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Framework for managing day-ahead trading and storage scheduling in PV-based prosumer microgrids with islanding capability

Abstract: The integration of photovoltaic (PV) generation and energy storage systems in prosumer microgrids enables active participation in electricity markets. However, efficient management

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of day-ahead trading and storage scheduling remains challenging, particularly under forecast uncertainties and the need for islanding readiness. This study aims to develop a comprehensive framework for managing day-ahead electricity trading and energy storage scheduling in PV-based prosumer microgrids. The framework seeks to maximize economic profit while ensuring operational reliability and maintaining adequate reserves for potential islanded operation. The proposed approach employs day-ahead optimization based on forecasts of solar generation and critical load demand. These forecasts serve as input data for determining market transactions and optimal storage operation strategies. The framework was evaluated using historical operational and market data to assess its effectiveness in achieving profitability and reliability. Simulation results demonstrate that the framework enables efficient coordination of market participation and energy storage operation, achieving improved economic outcomes and maintaining sufficient energy reserves for islanded operation. The methodology effectively balances trading benefits with the technical constraints of prosumer systems under forecast uncertainty. The proposed management framework enhances the economic and operational performance of PV-based prosumer microgrids. It provides a practical tool for supporting intelligent decision-making in electricity markets and contributes to the development of resilient, self-sufficient energy communities.

KEYWORDS: microgrid, economic dispatching, electricity trading, managing day-ahead trading, day-ahead scheduling

Introduction

The global energy transition toward decentralized and renewable-based power systems has led to the rapid emergence of prosumer microgrids – localized networks that both generate and consume electricity (Polyanska et al. 2024). Among renewable sources, photovoltaic (PV) systems play a dominant role due to their scalability and declining installation costs. However, the inherently intermittent nature of solar power, combined with fluctuating electricity market prices, significantly increases the complexity of operational planning for such systems (Beshta et al. 2015a). Traditional management approaches are often insufficient to balance electricity production, consumption, and storage while ensuring reliable operation during grid disturbances (Diachenko et al. 2025). Consequently, there is a growing need for intelligent frameworks capable of coordinating market participation with technical and operational constraints in PV-based microgrids (Bhattacharya and Mishra 2015).

Moreover, the rapid decentralization of modern power systems and the increasing penetration of renewable energy sources have transformed electricity consumers into prosumers – active market participants who both consume and generate electricity (Beshta et al. 2015b). Prosumer microgrids integrating photovoltaic (PV) generation and energy storage systems (ESS) play a critical role in enhancing sustainability, energy autonomy, and market flexibility (Polyanska et al. 2022). However, the intermittent nature of PV power and the uncertainty of electricity prices necessitate advanced operational strategies to ensure both economic efficiency and system reliability.

The development of a dedicated management framework for day-ahead energy trading and storage scheduling addresses two critical aspects of modern microgrid operation: economic optimization and system resilience (Shcherba et al. 2025a). On the one hand, efficient trading strategies allow prosumers to maximize profits by strategically selling excess electricity or purchasing energy at favorable prices (Pavlychenko et al. 2025). On the other hand, the inclusion of islanding capability, ensuring autonomous operation during grid outages, enhances the security and reliability of local supply (Beshta et al. 2024; Pavlychenko et al. 2025). Bridging these economic and technical dimensions requires integrated decision-support models that combine forecasting, optimization, and risk assessment (Bulińska et al. 2025). Despite significant advances in renewable integration, literature still lacks comprehensive methods that jointly optimize market interaction and islanding preparedness (Beshta et al. 2015b; Bulińska et al. 2025; Polyanska et al. 2024).

Day-ahead scheduling of energy trading and storage operation is a key component for prosumer microgrids seeking to minimize energy costs while participating in electricity markets (Pivnyak et. al. 2025). In this study, day-ahead schedules are developed based on the concept of rational prosumer behavior (Gitelman et al. 2019), where all decisions on electricity trading and storage operation are driven by cost minimization under forecast uncertainties and market constraints (Shcherba et al. 2025b). At the same time, maintaining islanding readiness, the capability to supply critical loads autonomously during grid outages, requires careful allocation of energy reserves in storage systems (Beridze et al. 2025). Balancing these dual objectives poses significant modelling and optimization challenges, especially under forecast uncertainties of PV generation and load demand (Brecl and Topič 2018; Bulińska et al. 2025).

Existing studies have explored day-ahead scheduling, stochastic optimization, and robust planning approaches for microgrids (Beshta et al. 2015a; Brecl and Topič 2018; Bulińska et al. 2025; Polyanska et al. 2024; Vladyko et al. 2025). Nevertheless, many of them either neglect the explicit consideration of islanding reserve constraints or fail to analyze their impact on rational prosumer behavior in electricity markets. Furthermore, the integration of trading decisions, storage operation, and islanding readiness into a unified day-ahead optimization framework remains underexplored (Bulińska et al. 2025; Kolb et al. 2020).

The remainder of this paper is structured as follows. Section 2 reviews related work on microgrid scheduling, energy trading, and reserve management. Section 3 presents research gaps and problem statement for models and methods in publication. Section 4 presents the mathematical models for energy trading, storage scheduling, and reserve allocation. Section 5 describes the optimization framework and solution methodology. Section 6 outlines the experimental research tasks, defines microgrid operating scenarios under characteristic conditions, and describes the data sources. Section 7 provides numerical results and discusses their implications for rational prosumer behavior. Finally, Section 8 concludes the paper and outlines future research directions.

Despite significant progress in the integration of renewable energy sources and the operation of prosumer microgrids, several critical gaps remain in the existing literature. Most studies either focus solely on day-ahead energy trading or on storage scheduling, without explicitly considering the interaction between market participation and islanding capability. Moreover, existing optimization approaches often overlook the influence of rational prosumer behavior under uncertainties in PV generation, load demand, and electricity prices. While stochastic and robust optimization methods have been applied to microgrid management, a unified framework that jointly addresses trading decisions, storage allocation, and reserve readiness is largely absent. This gap limits the practical applicability of current methods for ensuring both economic efficiency and operational resilience in real-world PV-based prosumer microgrids.

This study addresses these gaps by proposing a comprehensive, data-driven framework that integrates day-ahead energy trading, storage scheduling, and islanding readiness within a single optimization model. The novelty lies in combining economic objectives with technical constraints, explicitly modeling rational prosumer behavior, and accounting for uncertainties in generation and market conditions. By bridging market-oriented decision-making with grid-independent operational security, the proposed framework enables prosumer microgrids to achieve both profitability and resilience. The approach offers actionable insights for microgrid operators, policy makers, and energy aggregators, providing a scientifically grounded and practically relevant tool for enhancing sustainability, energy autonomy, and market flexibility in the evolving decentralized energy landscape. Therefore, this research is not only scientifically justified but also essential for enabling intelligent, market-oriented, and resilient operation of renewable microgrids in the evolving energy landscape.

1. Related works and reference background

Recent advances in distributed energy resources (DERs) and photovoltaic (PV) technologies have intensified research on intelligent management of prosumer microgrids within the context of liberalized electricity markets (Shcherba et al. 2024, 2025b; Silva et al. 2020). Numerous studies have explored day-ahead optimization frameworks that coordinate power generation, storage utilization, and energy trading to maximize economic benefits (Liu et al. 2017; Silva et al. 2020). Optimization-based methods, including mixed-integer linear programming (MILP), stochastic programming, and model predictive control, are widely employed to handle uncertainties in solar generation and demand forecasts (Liu et al. 2017; Pazynich et al. 2024). Furthermore, the integration of battery energy storage systems (BESS) has been identified as a key enabler for enhancing flexibility and mitigating the volatility of PV output (Faraji et al. 2020). Parallel research streams have focused on islanding operation and resilience, emphasizing the importance of maintaining sufficient energy reserves and seamless transition between grid-connected and autonomous modes (Bashynska et al. 2024; Faraji et al. 2020; Lewicka 2020). Despite these advances, most existing approaches treat market participation and islanding readiness as separate challenges, lacking a unified management strategy. Therefore, this study contributes by developing a holistic framework that integrates day-ahead market scheduling, energy storage optimization, and islanding capability assessment to support both economic efficiency and operational reliability in PV-based prosumer microgrids.

One of the fundamental bases in modeling microgrid modes is standardization, which sets common requirements for architecture, functionality, and control. Thus, (IEC TS 62898-1:2017) provides recommendations for the initial design of a microgrid: resource analysis, load and generation forecasting, distributed energy resources scheduling, technical constraints on control, protection, communications, and project estimation. Use case scenarios for microgrids coordinated with (EC SRD 62913-2-1:2019) are defined. Similarly, (IEEE Std 2030.9™-2019) provides practical recommendations for scheduling and designing microgrids, including configuration of distributed energy resources, security, electrical design, protection, connectivity, monitoring, and measurements. (IEC TS 62898-3-2:2024) Focuses on the technical requirements for energy control systems as a separate level of the control system in microgrids both connected to the distribution system (DS) and in the islanding mode. The document recommends functions for LV/MV systems, including active/reactive power control, energy flows forecasting, balancing be-tween upstream system and local energy resources, economic optimization, participation in market mechanisms, and reserves for increasing system stability. The standard (IEEE 2030.72017) intended for small microgrids, in which the controller implements the control system functions. The functional requirements for the microgrid control system are defined, which should provide both islanded and grid-connected operation as well as continuous transitions between modes, including black-start. The standard describes the required dispatch and transition functions, load balancing, frequency and voltage quality support, and co-ordination with the requirements of the network control system. In general, (IEC TS 62898-3-2:2024; IEEE 2030.72017) consider the efficient use of available energy resources for implementing various control tasks in islanded and grid-connected modes as well as indicate the need for coordinating the mode scheduling function modes with participation in the electricity market.

Planning of daily microgrid operation schedules, taking into account participation in electricity markets and control of energy storage, has been an intensively studied problem in recent years. The following several interrelated areas relevant to the subject of this article may be distinguished in the literature: classical mathematical models of daily schedules; stochastic and robust approaches to account for uncertainties in forecasts; islanding and seamless islanding reservation problems; integration of day-ahead market trading and bid submission strategies; storage sharing architectures, and trade between microgrids. Below, the main approaches and their applications for the problems close to the subject of this publication are briefly summarized.

Many works define the use case of constructing a daily schedule as a mixed integer linear (MILP) or nonlinear (MINLP) programming problem. The target functions in such models minimize the cost of energy procurement (or maximize profit) based on agreed constraints on generation, ESS charging/discharging, controlled loads, and connection point limits. Such models elaborately model battery dynamics (SOC, degradation cycles), schedule PV scheduling, and predict load shedding measures in extreme scenarios. The works (Shcherba et al. 2025b; Silva at al. 2020) provide an example of a full formalism of microgrid resources and a methodology for determining the cost of availability of elements.

