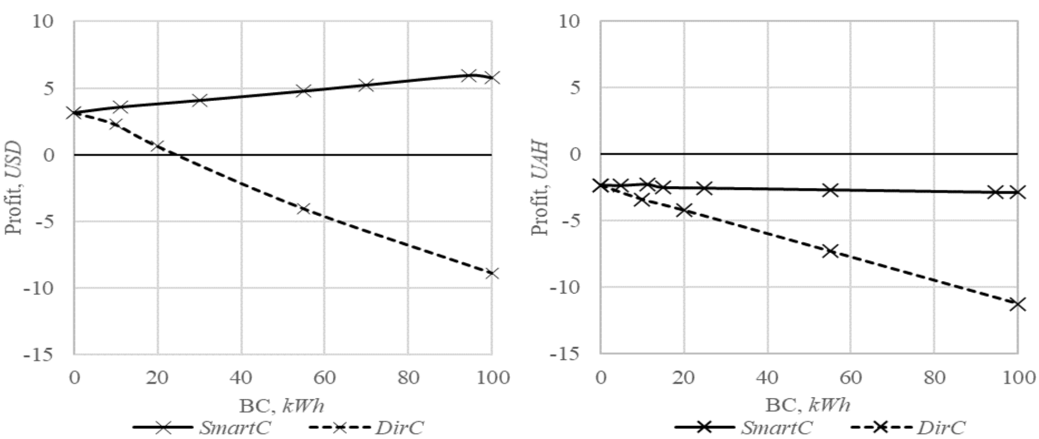


Fig. 9



a ***b***

Fig. 10

In the case of a "smart" controller algorithm, the optimal value of the ESS capacity will be 94.5 *kWh*. This is due to the fact that at lower values of the ESS capacity, the amount of energy purchased during peak hours is quite expensive. Otherwise, if the capacity of the ESS is higher than the optimal one, the cost of using a unit of ESS capacity makes the use of such systems economically unprofitable.

Based on the results from Table 2, In the winter season, the "direct" and "smart" controller algorithms are not profitable. This is due to the fact that, unlike the summer season, its own generation falls sharply. The optimal solution for a "direct" controller algorithm would be the rejection of ESS. In turn, the optimal value of the ESS capacity according to the "smart" controller algorithm allows us to reduce spending. It should be noted that the results obtained by the ESS capacity correspond to the goal of obtaining maximum profit and, when choosing a different management strategy, may differ significantly.

Conclusions. In this work, a detailed study of the influence of seasonality on the optimal capacity of ESS in prosumer's microgrid was carried out. The main purpose of the study is to determine the optimal strategies for ESS management to maximize profits from interaction with power grids in the context of variable seasonal characteristics of electricity generation and consumption.

The simulation results showed that in winter, when domestic electricity generation is significantly reduced, the controller algorithms of "direct" and "smart" management do not provide profit. This indicates that in conditions of low generation, the optimal solution may be to abandon the use of ESS, since the costs of its operation outweigh the possible benefits.

At the same time, in the summer season, when generation is more stable and higher, choosing a "smart" controller algorithm can significantly increase profits. If we take into account the limitations of the power grid connection, then the data of the optimal values of the ESS capacity will change. The next stage of the study involves determining the impact of constraints, connecting the power of the prosumer's microgrid to the power grid, on the optimal capacity of the ESS.

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УДК 621.3

ВПЛИВ СЕЗОННОСТІ ГЕНЕРАЦІЇ ТА НАВАНТАЖЕННЯ НА ОПТИМАЛЬНУ ЄМНІСТЬ СИСТЕМИ НАКОПИЧЕННЯ ЕЛЕКТРОЕНЕРГІЇ МІКРОМЕРЕЖІ ПРОСЬЮМЕРА

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У зв'язку з нестабільністю відновлюваних джерел енергії підтримка сталої роботи мікромереж стає актуальним і складним завданням. Системи накопичення енергії можуть забезпечити безперервне живлення для таких мікромереж, проте їхня інтеграція супроводжується викликами, пов'язаними з визначенням оптимальних параметрів систем накопичення енергії. У роботі представлено методику, що оптимізує ємність системи накопичення енергії, враховуючи різні алгоритми контролера для функціонування мікромережі просьюмера. Розроблено метод визначення оптимальної ємності системи накопичення енергії задля максимізації прибутку від взаємодії з мережею. Розглядаються два кардинально різних алгоритми контролера роботи мікромережі: перший зосереджений на максимальному використанні сонячної генерації, а другий – на збалансованому використанні усіх елементів системи, включаючи накопичувачі і споживачі енергії. Досліджено мікромережу на прикладі просьюмера, що включає сонячну фотоелектричну систему, профіль навантаження, систему накопичення електроенергії та підключення до енергомережі за тризонним тарифом. Задля оцінки ефективності обраних стратегій проведено аналіз показників для зимового та літнього днів, що дало можливість виявити вплив сезонності на роботу мікромережі. Запропонований метод дає змогу визначати ємність системи накопичення енергії під час проєктування індивідуальних фотоелектричних систем генерації. Бібл. 15, табл. 2, рис. 10.

Ключові слова: мікромережа, моделювання навантаження, просьюмер, системи накопичення енергії, відновлювані джерела енергії, оптимізація.

Received 28.10.2024
Accepted 20.01.2025