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CONSTRUCTION OF A MODEL FOR OPTIMAL SCHEDULING OF ENERGY STORAGE SYSTEMS IN THE DAY-AHEAD MARKET CONSIDERING MARKET STRATEGIES AND TECHNICAL CONSTRAINTS

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This study investigates the process of optimal planning of energy storage system operating schedules in the day-ahead market. The task addressed is to prevent unprofitable operation of energy storage systems.

A comprehensive mathematical model of daily planning of energy storage operation modes has been built, which takes into account technological efficiency, hardware wear processes, as well as asymmetry of market payments. This forms an adaptive filter with cutting off cycles of economically inefficient arbitrage. The approach is based on separation of the vector of control variables into two independent charging and discharging flows. This has made it possible to take into account the asymmetry of tariffs and the structure of losses in a differentiated manner.

The study on the sensitivity of the model revealed the existence of areas of adaptive regulation and parametric insensitivity to fluctuations in price signals. In the area of parametric insensitivity, the model forms a stable cost-effective solution regardless of price fluctuations. In the area of adaptive regulation, the model changes the volumes of a separate operating cycle depending on a change in the market price spread. It has been established that ignoring the accompanying payments for the area of adaptive regulation leads to an overestimation of income by 35.6 percent and the formation of unprofitable operations. Under conditions of low market price spread, the deviation in the financial result reaches 91.6 percent; however, the parametric insensitivity of the model guarantees profitable operation.

The scope of model's practical implementation is decision support systems for operators of energy storage systems. The conditions of use assume the presence of deterministic forecasts of market price signals for the calculated operating day. Implementing the model contributes to the extension of the life cycle and increase in the operational profitability of energy storage systems

Keywords: energy storage systems, price arbitrage, economic dispatch, day-ahead market

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1. Introduction

The current processes of global transformation of the electric power industry, aimed at its decarbonization and digitalization, are transforming electric power systems into complex cyber-physical structures [1]. This requires the development of decentralized intelligent control technologies [2] and the use of digital platforms to optimize [3] the work of electricity market participants.

The integration of stochastic generation from renewable energy sources (RES) creates significant imbalances in power systems [4], which stimulates the use of energy storage systems (ESSs) as a tool for maintaining dynamic stability [5] and balancing such systems on a daily planning horizon [6]. Under conditions of increased risks for energy infrastructure caused by man-made disasters, natural disasters or hostilities, the implementation of ESSs as objects of automated control is gaining critical importance for maintaining the stability of power systems [7].

Given such conditions, a relevant scientific task is to develop mathematical support and software to automate the planning of ESS operators' work in the day-ahead market (DAM) of Ukraine.

2. Literature review and problem statement

Price arbitrage is the basic strategy o ESS operator's participation in the spot electricity markets [8]. To implement the arbitrage strategy, ESSs are considered as complex objects of automated control under conditions of price volatility with compliance with the required payback indicators [9].

In most publications, the issue of energy arbitrage is solved in a simplified way [8]. The vector of price signals is taken into account invariantly to the procedures for buying or selling electricity. Sometimes the asymmetric costs of ESS operator in the market are considered to be unchanging exogenous parameters [10]. This creates a static filter of low-profit operations in economic dispatching problems. However, this approach provides adequate results only for certain segments in the electricity market.

In [11], a step-by-step method for choosing the optimal ESS control strategy to increase the equipment's service life is proposed. However, such an optimality criterion is appropriate for investment analysis. Instead, in daily planning tasks, the main goal of ESS operator is to obtain maximum profit from a limited operational resource.

Particular attention in the literature is paid to studies on the degradation of ESS characteristics. Detailed modeling of physicochemical processes in electrolytes is given in [12]. Work [13] proposes an approach using special weighting factors based on statistical energy storage degradation curves. The practical value of such approaches is limited due to dependence on the design features of specific energy storage devices.

A number of studies suggest using the normalized cost of energy storage [9] with the distribution of the cost of the charging/discharging resource over the entire life cycle. However, these approaches simulate resource wear over a long-term planning horizon (months or years). At the same time, the static wear coefficient of hardware resources does not make it possible to take into account the different intensity of ESS operation depending on current market signals.

A separate area of research is aimed at modeling round-trip efficiency (RTE). Thus, paper [14] investigates irreversible losses in conversion processes based on Ragone diagrams. In [3], a practical mechanism for taking RTE into account by energy loss functions is proposed.