To correctly account for price, demand and generation uncertainty, two-stage stochastic models (scenario approach), robust formulations and chance-constraint approaches with risk metrics (e.g., CVaR) have emerged. These approaches allow planning reserves and determining operating schedules that maintain an acceptable level of risk in case of a wide range of scenarios. The individual studies also combine data-driven estimation of uncertainty distribution with robust algorithms for day-ahead and intraday co-ordination. An example of applying such approaches is (Yang et al. 2018). Similarly, (Kyrylenko et al. 2025) describes a robust foundation for designing smart, adaptive, and economically viable with high renewable penetration. In addition, (Chen et al. 2022) provides formalisms for considering the probability of DS power failure in optimization procedures based on economic criteria.

An alternative approach to considering uncertainties is represented by intelligent control systems based on artificial intelligence with machine learning. The complex intelligent energy control system in a residential house microgrid presented in (Gbadega et al. 2024) takes into account both local energy generation and storage systems and various types of energy consumers. (Blinov et al. 2025) provides the Deep Neural Networks apparatus for smart management of energy losses in electrical distribution networks. Several publications consider the complex of sequential solution of day-ahead scheduling problems with subsequent adjustment of schedules during the day. For example (Ahmed et al. 2021), provides a two-stage model with a day-ahead schedule and intraday adaptation.

An individual group consists of works that directly take into account the possibility of transition to the islanding mode: they define the volumes of energy reserve, requirements for reserve power and algorithms for continuous switching (seamless islanding). Such models also use two-stage procedures, initial day-ahead reservation and subsequent real-time adjustment, and may include restraints on readiness for autonomous operation for critical loads. Publications on this subject provide risk-managed and distributed approaches to reserve scheduling to increase reliability in case of outages. For example, in (Nikolsky et al. 2022) a chance-constrained model with reservation for the islanding mode needs is presented and in (Liu et al. 2017) a risk-based day-ahead reservation model is provided.

Trade studies show that optimal participation of microgrids (and prosumers) in day-ahead markets requires modeling of both the energy flow and the ESS capabilities: optimal bid format, input/output times, and consideration of service revenues (reserves, regulation). Classic works on microgrid bidding strategies and hybrid stochastic/robust solutions (bidding strategies) demonstrate the importance of simultaneously optimizing trading and ESS operating modes. In particular, (Nikolsky et al. 2022b) provides game-theoretic approaches to developing a bidding strategy. (Parus et al. 2025) studies an adaptive strategy of participating in the prosumer in bids with responses to changing the market behavior.

Recent research extend the problem: sharing ESS resources (shared ESS) for multiple prosumers, intermicrogrid biding and multi-energy approaches (including hydrogen/heat). These architectures change the optimization criteria (cooperative profits, reserve distribution) and complicate the problem formulation but at the same time provide new opportunities to increase profitability and reliability for a group of microgrids. In particular, (Jani et al. 2023) provides a multi-objective model for coordinating the modes of multiple microgrids. In (García et al. 2023), attention is focused on scenarios of optimal interaction of local electricity sources and ESS with provision of islanding reserves. In (Dąbek et al. 2023), attention is focused on the mode scheduling of the Campus Prosumer Microgrid, in which unregulated (PV) and regulated (diesel generator) energy sources are integrated.

Several publications study the procedures for optimizing modes and electricity trading, taking into account the peculiarities of the structure and pricing rules of national electricity markets. For example, (Jongbaek et al. 2025) is related to the strategy of P2P trading of electricity in a microgrid between the consumer and prosumer by considering the actual electricity market structure in South Korea. In (Parus et al. 2025), models for scheduling microgrid modes are provided, taking into account the peculiarities of pricing in the Brazilian electricity market.

A significant number of publications are related to specifying individual characteristics of the functioning of microgrid energy equipment. For example, (Kumar et al. 2023) provides formalisms for taking into account the degradation of ESS batteries. (Denysiuk and Derevianko 2020) provides models to perform analyses and optimization in real time taking into account power quality issues from different types of distributed generation sources.

Publications on the subject of scheduling microgrid functions reproduce a complex set of problems with the need for coordination of the structure of microgrid energy resources, the purpose and target use cases of the microgrid, the peculiarities of pricing in the national electricity market, the uncertainty of a number of characteristics, and the need to detail the main technological processes of microgrid energy equipment (Denysiuk and Derevianko 2020; Pyzalski et al. 2025). At the same time, a review of the tasks of scheduling microgrid modes has shown a lack of attention to the tasks of scheduling microgrid modes for the prosumer as a participant in the electricity market, taking into account primarily its own economic interests in the complex solution of the tasks of efficient use of available energy resources for regulating the modes and maintaining the state of readiness for the islanding mode. Therefore, the article describes models and calculation methodologies that take into account the joint use of ESS capacity to maintain the state of readiness for the islanding mode and to optimize the electricity balances in the microgrid. According to the results of the calculations, optimal electricity buys, and sale schedules are obtained in terms of economic criteria, which form the basis for forming bids in the electricity trading segments. In addition, the result of the calculations provides for the formation of an optimal ESS charging/discharging schedule. The mathematical apparatus meets the following additional conditions.

The methodological foundation of this research integrates the formalisms of Mixed Integer Linear Programming (MILP), Mixed Integer Quadratic Programming (MIQP), and Mixed Integer Nonlinear Programming (MINLP) to address the optimization of microgrid operation under market-connected conditions. The mathematical models are expressed in canonical form, enabling the application of established optimization solvers and facilitating reproducibility. When necessary, the proposed framework can be extended with robust or stochastic formulations to more accurately represent the uncertainty of key parameters, such as demand forecasts or solar generation profiles.

The concept of reserve for islanding is embedded into the model as a constraint that governs the optimal allocation of the Energy Storage System (ESS) capacity. This dual-purpose allocation ensures that the ESS supports both operational readiness for potential islanded operation and the maximization of economic benefits derived from electricity trading while connected to the distribution system.

The input data consists of day-ahead forecasts of electricity consumption, critical load demand, PV generation, and market prices for electricity purchase and sale. It is assumed that all forecasting tasks have been previously completed, and the resulting data serve as the foundation for the day-ahead optimization process. The model also enables simulation of efficient prosumer behavior, providing an optimal bidding strategy in the day-ahead electricity market that reflects individual economic objectives. Deviations between the actual and scheduled energy balances may indicate forecasting inaccuracies or market manipulation. Hence, the developed models can also be used to generate training datasets for developing intelligent microgrid control and decision-support systems.

The practical orientation of the proposed framework ensures its applicability in real operational environments. The ESS parameters reflect their actual technical condition and can be identified based on operational statistics. Incorporation of real market price schedules guarantees compatibility with the structural requirements of most national electricity markets. The primary objective function of the optimization process is to maximize the prosumer's economic profit, while providing optimal buy/sell schedules that serve as a reliable basis for forming market bids and improving microgrid energy management efficiency.

2. Methodology and methods for the study of day-ahead trading and storage scheduling in PV-based prosumer microgrids with islanding capability

The study employs a structured methodological framework to analyze and optimize day-ahead trading and storage scheduling in PV-based prosumer microgrids, with explicit consideration of islanding capability. The approach integrates mathematical optimization techniques, including Mixed Integer Linear Programming (MILP), Mixed Integer Quadratic Programming (MIQP), and Mixed Integer Nonlinear Programming (MINLP) – to formulate and solve operational and market-participation challenges. Forecasted data for electricity consumption, critical loads, PV generation, and market prices serve as primary inputs, enabling the determination of optimal storage utilization and trading strategies that balance economic profit with operational reliability. Additionally, the methodology allows simulation of prosumer behavior under market and technical constraints, providing a foundation for intelligent decision-making and training of automated control systems. By combining rigorous optimization modeling with practical operational considerations, this framework ensures both efficient energy management and resilience in microgrid operation.

Conceptual bases for building mathematical models. Mathematical models are intended for use in the tasks of scheduling prosumer modes. The main objective of scheduling is to form optimal daily electricity buy/sale schedules according to economic criteria as well as ESS charging/discharging schedules, which implement optimal electricity balances in the local electricity system of the prosumer. According to the results of the modeling, electricity buy/sale schedules are formed that correspond to the concept of rational behavior of the market participant (Gitelman et al. 2019).

The mathematical model takes into account a minimum set of energy equipment of the prosumer (Fig. 1) such as: solar power plant (SPP) as a non-dispatchable generation source based on PV technology and ESS (energy storage system) that is the main means of balancing energy in the local electric power system of the prosumer. It is assumed that the SPP and ESS are connected to an inverter, which implements monitoring and control functions. It is assumed that the volumes of energy output to and received from the DS are recorded by a certified meter as a point of commercial metering of the prosumer.

It is assumed that electricity losses are taken into account in the total values of the volumes of own electricity consumption. The exceptions are the losses of electricity in the ESS that occur in case of its charging and discharging currents. The volumes of such energy losses significantly affect the efficiency of the ESS, i.e., the ratio between the volumes of stored and energy output. Therefore, the losses of electricity in the ESS that occur in case of flow charging and discharging currents are taken into account in the equations of balances of the energy stored in the ESS. In the equations of balances in the local electric power system of the prosumer, the volumes of energy stored in the ESS and output by the ESS correspond to the indicators of monitoring the modes at the node of connecting the ESS to the inverter.

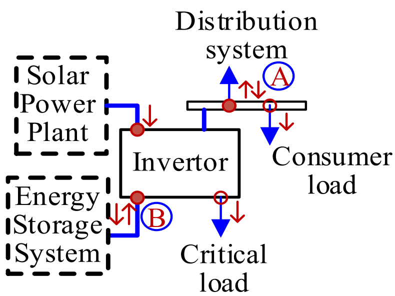


Fig. 1. Single-line diagram for simulating the functions of monitoring and controlling energy flows

Rys. 1. Schemat jednokreskowy symulujący funkcje monitorowania i sterowania przepływami energii

In the mathematical model, the scheduling task is solved taking into account hourly prices in the Day-ahead market segment as an indicator of the market cost of electricity. Therefore, the scheduling task is carried out to generate optimal daily electricity buy/sale schedules (economic day-ahead dispatching according to the classification in (Woźniak et al. 2024)). At the same time, daily electricity buy/sale schedules are segmented into individual calculation periods defined in (Rules of the market. NERC Resolution № 307 from 14.03.2018) as time intervals of 60 minutes. In case of the need for more accurate consideration of the peculiarities of technological processes in the microgrid, shorter time intervals are applied.

Several approaches to electricity metering and pricing schemes for prosumers have been discussed in (Procedure for the sale and accounting of electricity generated by active consumers, and payments for it. NERC Resolution № 2651 of 29.12.2023). In addition, electricity suppliers have the right to establish their own conditions for metering and calculating the cost of electricity for prosumers in commercial agreements. The study of various forms of prosumer participation in the electricity market is beyond the scope of the publication. Therefore, the mathematical models provided define that the prices of electricity buy and sale for each calculation period are input data calculated in advance according to the status and concluded prosumer contracts. In case of the need the framework is expanded with functions for simulating pricing processes in competitive market segments (Ivanov et al. 2019).

Objective function. When formalizing the scheduling objectives, it is essential to consider multiple use cases that leverage the microgrid's energy resources. First, the framework must ensure that the ESS maintains sufficient energy reserves to supply the critical portion of the load during islanded operation. Second, it should enable the efficient utilization of available energy to meet the prosumer's own electricity demand while minimizing costs for electricity imported from the distribution system, particularly when local generation is insufficient for market transactions. Finally, the methodology aims to maximize the prosumer's economic profit by optimizing the deployment of energy resources to fulfill electricity purchase and sale agreements. Collectively, these objectives ensure a balanced approach that combines operational reliability with economic efficiency in PV-based prosumer microgrids.

If the ESS in the microgrid is operated exclusively to support the power supply of the critical part of the load in the islanding mode, the obvious scheduling objective is to maximize the volume of energy stored in the ESS. Such a use case is quite simply implemented by accumulating the full capacity of the ESS and regular charging to compensate for the self-discharge of the storage unit and the costs of the energy stored in the ESS to power the means of monitoring and controlling the storage system. Then, at the beginning of the islanding mode, the ESS will have the maximum energy reserve that provides the maximum power supply of a given critical load, or the maximum power of the critical load for a given period. The value of the critical load power and the critical load power supply time interval may be used as secondary optimization objectives when scheduling technological processes in the islanding mode of operation of the microgrid. However, regardless of the importance of each of the two additional optimization objectives, the primary objective, i.e., the maximum storage of energy in the ESS when connected to the DS, remains unchanged.

The use case of efficient use of available energy resources when connecting the microgrid to the DS involves objectives such as minimizing the costs of buying electricity for the consumer or maximizing the profit (the difference between the cost of sold and bought electricity) for the prosumer. The environmental use cases of microgrid operation may be taken into account by the sum of actual or imaginary payments for harmful emissions. At the same time, increasing the storage unit capacity allocated for the needs of regulating the microgrid modes will increase the economic effect of implementing such a function.

If the operation of the microgrid involves the joint implementation of the use cases of maintaining the state of readiness for the islanding mode and the efficient use of energy resources when connected to the DS, an additional problem of distributing the ESS capacity for the implementation of each of these two tasks arises. The methods for solving this problem are determined primarily by the ratio of the time of operation of the microgrid synchronized with the DS to the time of the islanding mode. The following scenario is considered within the scope of the publication:

- the microgrid operates in the islanding mode at predetermined hours of the day (i.e., disconnection from the DS occurs mainly according to the schedules prepared by the grid operator);
- the available resources of own generation and available volumes of energy import from the DS are sufficient to restore and further maintain the state of readiness of the microgrid for operation in the islanding mode.

Then the following tasks are highlighted in the procedures for scheduling the microgrid modes:

- generating a schedule of minimum volumes of energy stored in the ESS for each calculation period for the needs of powering the predetermined volumes of critical load for not less than the predetermined time of the islanding mode;
- optimizing the microgrid modes during hours of operation synchronized with the DS, where the schedule of minimum energy storage volumes in the ESS is provided by a system of constraints on the minimum permissible volumes of energy stored in the ESS.

In the tasks of scheduling commercial activities, the main objective is to maximize the profit received. For the consumer, the maximization of the profit is achieved by increasing (maximizing) the numerical value of the difference between financial revenues from the sale of electricity and payments for bought electricity:

$$Max\left(GF_{prof}\right)=\sum_{h=1}^{24}\left(-C_h^{buy}\cdot V_{buy,h}^{AC}+C_h^{sale}\cdot V_{sale,h}^{AC}-C_h^{sale}\cdot V_{R,h}^{SPP}\right)-\sum SP \qquad (1)$$

where:

C_h^{buy}, C_h^{sale}	–	prices for the electricity buy and sale, respectively, from the electricity supplier in the calculation period h [₴/kWh],
$V_{buy,h}^{AC}, V_{sale,h}^{AC}$	–	optimization variables, volumes of bought and sold electricity in the calculation period h [kWh],
SP	–	penalty functions, the purpose and description of which are provided below.

Electricity buy/sale schedules correspond to electricity flow schedules at the point of commercial metering of the prosumer. If in scheduling tasks the electricity flow at the point of commercial metering is provided by one variable, the flow direction is determined by the sign, e.g., by positive values of volumes for electricity export to the DS (sale of sold electricity) and negative values of volumes for electricity import from the DS (consumption of bought electricity). However, in the general case, the prices for the electricity buy and sale for an individual calculation period do not have the same values. Therefore, it is convenient to formalize the calculations of the cost of electricity in (1) by two optimization variables: separately for the buy volumes and separately for the sale volumes of electricity. Then, for each direction of the electricity flow through the commercial metering point (import or export), the corresponding value of the electricity price (buy or sale) is provided separately in the objective function (1).

Models for controlling energy flow in given directions. The model is designed to control the direction of energy flows in connection to an individual node in the electrical connection diagram of the prosumer. The principles of formation and the main components of the model for controlling energy flows in given directions are shown in Figure 2.

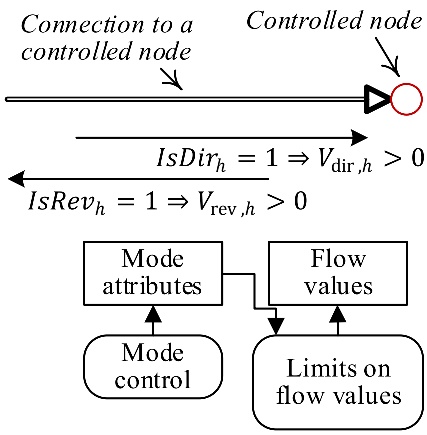


Fig. 2. Structure of the energy flow control model

Fig. 2. Struktura modelu sterowania przepływem energii

For connection to a controlled node, binary attributes denote such modes of the direction of energy flows as: “direct” (direction to the controlled node) and “reverse” (direction from the controlled node). The “standby” mode with a zero value of energy flows is separately distinguished. The model determines the admissibility of the existence of only one mode during the calculation period:

$$IsDir_h + IsRev_h \leq 1 : \forall h = [1..24]$$

where:

$IsDir_h$, $IsRev_h$ – optimization variables, binary attributes of the direct and reverse directions of energy flow in the calculation period h.

For the direct and reverse directions of energy flow, the corresponding variables with the values of such flows are determined. The model sets the following rules for the values of energy flow:

$$\begin{array}{l} V_{dir,h} = \begin{cases} 0 : IsDir_h = 0 \\ 0 : IsDir_h = 1 \end{cases} \\ V_{rev,h} = \begin{cases} 0 : IsRev_h = 0 \\ 0 : IsRev_h = 1 \end{cases} \end{array} : \forall h = [1..24]$$

If the binary attribute of the direct direction of the energy flow is zero, the variable that determines the amount of energy flow in this direction should be zero. If the binary value of the attribute of the direct direction of the energy flow is one, the variable that determines the amount of energy flow in this direction should be greater than zero. These rules are implemented by a system of constraints:

$$\begin{cases} V_{dir,h} - IsDir_h \cdot V_{dir,\max} \le 0 \\ IsDir_h \cdot V_{dir,\min} - V_{dir,h} \le 0 \end{cases} : \forall h = [1..24]$$

where:

$V_{dir,h}$ – a variable, volume of electricity in the direct direction for the calculation period h [kWh],

$V_{dir,\max}$ – the maximum value of volume of electricity in the direct direction for the calculation period h [kWh],

$V_{dir,\min}$ – the minimum value of volume of electricity in the direct direction for the calculation period h [kWh].

The restraint of the minimum volume value for electricity flow in the direct direction is introduced to cut off non-intuitive situations of zero values of electricity volume with the activated direct flow attribute:

$$\left(IsDir_h = 1 \wedge V_{dir,h} = 0\right) \nexists : \forall h = [1..24]$$

Thus, the minimum value of the volume for electricity flow in the direct direction determines the threshold of numerical values, above which the flow value should be considered non-zero.

Similarly, a system of constraints is formed to control the reverse direction of electricity flow:

$$\begin{cases} V_{rev,h} - IsRev_h \cdot V_{rev,\max} \le 0 \\ IsRev_h \cdot V_{rev,\min} - V_{rev,h} \le 0 : \forall h = [1..24] \\ \left(IsRev_h = 1 \wedge V_{rev,h} = 0 \right) \nexists \end{cases}$$

where:

$V_{rev,h}$ – a variable, the electricity volume in the reverse direction for the calculation period h [kWh],

$V_{rev,\max}$ – the maximum value of the electricity volume in the reverse direction for the calculation period h [kWh],

$V_{rev,\min}$ – the minimum value of the electricity volume in the reverse direction for the calculation period h [kWh].

In the scheduling task for the electricity buy/sale schedules by the prosumer, control of the energy flow direction is implemented for two connections:

- connection of the prosumer's power supply system to the commercial electricity metering point in the DS (connection A in Figure 1);
- connection of the ESS to the inverter (connection B in Figure 1).

For the connection of the prosumer's power supply system to the commercial electricity metering point, the directions of the energy flow are interpreted in terms of buy (direction of the electricity flow from the DS to the prosumer's power supply system) and sale (direction of the electricity flow from the prosumer's power supply system to the DS):

$$\begin{cases} IsBuy_h^{AC} + IsSale_h^{AC} \le 1 \\ V_{buy,h}^{AC} - IsBuy_h^{AC} \cdot V_{buy,\max}^{AC} \le 0 \\ IsBuy_h^{AC} \cdot V_{buy,\min}^{AC} - V_{buy,h}^{AC} \le 0 \\ V_{sale,h}^{AC} - IsSale_h^{AC} \cdot V_{sale,\max}^{AC} \le 0 \\ IsSale_h^{AC} \cdot V_{sale,\min}^{AC} - V_{sale,h}^{AC} \le 0 \end{cases} \begin{bmatrix} \nexists \left(IsBuy_h^{AC} = 0 \wedge V_{buy,h}^{AC} > 0 \right) \\ \nexists \left(IsBuy_h^{AC} = 1 \wedge V_{buy,h}^{AC} = 0 \right) \\ \nexists \left(IsSale_h^{AC} = 0 \wedge V_{sale,h}^{AC} > 0 \right) \\ \nexists \left(IsSale_h^{AC} = 1 \wedge V_{sale,h}^{AC} = 0 \right) \end{bmatrix} : \forall h = [1..24] \quad (2)$$

where:

$IsBuy_h^{AC}, IsSale_h^{AC}$ – optimization variables, binary attributes of electricity buy and sale in the calculation period h,

$V_{buy,h}^{AC}, V_{sale,h}^{AC}$ – variables, volumes of electricity buy and sale for the calculation period h [kWh],

$V_{buy,\max}^{AC}, V_{sale,\max}^{AC}$ – maximum values of volumes of electricity buy and sale for the calculation period h [kWh],

$V_{buy,\min}^{AC}, V_{sale,\min}^{AC}$ – minimum values of volumes of electricity buy and sale for the calculation period h [kWh].

For connecting the ESS to the inverter, the directions of electricity flow are interpreted by the terms charging (direction of electricity flow from the inverter to the ESS) and discharging (direction of electricity flow from the ESS to the inverter):

$$\begin{cases} IsCh_h^{ESS} + IsDCh_h^{ESS} \le 1 \\ V_{ch,h}^{ESS} - IsCh_h^{ESS} \cdot V_{ch,\max}^{ESS} \le 0 \\ IsCh_h^{ESS} \cdot V_{ch,\min}^{ESS} - V_{ch,h}^{ESS} \le 0 \\ V_{dch,h}^{ESS} - IsDch_h^{ESS} \cdot V_{dch,\max}^{ESS} \le 0 \\ IsDch_h^{ESS} \cdot V_{dch,\min}^{ESS} - V_{dch,h}^{ESS} \le 0 \end{cases} \begin{bmatrix} \nexists\left(IsCh_h^{ESS} = 0 \wedge V_{ch,h}^{ESS} > 0\right) \\ \nexists\left(IsCh_h^{ESS} = 1 \wedge V_{ch,h}^{ESS} = 0\right) \\ \nexists\left(IsDch_h^{ESS} = 0 \wedge V_{dch,h}^{ESS} > 0\right) \\ \nexists\left(IsDch_h^{ESS} = 1 \wedge V_{dch,h}^{ESS} = 0\right) \end{bmatrix} : \forall h = [1..24] \quad (3)$$

where:

$IsCh_h^{ESS}, IsDch_h^{ESS}$	–	optimization variables, binary attributes of the modes of charging and discharging of the ESS in the calculation period *h,*
$V_{ch,h}^{ESS}, V_{dch,h}^{ESS}$	–	optimization variables, volumes of buy and sale of electricity for the calculation period *h* [kWh],
$V_{ch,\max}^{ESS}, V_{dch,\max}^{ESS}$	–	maximum values of volumes of charging and discharging of the ESS for the calculation period *h* [kWh],
$V_{ch,\min}^{ESS}, V_{dch,\min}^{ESS}$	–	minimum values of volumes of charging and discharging of the ESS for the calculation period *h* [kWh].

Electricity balances of the prosumer. The volumes of electricity flows in the controlled nodes are related by the equations of general energy balances in the electrical connection diagram of the prosumer:

$$V_{buy,h}^{AC} - V_{sale,h}^{AC} + V_{dch,h}^{ESS} - V_{ch,h}^{ESS} - V_{R,h}^{SPP} = V_{oc,h}^{AC} - V_h^{SPP} : \forall h = \left[1..24\right] \quad (4)$$

where:

$V_{oc,h}^{AC}$	–	the forecast volume of the prosumer's own electricity consumption in the calculation period *h* [kWh],
V_h^{SPP}	–	the forecast volume of electricity supply from the SPP in the calculation period *h* [kWh],
$V_{R,h}^{SPP}$	–	forecast volumes of the restraint of the uncompensated surplus of the SPP in the calculation period *h* [kWh].

When scheduling the microgrid modes by the prosumer, a restraint on the volumes of electricity export (sale) is usually determined as follows:

$$V_{buy,h}^{AC} \le V_{buy,\max}^{AC} : \forall h = \left[1..24\right] \quad (5)$$

where:

$V_{buy,\max}^{AC}$ – the maximum permitted volume of electricity export (sale) in the calculation period h, [kWh].

Constraint (5) may be determined by the conditions of connection to the electric grids, the rules of the national electricity market, or the current mode restraints.

Simulation of ESS modes. The mathematical model of the ESS is intended for simulating technological processes in such a plant for use in the procedures for finding optimal schedules of operation of the power equipment of the microgrid. The functional structure of the mathematical model of the ESS is shown in Figure 3.

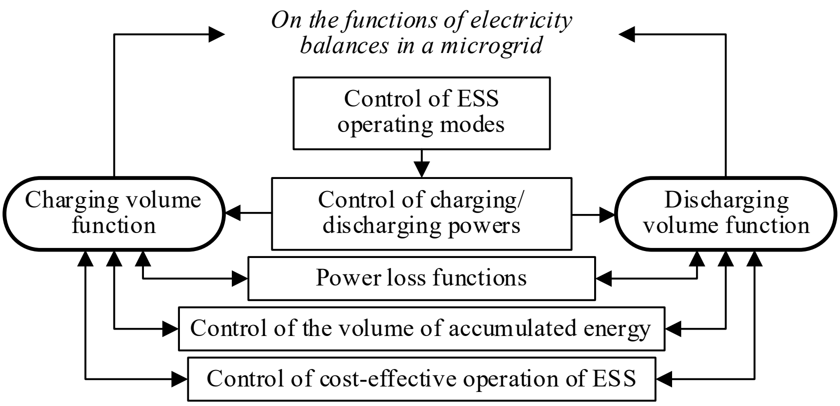


Fig. 3. Functional structure of the mathematical model of the ESS

Rys. 3. Struktura funkcjonalna modelu matematycznego ESS

The mathematical model of the microgrid uses the values of the ESS charging and discharging volumes at the inverter connection node. The ESS charging and discharging volumes are represented in the mathematical model of the microgrid by two corresponding optimization variables used in the microgrid electricity balance equations and their numerical value corresponds to the charging and discharging energy values obtained by means of monitoring and controlling the inverter modes. Representing the ESS operating modes by two optimization variables allows us to take into account the different structure of energy losses (Fig. 4), charging and discharging modes of the energy storage unit.

For compatibility with the microgrid energy balance equations, the charging and discharging processes are represented by the volumes of electricity with the assumption of a uniform charging/discharging capacity of the storage unit during the calculation period. The function of energy losses in the ESS in the charging mode is formed based on two characteristic modes of operation of the storage unit: energy losses in the standby mode (ESS self-discharge) and energy losses in the mode with maximum charging power. Similarly, the function of energy losses in

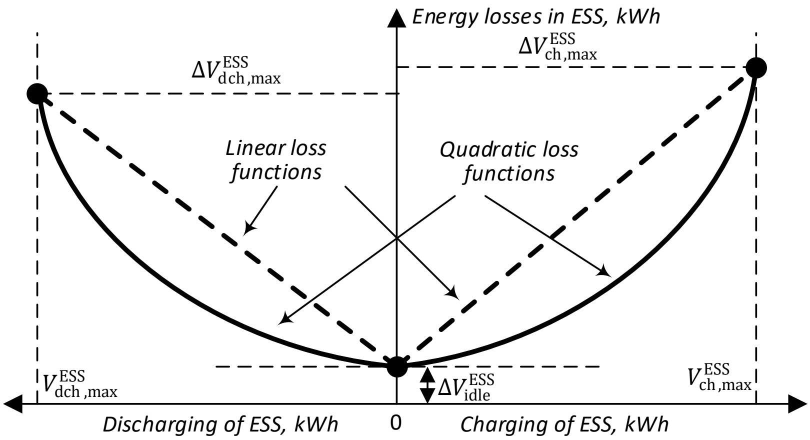


Fig. 4. Energy loss functions in the ESS

Rys. 4. Funkcje strat energii w ESS

the ESS in the discharge mode is formed based on two characteristic modes of operation of the storage device: energy losses in the standby mode and energy losses in the mode with maximum discharging power. Linear characteristics of energy losses in the ESS allow a simplified estimation of the volume of stored energy in the ESS when solving individual tasks of scheduling the microgrid modes (Blinov et al. 2021):

$$\begin{cases} \Delta W_{ch,h}^{ESS}\left(V_{ch,h}^{ESS}\right) = A_{\Delta Sch(l)}^{ESS} \cdot V_{ch,h}^{ESS} \left[A_{\Delta Sch(l)}^{ESS} = \dfrac{\Delta V_{ch,\max}^{ESS}}{V_{ch,\max}^{ESS}} \right. \\ \Delta W_{dch,h}^{ESS}\left(V_{dch,h}^{ESS}\right) = A_{\Delta Sdch(l)}^{ESS} \cdot V_{dch,h}^{ESS} \left[A_{\Delta Sdch(l)}^{ESS} = \dfrac{\Delta V_{dch,\max}^{ESS}}{V_{dch,\max}^{ESS}} \right. \end{cases} : \forall h = [1..24] \quad (6)$$

where:

- $V_{ch,h}^{ESS}$ – an optimization variable, volume of energy storage in the ESS for the calculation period h [kWh],
- $V_{ch,\max}^{ESS}$ – a volume of energy storage in the ESS in conditions of maximum charging power during the calculation period h [kWh],
- $\Delta V_{ch,\max}^{ESS}$ – electricity losses in conditions of maximum charging power during the calculation period h [kWh],
- $V_{dch,h}^{ESS}$ – an optimization variable, volume of energy output from the ESS for the calculation period h [kWh],
- $V_{dch,\max}^{ESS}$ – a volume of energy release from the ESS in conditions of maximum discharge power during the calculation period h [kWh],
- $\Delta V_{dch,\max}^{ESS}$ – electricity losses in conditions of maximum discharge power during the calculation period h [kWh].

Linear functions of energy losses in the ESS (6) allow for the estimation modeling of the microgrid modes using linear programming methods. However, as experimental calculations have shown, a more accurate taking into account electricity losses in different modes of the ESS operation is achieved using quadratic loss functions:

$$\begin{cases} \Delta W_{ch,h}^{ESS}\left(V_{ch,h}^{ESS}\right)^2 = A_{\Delta Sch(2)}^{ESS}\cdot\left(V_{ch,h}^{ESS}\right)^2 \left[A_{\Delta Sch(2)}^{ESS} = \dfrac{\Delta V_{ch,\max}^{ESS}}{\left(V_{ch,\max}^{ESS}\right)^2} \right. \\ \Delta W_{dch,h}^{ESS}\left(V_{dch,h}^{ESS}\right)^2 = A_{\Delta Sdch(2)}^{ESS}\cdot\left(V_{dch,h}^{ESS}\right)^2 \left[A_{\Delta Sdch(2)}^{ESS} = \dfrac{\Delta V_{dch,\max}^{ESS}}{\left(V_{dch,\max}^{ESS}\right)^2} \right. \end{cases} : \forall h = [1..24] \tag{7}$$

The volume of energy stored in the ESS at the end of an arbitrary calculation period of time *h*, taking into account the quadratic functions of energy losses, is calculated by the formula:

$$W_h^{ESS} = W_{beg,h}^{ESS} + \sum_{k=1}^{h}\left(V_{ch,k}^{ESS} - V_{dch,k}^{ESS} - \Delta W_{ch,k}^{ESS}\left(V_{ch,k}^{ESS}\right)^2 - \Delta W_{dch,k}^{ESS}\left(V_{dch,k}^{ESS}\right)^2 - \Delta W_{idle}^{ESS} \right) \\ : \forall h = [1..24] \tag{8}$$

where:

$W_{beg,h}^{ESS}$ – a volume of electricity stored in the ESS at the beginning of the day [kWh],

$V_{ch,k}^{ESS}, V_{dch,k}^{ESS}$ – volumes of electricity in the periods of charging and discharging the ESS, respectively [kWh],

$\Delta W_{ch,k}^{ESS}(V_{ch,k}^{ESS})^2, \Delta W_{dch,k}^{ESS}(V_{dch,k}^{ESS})^2$ – quadratic functions of energy losses (7) in the modes of the function of charging and discharging the ESS, respectively [kWh],

ΔW_{idle}^{ESS} – energy losses in the ESS in the standby mode during the calculation period *h* [kWh].

The system of restraints for controlling volumes of electricity stored in the ESS at the end of the calculation period has the following form:

$$W_{\min,h}^{ESS} \le W_h^{ESS} \le W_{work}^{ESS} : \forall h = [1..24] \tag{9}$$

where:

$W_{\min,h}^{ESS}$ – the minimum level of electricity storage in the ESS at the end of the calculation period *h* [kWh],

W_{work}^{ESS} – the working capacity of the energy storage unit in the ESS as the product of the nominal capacity and nominal depth of discharge [kWh].

Linear energy loss functions (6) are like taking into account a fixed value of the efficiency coefficient in (8) and (9). Using (7) simplifies calculations for long periods of time (e.g., a year) with a fixed number of the ESS charging/discharging cycles during the day. Quadratic energy loss functions (7) allow for additional taking into account time components in the ESS charging/discharging cycle, which significantly affects the actual value of the ESS efficiency coefficient.

The use of quadratic energy loss functions (7) necessitates the use of nonlinear (in particular, quadratic) optimization methods in the microgrid operation mode modeling problems. At the same time, the quadratic energy loss functions additionally allow us to implement a non-price optimization criterion, namely, ensuring, if possible, the same volumes of charging or discharging of the ESS in hours with the same market prices. The need to use such a penalty function is due to the fact that for linear components of the cost in (1) in calculation periods with the same market prices, an area of admissible solutions is formed with an edge (or plane) oriented perpendicular to the axis of the target function values. As a result, a set of equally optimal solutions is formed for periods with the same market prices. One of the methods for solving the problem is to introduce non-linearity into the graph of such an edge (or plane). For this, a nonlinear function of the cost of energy losses in the energy unit, which has the greatest impact on the adjustment of energy balances (4), is added to the linear components of the profit in (1). For the microgrid of Figure 1, such a unit is the ESS. Therefore, an additional non-price optimization criterion is taken into account in the form of a penalty function with the value of the cost of electricity losses in the ESS charging/discharging modes:

$$PF_{\Sigma}^{ESS} = PK_{\Sigma}^{ESS} \cdot \sum_{h=1}^{24} \left(C_h^{buy} \cdot \Delta W_{ch,h}^{ESS} \left(V_{ch,h}^{ESS} \right)^2 + C_h^{sale} \cdot \delta W_{dch,h}^{ESS} \left(V_{dch,h}^{ESS} \right)^2 \right) \tag{10}$$

where:

PK_{Σ}^{ESS} – the penalty coefficient.

The penalty coefficient is applied to minimize distortions in the diagram of the target function (1). The dimension of the penalty coefficient depends on the ratio of market prices and volumes of electricity import/export in the microgrid.

It should be emphasized that the effect of aligning the ESS charging/discharging schedules in periods with the same market prices is introduced by the penalty function of the cost of energy losses (10) formed based on quadratic loss functions (7). The linear loss function (6) in (10) will not affect the optimization results obtained based on the linear components (1). On the other hand, the quadratic loss function (7) in (8) introduces a relatively small fraction of changes in the energy balance equation (4). Therefore, the quadratic loss function (7) in (8) has an extremely weak effect on the optimal solution according to (1).

Restraint of the SPP generation surplus. The concept of surplus of unregulated generation is related to the structure of the microgrid's power equipment, the objectives of the microgrid's operation, and the rules of the national electricity market. When performing practical calculations, it is necessary to separately define "generation surplus, which when used for storage in the ESS may be calculated with zero cost" as well as "generation surplus, which should be forcibly constrained." For example, for a microgrid with the structure of Figure 1, if it is used exclusively for optimizing its own electricity consumption (export of electricity in the DS is prohibited), storage in the ESS with zero cost is determined for part of electricity from the SPP, provided that its own electricity consumption is already fully provided by unregulated generation. Then "generation surplus, which should be forcibly constrained" is defined as part of generation, which may no longer be directly consumed or stored in the ESS.

The peculiarities of taking into account various conditions that affect the definition of the terms "surplus of unregulated generation" require a separate study. Mathematical models for taking into account the zero cost of the surplus of unregulated generation stored in the ESS for the microgrid structure on Figure 1 are provided in (Parus and Blinov 2025). In context of this publication, the term "surplus" is defined for that part of the unregulated generation that may no longer be directly consumed, or exported in the DS, or stored in the ESS. Such a part of the surplus of unregulated generation is forcibly constrained.

The function of forced restraint of unregulated generation is simulated by the penalty function:

$$PF_{\Sigma}^{SPP} = PK_{\Sigma}^{SPP} \cdot \sum_{h=1}^{24}\left(C_h^{buy} \cdot V_{R,h}^{SPP}\right) \tag{11}$$

where:

PK_{Σ}^{SPP} – the penalty coefficient for uncompensated surplus of unregulated generation.

The penalty function (11) in (1) determines the amount of profit lost because of forced restraint of unregulated generation. In most situations, it is sufficient to equate the penalty coefficient in (11) to one. In conditions of low market prices, for the correct use of the penalty function (11), in accordance with the energy balance equations (4), the penalty coefficient value greater than one should be used.

Profitability of the ESS operation. In (Blinov et al. 2024), the need to take into account the cost of the ESS resources to ensure profitable operation of the plant is justified. In contrast to the estimation of the cost of the ESS charging/discharging cycle for optimizing the modes of own energy consumption provided in (Blinov et al. 2024), in the local energy system of the prosumer, it is necessary to take into account both the directions of energy flows at the node of the ESS connection to the inverter and the directions of energy flows at the commercial metering point of the prosumer. The principles of calculating cost components for evaluating the profitable operation of the ESS are summarized in Table 1.

The difference between the profit and cost components listed in the Table should be not less than the estimated cost of the ESS charging/discharging resource:

$$\sum_{h=1}^{24}\Big(\left(C_h^{buy} - C_{f,dch}^{ESS}\right)\cdot V_{dch,h}^{ESS} \cdot IsBuy_h^{AC} + \left(C_h^{sale} - C_{f,dch}^{ESS}\right)\cdot V_{poz,h}^{ESS} \cdot IsSale_h^{AC} - \\ C_h^{buy} \cdot V_{ch,h}^{ESS} \cdot IsBuy_h^{AC} - C_h^{sale} \cdot V_{ch,h}^{ESS} \cdot IsSale_h^{AC}\Big) \geq B_{\mathfrak{Z}}^{ESS} \tag{12}$$

where:

$C_{f,dch}^{ESS}$ – threshold difference in prices of stored and output electricity, which ensures profitable operation of the ESS [₴/kWh],

$B_{\text{Э}}^{ESS}$ – minimum costs for ensuring the state of readiness for the islanding mode (calculated at a separate optimization stage) [₴].

Table 1. The principles of calculating cost components of the ESS

Tabela 1. Zasady obliczania składników kosztów ESS

Market operations	ESS mode	Cost component
Electricity buy *IsBuy* = 1	Charging *IsCh* = 1	The ESS is charged with electricity received from the DS. The charging costs are taken into account at the price of electricity buy.
	Discharging *IsDch* = 1	The ESS is discharged to cover part of its own electricity consumption. The profit corresponds to the sum of the reduction in electricity costs. The profit from discharge is taken into account at the price of electricity buy.
Electricity sale *IsSale* = 1	Charging *IsCh* = 1	The ESS is charged from the surplus of the SPP generation. The costs correspond to the sum of the profit lost because of refusal to sell the corresponding volume of electricity. The charging costs are taken into account at the price of electricity sale.
	Discharging *IsDch* = 1	The ESS is discharged to cover part of its own electricity consumption and energy sale. The profit from discharge is taken into account at the price of electricity sale.

The IEEE Std 2030.2.1™ (IEEE Std 2030.2.1-2019) defines cycle as “the process of BESS discharging or charging from initial state of charge to the same state within a single discharge and charge.” If the prosumer does not provide mode regulation services in the power system (e.g., frequency regulation services), the daily schedule of the ESS operation is determined by multiple cycles of full charging and full discharging. Therefore, the cost of the charging/discharging cycle may be estimated by the working capacity of the storage unit. Then the threshold difference in prices of stored and output electricity, which ensures profitable operation of the ESS is estimated by the formula:

$$C_{f,dch}^{ESS} = \frac{Cost_{full}^{ESS}}{W_{nom}^{ESS} \cdot DoD_{norm}^{ESS} \cdot N_{norm}^{ESS}} \tag{13}$$

where:

$Cost_{full}^{ESS}$ – costs for buying, installing and maintaining the ESS [₴],

N_{norm}^{ESS} – normalized number of charge/discharge cycles of the ESS,

W_{nom}^{ESS} – nominal capacity of the ESS storage unit [kWh],

DoD_{norm}^{ESS} – manufacturer-normalized depth of discharge of the ESS storage unit.

The methodology for calculating the volumes of energy reserves to support the state of readiness for the islanding mode, taking into account the forecast of the SPP generation.

If the microgrid energy management system performs only the task of supporting the critical load in the islanding mode, it is advisable to ensure the technical maximum of energy storage in the ESS. Such an ESS operation strategy ensures the maximization of the maintaining time and the possibility of increasing the volumes of electricity consumption in the islanding mode:

$$Max\left(GF_{isol}\right) = f\left(V_{cr}, T_{isol}\right)$$

where:

V_{cr} – critical load volumes,

T_{isol} – the microgrid operation time in the islanding mode.

If the task of optimizing the operation of the microgrid power equipment is additionally performed to minimize the cost of electricity buy, it is advisable to maintain only a certain minimum volume of energy stored in the ESS to maintain the critical load for a given time of the islanding mode. Then the output capacity of the ESS storage unit is used to solve the use case of minimizing the cost of electricity bought when connecting to the DS.

For *K* calculation periods of the islanding mode, the electricity consumption of the critical load is provided by the energy stored in the ESS and electricity generation in the SPP. Then the minimum volume of energy storage in the ESS for the period *h* of the beginning of the islanding mode with a duration of *K* periods is estimated using the following methodology:

(1) Coverage of the critical load from the SPP in period *h* of the islanding mode:

$$V_h^{SPP2CL} = \begin{cases} V_h^{SPP} : V_h^{SPP} - V_{(kr)h}^{MG} < 0 \\ V_{(kr)h}^{MG} : V_h^{SPP} - V_{(kr)h}^{MG} \geq 0 \end{cases} : \forall h = [1..24]$$

where:

V_h^{SPP} – forecast volume of the SPP generation in period *h* [kWh],

$V_{(kr)h}^{MG}$ – forecast volume of electricity consumption by critical load in period *h* [kWh].

(2) The volume of energy stored in the ESS, which is allocated to cover the needs of electricity consumption of critical load in period *h* of islanding mode:

$$W_{i.p.,h}^{ESS} = \left(V_{(kr)h}^{MG} - V_h^{SPP2CL}\right) \cdot \left(1 + A_{\Delta Sdch(l)}^{ESS}\right) + \Delta W_{idle}^{ESS} : \forall h = [1..24] \quad (14)$$

(3) Minimum ESS storage in period *h* of the beginning of the islanding mode with a duration of *K* periods:

$$W_{\min,h}^{ESS(b)} = \sum_{k=h}^{h+K-1} W_{i.p.,h}^{ESS} : \forall h = [1..24]$$

(4) Minimum ESS storage at the end of period h:

$$W_{\min,h}^{ESS(e)} = W_{\min,h}^{ESS(b)} - \Delta W_{idle}^{ESS} : \forall h = [1..24]$$

(5) The value of the volume of energy stored in the ESS at the beginning of the day:

$$\begin{gathered} W_{beg}^{ESS} = Min\Big(Max\Big(W_{\min,[1]}^{ESS(b)} - V_{ch,\max}^{ESS} \cdot \Big(1 - A_{\Delta Sch(l)}^{ESS}\Big); 0\Big); \\ Min\Big(W_{\min,[1]}^{ESS(b)} + V_{dch,\max}^{ESS} \cdot \Big(1 + A_{\Delta Sdch(l)}^{ESS}\Big); W_{work}^{ESS}\Big)\Big) \end{gathered} \tag{15}$$

where:

$W_{\min,[1]}^{ESS(b)}$ – minimum ESS storage for the islanding mode at the beginning of the day (h = 1) [kWh].

(6) Minimum volume of storage in the ESS for period h for the use in constraints (9):

$$W_{\min,h}^{ESS} = W_{\min,h}^{ESS(e)} - W_{beg}^{ESS} + K \cdot \Delta V_{idle}^{ESS} : \forall k = [1..24] \tag{16}$$

When jointly performing the use cases of maintaining the critical load in the islanding mode and optimizing the operation of energy equipment during the synchronous operation of the microgrid with the DS, the value of the energy volume stored in the ESS at the beginning of the day is fixed according to the results of calculations according to (15). In order to estimate the minimum volumes of energy stored in the ESS in (K-1) final periods of the day and the minimum volume of energy stored in the ESS at the end of the current day (which is equal to the minimum volume of energy stored in the ESS at the beginning of the next day), forecasts are used for the corresponding number of calculation periods of the next day. In some cases, it is permissible to use the forecast values of (K-1) calculation periods at the beginning of the current day in the calculations.

The provided algorithm does not take into account the possibility of storing a surplus of the SPP generation during islanding hours. However, to simulate such a function, it is necessary to know the time of the beginning of the islanding mode and the volume of energy reserved in the ESS at this moment for using in (9). These characteristics are additional factors of uncertainty, taking into account of which requires the involvement of game-theoretic approaches, for example (Nikolsky et al. 2022; Lapshyn 2025). Such complication of the mathematical apparatus is fundamentally possible but does not agree with the objectives of this publication aimed at highlighting other peculiarities of scheduling tasks.

The methodology for minimizing costs for maintaining the state of readiness for the islanding mode. In order to solve the problem, a simulation of the microgrid operation mode is performed with a prohibition against the sale of electricity and the operation of the ESS exclusively to ensure the power reserve of the critical load in the islanding mode. At the same time, a mathematical model with the target function (1) and the penalty functions (10) and (11) is used. The system of constraints is formed from (2)–(5), (7)–(9) without the condition of ensuring the profitable operation of the ESS (12) and with additional conditions:

$$IsDch_h^{ESS} = 0 : \forall h = [1..24] \tag{17}$$

$$IsSale_h^{AC} = 0 : \forall h = [1..24] \tag{18}$$

Condition (17) blocks the ESS discharge modes. And the use of the penalty function (10) in (1) constrains the ESS charging only to the volumes required for maintaining reserves for the needs of the islanding mode. Therefore, in the simulation model, the function of regulating the microgrid modes is blocked and only the function of maintaining the state of readiness for the islanding mode remains.

The export prohibition (18) results in obtaining zero values of the profit from electricity sailing in the target function (1). Then (1) will define as the main objective the minimization of the costs of buying electricity for the needs of its own electricity consumption and for charging the ESS to maintain the state of readiness for operation in the islanding mode. However, if the ESS is not used to optimize the microgrid modes, the plans for buying electricity to ensure the electricity consumption of the microgrid are not changed during the optimization process. Therefore, (1) searches for optimal solutions to the task of minimizing the costs of buying electricity solely for the purpose of charging the ESS to ensure readiness for the islanding mode.

Based on the optimization results, the minimum costs for maintaining the state of readiness for the islanding mode are calculated (taking into account the resources of unregulated SPP generation):

$$B_{\text{Э}}^{ESS} = \sum_{h=1}^{24} V_{ch,h}^{ESS} \cdot C_h^{buy} \tag{19}$$

which are used in the condition of ensuring profitable operation of the ESS (12).

The methodology for scheduling the microgrid operating modes. The provided mathematical apparatus is used in the complex scheduling of the microgrid operating modes with the joint implementation of two use cases: maintaining the readiness of the microgrid to operate in the islanding mode and optimizing the use of available energy resources to reduce the cost of buying electricity in conditions of synchronization of the microgrid with the DS. The sequence of scheduling procedures for solving the tasks is as follows.

Preliminary data preparation. The data required for carrying out calculations is collected and structured. The input data includes technical characteristics of the SPP and ESS, forecasts of electricity consumption in the microgrid (including forecasts of critical load values), forecast of electricity output from the SPP and forecasts of market prices. Calculations of the arguments of the mathematical model are carried out, which are used as constant coefficients in the optimization processes.

Calculations of the volumes of energy reserves required to maintain the state of readiness for the islanding mode. Calculations are carried out according to the methodology provided in the relevant section of the publication. Based on the results of calculations according to (15), the volume of energy stored in the ESS at the beginning of the day is determined and, according to (16), the minimum volumes of energy storage in the ESS for individual calculation periods of the day are determined.

Calculations of costs for maintaining the state of readiness for the islanding mode. The operation of the microgrid is simulated with the replenishment of the charge in the ESS and the prohibition of the output of electricity from the ESS. The procedure for optimizing the microgrid modes with the target function (1) and the systems of constraints (2)–(5), (7)–(9), (17), and (18) is performed. Based on the results of optimization according to (19), the amount of costs for maintaining the state of readiness for the islanding mode is calculated.

Optimization of the operating modes of microgrid power equipment. The procedure for optimizing the microgrid modes with the target function (1) and the systems of constraints (2)–(5), (7)–(9), (12) is performed. Based on the optimization results, the ESS mode regulation schedule and electricity buy/sale schedules by the electricity supplier are obtained.

The presented MILP/MIQP/MINLP models and penalty functions collectively enable the determination of optimal ESS charging/discharging schedules, electricity buy/sale strategies, and microgrid operation under both islanded and grid-connected modes. By integrating forecasting data, operational constraints, and market conditions, the methodology provides a structured and comprehensive approach for balancing economic efficiency with operational reliability in PV-based prosumer microgrids.

In summary, the methodological framework systematically addresses the key operational and economic challenges of prosumer microgrids. The combination of rigorous optimization models, energy flow control mechanisms, and penalty functions ensures that ESS and PV resources are utilized efficiently, critical loads are maintained during islanding, and prosumer profits are maximized under varying market conditions. These intermediate conclusions facilitate the reader's understanding of how each component contributes to the overall scheduling and optimization objectives, providing a clear synthesis of the study's core methodological contributions.

3. Results of the research and discussion

To conduct the research, it is necessary to identify the input data and calculation conditions. To highlight the most significant trends affecting scheduling results using the proposed models and framework, the following microgrid operation scenarios are defined for practical calculations:

(A) Minimizing the cost of electricity purchased to recharge the ESS while maintaining readiness for islanded operation:

- A1 – The reserve volume is calculated based on the maximum critical load for 4 hours; the market price of electricity remains constant; no SPP surplus is available.
- A2 – The reserve volume is calculated based on the maximum critical load for 4 hours; the market price of electricity remains constant; SPP surplus is available.

(B) Minimizing the cost of electricity purchased for self-consumption while maintaining ESS reserves for islanding and optimizing local consumption schedules:

- B1 – Simulation of the summer season with SPP generation surplus.
- B2 – Simulation of the winter season without SPP generation surplus.

(C) Maximizing the prosumer's profit when scheduling daily electricity buy/sell operations in the summer season, without considering ESS reserves for islanding.

In the A1 and A2 scenarios, a simplified approach to determining the volumes of energy reserves for the islanding mode is used compared to the calculations according to (16). The peak value of the critical load of 8 kWh is taken as the required volume of the reserve for each hour of the day. Then, taking into account energy losses in the ESS discharge mode, for operation in the islanding mode for 4 hours, it is necessary to maintain a reserve of 33.08 kWh for each hour. Such a simplified uniform schedule of the required reserves allows to more clearly distinguish the peculiarities of individual calculation results.

The following technical characteristics of the ESS are determined for modeling: nominal capacity W_{nom}^{ESS} = 100 kWh; depth of discharge DoD_{norm}^{ESS} = 0.5; maximum hourly charge $V_{ch,\max}^{ESS}$ = 100 kWh with losses $\Delta V_{ch,\max}^{ESS}$ = 3 kWh; maximum hourly discharge $V_{dch,\max}^{ESS}$ = 50 kWh with losses $\Delta V_{dch,\max}^{ESS}$ = 1.5 kWh; hourly loss of the ESS charge (self-discharge and power supply of battery control sensors) ΔW_{idle}^{ESS} = 0.03 kWh; the threshold price difference for profitable operation of the ESS according to (13) $C_{f,dch}^{ESS}$ = 4.63 ₴/kWh.

For the calculations, statistical values of daily electricity consumption and solar generation schedules in the microgrid of a building in Kyiv are used. The critical part of the microgrid load is determined by the power supply of the institution's servers.

The electricity consumption, solar generation and market price schedules are selected for two days that reproduce typical seasonal conditions:

- statistics for the summer period (07/28/2025), which is characterized by reduced volumes of own electricity consumption and a surplus of solar generation;
- statistics for the winter period (02/26/2025), which is characterized by increased volumes of own electricity consumption and the absence of a surplus of solar generation.

The values of hourly market prices are calculated using the formula most common in the retail market of Ukraine:

$$C_h^{buy} = C_h^{DAM} + T^{MO} + T_T^{TSO} + T_D^{DSO} + T^{Supl} \forall h = [1..24] \tag{20}$$

where:

C_h^{DAM}	–	hourly market price at hour *h* according to the statistics provided in (Market Operator 2025),
T^{MO}	–	tariff for market operator services approved in (NERC Resolution № 2103 from 10.12.2024),

T_T^{TSO}	–	tariff for transmission system operator services in part of electricity transmission approved in (NERC Resolution № 2200 from 19.12.2024),
T_Π^{DSO}	–	tariff for the DS operator services approved in (NERC Resolution № 2209 from 19.12.2024),
$T^{Supl} = 0.1$ (₴/kWh)	–	electricity supplier margin.

As an alternative form of pricing, a fixed tariff is applied in the calculations, which was determined as the average value of hourly market prices individually for each studied season of the year. The penalty coefficients in (10) and (11) are equal to 1 by default. During experimental studies, the values of the coefficients were changed to estimate the impact of penalty functions on the optimization results. The optimization problems are solved using Gurobi solvers (Gurobi Optimization LLC 2025).

Results of numerical modeling. The A1 scenario involves energy replenishment in the ESS only due to importation from the DS. The minimum hourly reserve volume in the ESS and the market cost of energy is not changed during the day. As a result of the optimization, a schedule of uniform replenishment of charge of 0.03 kWh per hour is formed to compensate for the loss of charge in the ESS. The expected optimization result demonstrates the effect of aligning the ESS charging schedule at a constant cost of electricity created by the penalty function (10).

In the A2 scenario, the ESS reserve is allowed to be replenished by import from the DS and a surplus of the SPP generation. The formulation of the scheduling task defines the term of the SPP generation surplus as the difference between the volumes of the SPP generation and its own electricity consumption in the microgrid. Export (sale) of electricity in the DS is prohibited, therefore the cost of the SPP generation surplus aimed at replenishing the energy reserve in the ESS is equal to zero. The SPP generation surplus not used for charging the ESS is forcibly constrained. The energy reserve in the ESS at the beginning of the day is calculated as 33.08 kWh – the minimum level required for maintaining the state of readiness for the islanding mode. The optimal schedule for the ESS charge replenishment is shown in Figure 5.

Since the initial energy reserve in the ESS is set at the minimum permissible level, at the first hours of the day the energy reserve replenishment is performed by importing from the DS to compensate for the loss of charge in the ESS. The SPP surplus of 2.26 kWh occurs at 9 a.m. and is fully used to replenish energy in the ESS. From 10 a.m. to 2 p.m., the ESS is evenly charged with hourly volumes of 2.97 kWh until the ESS operating capacity is filled. The unused SPP surplus is forcibly constrained. The ESS, after the operating capacity is fully filled, is in standby mode until the end of the day.

The model used for the A2 scenario constrains buying energy to the minimum required for maintaining the state of readiness for the islanding mode. At the same time, the maximum filling of the ESS with the SPP generation surplus with a conditionally zero energy cost is not prevented. Then, planning the ESS charging schedule for the next day will result in a charge replenishment scheme exclusively from the SPP generation surplus.

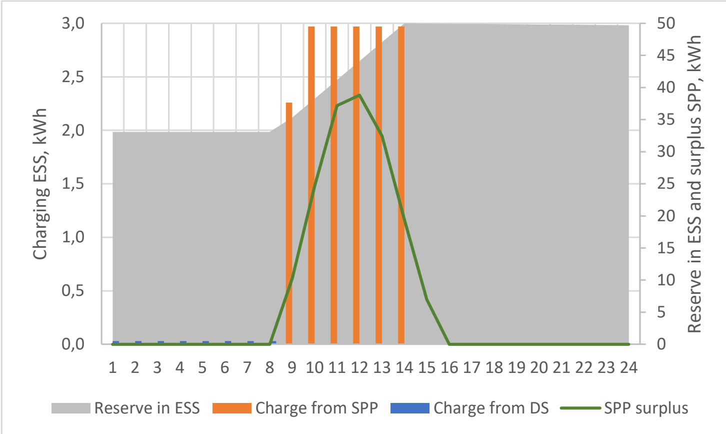


Fig. 5. Schedule for the energy reserve replenishment in the ESS according to the A2 scenario

Rys. 5. Harmonogram uzupełniania zapasów energii w ESS według scenariusza A2

The ESS operating schedule involves a zero cost of the SPP surplus in the conditions of a prohibition of energy export. However, for a prosumer with no restraints on energy export, the entire unrealized SPP generation surplus is estimated as a lost profit at the sale price. This condition in the task statement will lead to the formation of a daily ESS charging schedule only with the volumes minimally required for maintaining the state of readiness for the islanding mode (similarly to the schedule from the 1st to the 8th hour in Figure 5).

For the B1 scenario, the schedule of the volumes of energy reserves in the ESS for maintaining the state of readiness for the islanding mode is calculated according to (16). The main components of the calculations are shown in Figure 6.

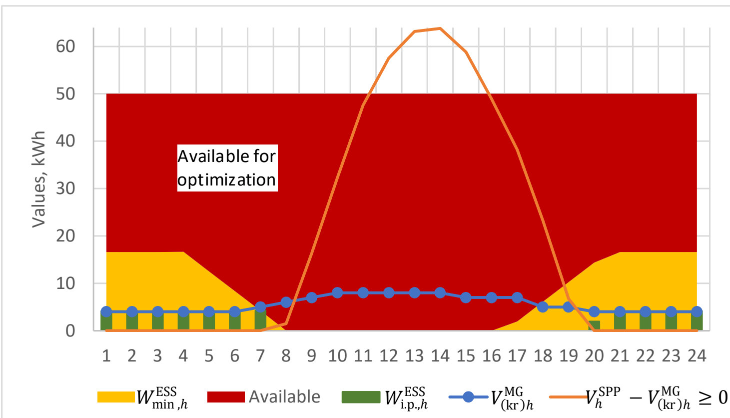
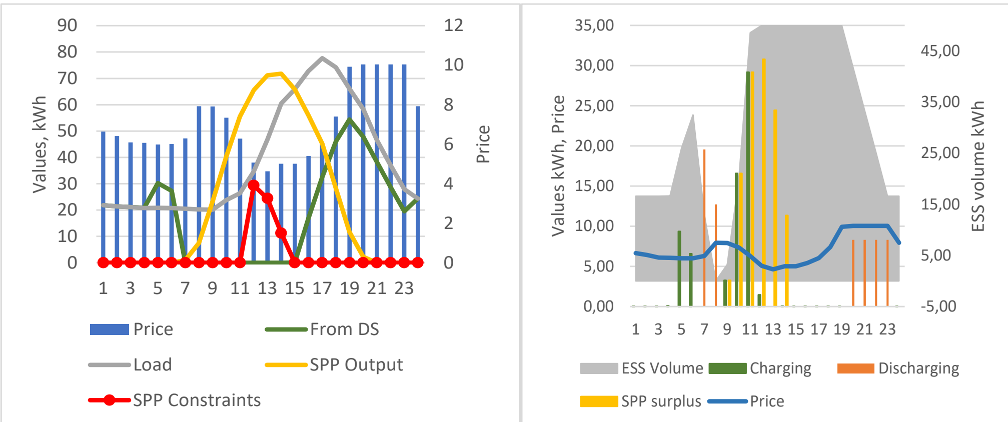


Fig. 6. Schedules of readiness for the islanding mode according to the B1 scenario

Rys. 6. Harmonogramy gotowości do pracy w trybie wyspowym według scenariusza B1

Maintaining energy reserves to power the critical load in the islanding mode is a top priority when scheduling methods for efficiently using ESS resources. However, the application of economic optimization criteria reduces the volumes of the ESS resources allocated for these needs to a threshold minimum similarly to the results in the A1 scenario and the first 8 hours in the A2 scenario. The storage of SPP surplus in the scenario is redundant for the use case of maintaining readiness for the islanding mode and may be used to solve other use cases. Accordingly, the area highlighted in red in Figure 6 shows the ESS resources available for the use case of minimizing the cost of buying electricity for the needs of the microgrid's own electricity consumption. The main results of solving the use case for the B1 scenario are shown in Figure 7.



(a) (b)

Fig. 7. Scheduling results according to the B1 scenario (summer season): (a) energy balances; (b) ESS schedule

Rys. 7. Wyniki harmonogramowania według scenariusza B1 (sezon letni): (a) bilanse energetyczne; (b) harmonogram ESS

The optimal electricity import (buy) schedule coincides with the load schedule only for a few hours. For other hours of the day, optimization is carried out due to the SPP generation and ESS modes regulation. At the same time, not all SPP generation volume is used from 12 a.m. to 2 p.m. (12^{th} to 14^{th} hour). It should also be noted that from 8 p.m. to 11 p.m. (20^{th} to 23^{rd} hour), the same market prices have been increased. A few hours of the day with the same market prices are a typical phenomenon for the Day-ahead market of Ukraine since its launch in 2019. Therefore, the problem of a plurality of equally optimal solutions remains relevant, which is solved using the penalty function (10). The need in (10) also arises when mathematical models perform optimization with time intervals shorter than the calculation period to detail individual technological processes.

The ESS schedule provides for two charging/discharging cycles. The morning cycle from 5 a.m. to 8 a.m. performs regulation by balancing the energy import from the DS based on the difference in the cost of electricity sufficient to meet the ESS profitability constraint (12). By the end of the 8th hour, the ESS capacity is completely released. And from the 9th hour, the charging of the SPP surplus is implemented until the ESS operating capacity is fully filled. The energy stored in the ESS is used to power the microgrid load in the evening hours of maximum market prices.

The B2 scenario simulates the conditions of the winter period that is characterized primarily by the absence of the SPP surplus. The ESS mode schedule for the conditions of the B2 scenario is shown in Figure 8.

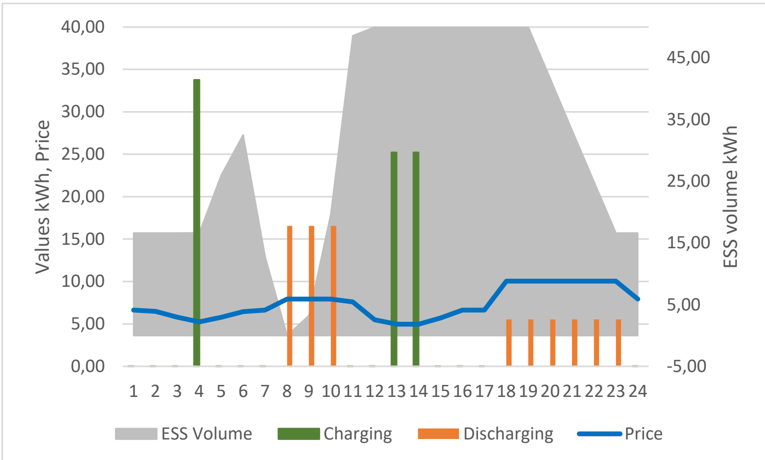


Fig. 8. The ESS mode schedule according to the B2 scenario (winter season)

Rys. 8. Harmonogram trybu ESS według scenariusza B2 (sezon zimowy)

In the absence of the SPP generation surplus, the ESS regulation is implemented solely by balancing energy import from the DS based on the difference in electricity prices sufficient to meet the ESS profitability constraint (12). It should be noted that in both B1 and B2 scenarios, the difference in market prices is insufficient to fully utilize the available ESS capacity (morning cycle). The main factor of constrained ESS utilization in this case is the inclusion of energy losses in the ESS balance structure.

The C scenario is developed to study the main trends that affect optimal electricity buy/sale schedules. The results of solving scheduling tasks according to the C scenario are shown in Figure 9. For the C scenario, the SPP generation surplus was observed from 9 a.m. to 2 p.m. (9th to 14th hour). Electricity export (sale) schedules were formed for these hours. The exception is 1 p.m. (13th hour), for which electricity import (buy) is scheduled. To determine the reasons for this exception, it is necessary to additionally analyze the scheduled ESS balances (shown in Figure 9b). At 1 p.m. (13th hour), the lowest market price for electricity during the day was formed. Accordingly, the 13th hour is the best for replenishing energy reserves in the ESS.

Charging the ESS at this hour from the SPP surplus and from import from the DS leads to a decrease in the total daily costs for buying electricity with a value numerically greater than the loss of profit due to the refusal to sell electricity.

Experimental calculations using the framework covered in the publication allowed us to identify the following main trends. In most cases, charging ESS and selling electricity are competing methods of using the surplus of unregulated generation. With high market prices, preference is given to selling electricity. With low market prices, the surplus of unregulated generation is used to charge the ESS, if later this charge is used to cover own electricity consumption or electricity sale during periods with high market prices.

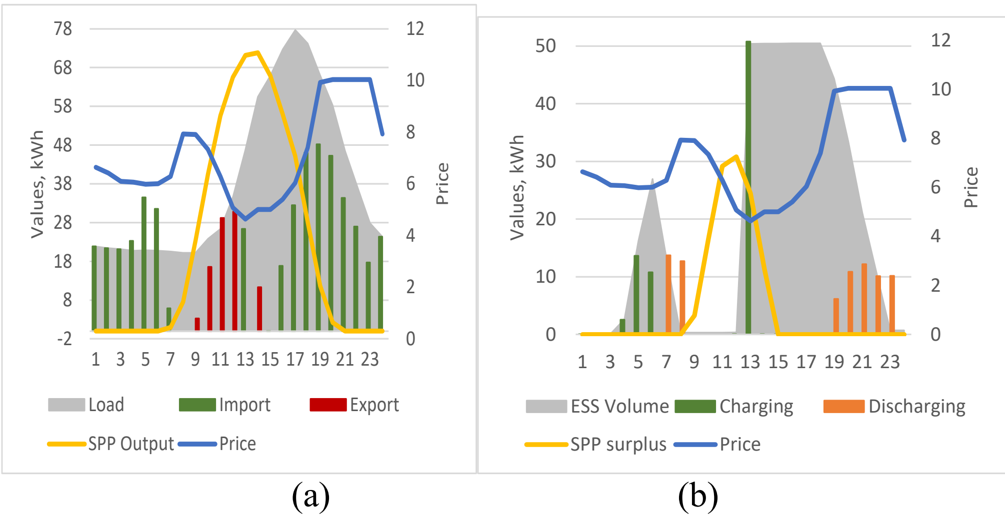


Fig. 9. Scheduling results according to the C scenario (summer season): (a) energy balances; (b) ESS schedule

Rys. 9. Wyniki harmonogramowania według scenariusza C (sezon letni): (a) bilanse energetyczne; (b) harmonogram ESS

The use of the ESS charge for electricity sale is possible during hours with high market prices, if the total resource of unregulated generation and energy stored in the ESS is sufficient to cover its own electricity consumption until the end of the day. Such a situation may occur on weekends when the daily electricity consumption of a non-domestic institution is reduced to a minimum. For such days, it is recommended to expand the scheduling horizon to take into account the time intervals between the beginning of the unregulated generation surplus in the current day and next one.

Additional peculiarities that should be taken into account when performing practical calculations are as follows. Changing the value of the penalty coefficient in (10) leads to a proportional change in the effect of aligning the ESS charging/discharging schedules in hours with the same market prices and with small fluctuations in market prices.

At the stage of setting the scheduling task, the following two opposite trends in the application of penalty functions should be taken into account: an increase in the penalty coefficient in (10) enhances the effect of aligning the ESS charging/discharging schedules and an increase in the penalty coefficient in (11) enhances the effect of aligning the schedules of constraining the unused SPP generation surplus.

The difference in the prices of energy buy and sale with a fixed ratio for all hours of the day (e.g., if the electricity sale price is always half of the buy price) does not change the optimization results obtained in the conditions of the same energy buy and sale prices for each calculation period. Similarly, the difference in the prices of energy buy and sale with the formula of pricing (19), when fixed tariffs are added to the indicative market price, will not affect the results of the optimal electricity buy/sale schedule. These properties can be theoretically justified.

Conclusion

The framework provided in the publication allows solving complex tasks of economic day-ahead dispatching for a microgrid with an unregulated generation source and an energy storage unit. The framework meets the international requirements for economic optimization, reserve readiness, and market integration of microgrids on a daily horizon. Mathematical models solve the problem of economic dispatching according to the criterion of minimizing the cost of buying electricity for the consumer and maximizing the profit for the prosumer in the conditions of sharing the resources of the energy storage system for use cases such as maintaining the state of readiness for the islanding mode and efficient use of local energy resources when connected to the DS. Additionally, the models apply a non-price optimization criterion, namely, aligning the ESS charging/discharging schedules in hours with the same market prices and with insignificant fluctuations in market prices.

The framework is aimed at practical use in the tasks of day-ahead scheduling bids of buy/sale electricity with the concept of rational behavior of the market participant. Therefore, the framework may be implemented as an online service for consumers and prosumers as well as applied in creating a training sample for training intelligent microgrid control systems.

Future research would focus on expanding the proposed framework by integrating longer-term forecasting of unregulated generation and consumption patterns to improve ESS utilization and scheduling accuracy. Investigations would also explore adaptive penalty function tuning to align ESS charging/discharging schedules under highly volatile market prices, as well as the inclusion of multiple prosumers and dynamic electricity export opportunities. Additionally, extending the scheduling horizon to cover multi-day operations and weekends, when consumption patterns differ significantly, would further enhance the economic and operational performance of microgrids. Further studies would also consider the implementation of real-time control and machine learning approaches to optimize energy storage management under uncertainty, market fluctuations, and variable renewable generation.

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All authors have read and approved the final version of the manuscript.

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Data Availability Statement: The code scripts and data can be obtained from the corresponding author upon request.

The Authors have no conflicts of interest to declare.

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Eugene Parus, Ihor Blinov, Dariusz Sala, Volodymyr Miroshnyk, Ievgen Zaitsev, Volodymyr Artemchuk, Yuliya Pazynich

Struktura zarządzania handlem na dzień następny i harmonogramowaniem magazynowania w mikrosieciach prosumenckich opartych na energii fotowoltaicznej z możliwością pracy wyspowej

Streszczenie

Integracja generacji fotowoltaicznej (PV) i systemów magazynowania energii w mikrosieciach prosumenckich umożliwia aktywny udział w rynkach energii elektrycznej. Jednak efektywne zarządzanie handlem na dzień następny i harmonogramowaniem magazynowania pozostaje wyzwaniem, szczególnie w warunkach niepewności prognoz i konieczności gotowości do pracy wyspowej. Niniejsze badanie ma na celu opracowanie kompleksowych ram zarządzania handlem energią elektryczną na dzień następny i harmonogramowaniem magazynowania energii w mikrosieciach prosumenckich opartych na energii fotowoltaicznej. Ramy te dążą do maksymalizacji zysku ekonomicznego przy jednoczesnym zapewnieniu niezawodności operacyjnej i utrzymaniu odpowiednich rezerw na potrzeby potencjalnej pracy wyspowej.

Proponowane podejście wykorzystuje optymalizację na dzień następny w oparciu o prognozy generacji słonecznej i krytycznego zapotrzebowania na moc. Prognozy te służą jako dane wejściowe do określania transakcji rynkowych i optymalnych strategii działania magazynowania. Ramy zostały ocenione przy użyciu historycznych danych operacyjnych i rynkowych w celu oceny ich skuteczności w osiąganiu rentowności i niezawodności. Wyniki symulacji pokazują, że ramy umożliwiają efektywną koordynację udziału w rynku i operacji magazynowania energii, pozwalając na osiągnięcie lepszych wyników ekonomicznych i utrzymanie wystarczających rezerw energii na potrzeby pracy wyspowej. Metodologia skutecznie równoważy korzyści handlowe z ograniczeniami technicznymi systemów prosumenckich w warunkach niepewności prognoz. Proponowane ramy zarządzania poprawiają efektywność ekonomiczną i operacyjną mikrosieci prosumenckich opartych na fotowoltaice. Stanowią praktyczne narzędzie wspierające inteligentne podejmowanie decyzji na rynkach energii elektrycznej i przyczyniają się do rozwoju odpornych, samowystarczalnych społeczności energetycznych.

Słowa kluczowe: mikrosieci, dyspozycja ekonomiczna, handel energią elektryczną, zarządzanie handlem na dzień następny, planowanie na dzień następny