Current scientific research pays considerable attention to solving the problem of uncertainty of forecasts. For this purpose, stochastic programming methods [15] and predictive models [16] are used. However, to solve planning tasks, intelligent systems still need deterministic models as a mathematical basis for simulating technological processes or forming a training sample.

Our review of related literature shows that most studies focus only on individual characteristics of ESS. Other important components are mainly taken into account in a simplified manner or are ignored altogether. All this allows us to state that it is advisable to conduct research into the construction of a mathematical model with comprehensive consideration of technological efficiency, hardware wear, as well as loss asymmetry and market and system-related charges (MSRC).

3. The aim and objectives of the study

The purpose of our study is to construct a comprehensive mathematical model for planning optimal schedules of energy storage systems in the day-ahead market. This model should consistently take into account technological efficiency indicators, hardware wear processes, as well as asymmetry of market payments, which will make it possible to automate the processes of planning the cost-effective operation of ESS.

To achieve the goal, the following tasks were set:

– to formalize the objective function and the system of constraints for optimizing daily ESS operation modes;

– to investigate the impact of market and system-related charges on the results of solving planning problems;

– to investigate the impact of operating costs on the formation of optimal ESS operation schedules in the electricity market of Ukraine.

4. The study materials and methods

The object of our study is the process of optimal planning of energy storage system operation schedules in the day-ahead market.

The principal hypothesis of the study assumes that taking into account market and system-related charges significantly affects the profitability of ESS operation and causes a change in optimal solutions.

Assumptions adopted in the study: market price signals are deterministic and predictable on the planning horizon. All components of operating costs are considered additive. The values of capacities during the calculation hour are assumed to be constant.

Simplifications accepted in the study: the duration of transient processes in power electronics is ignored. Equipment wear within one day is assumed to be quasi-stationary. The volumes of ESS self-discharge are assumed to be invariant to the operating mode.

To build a mathematical model, the methods of system analysis, linear and quadratic programming were used. They allowed us to formalize control processes and find the optimal vector of control variables.

To verify the model, a series of numerical experiments were conducted. The object of modeling was an ESS with the following specifications: rated capacity of 10 MWh; standard depth of discharge of 0.9; maximum charging power of 10 MW and discharging power of 5 MW. The parameters of RTE are given by hourly losses under the modes of maximum charging power of 0.5 MWh and discharging power of 0.25 MWh. The residual resource value (RRV) is set at 950 m.u./MWh.

To unify the analysis, the concept of a "calculated cycle" was used – a unit of resource, which is defined as the total useful energy output in the volume of the current usable capacity. The number of cycles n on the daily horizon D is calculated as a continuous value calculated by the ratio of the total usable energy output on the daily planning horizon to the operating capacity of ESS

$$n = \frac{\sum_{h \in D} V_{\mathrm{dch},h}^{\mathrm{ESS}}}{W_{\mathrm{work}}^{\mathrm{ESS}}} : n \in \mathbb{R}.$$

Information support and input data. For the simulation modeling of the market environment, retrospective samples of the DAM limit prices published on the official website of AT "Market Operator" were used. To take into account seasonal price volatility, two test scenarios were formed:

– winter profile: time series of prices for 12/26/2025;
– summer profile: time series of prices for 06/04/2025.

These dates were chosen as representative for the winter and summer seasons due to the characteristic price volatility and consumption profiles in the United Energy System of Ukraine.

The parameters of market and system-related charges (MSRC) were updated in accordance with the current transmission tariffs and operating fees for 2025.

Since our experimental studies are based on retrospective data on the Ukrainian electricity market, the national currency of Ukraine – hryvnia (₴) – was used as the base monetary unit (m.u.) for numerical modeling. The average exchange rate of the Interbank Currency Exchange (according to the official website of the Ministry of Finance of Ukraine) over the period of our research was approximately 49.6 ₴/€ on 12/26/2025, and 47.4 ₴/€ on 06/04/2025.

Numerical experiments are aimed at solving the tasks of comparative analysis and studying the sensitivity of the model in the following areas:

Task 1. Assessment of the impact of MSRC. Study of changes in the structure of the optimal schedule of ESS operation when taking into account MSRC in the structure of the objective function. Comparison is made between scenarios without MSRC and with MSRC for the summer and winter seasons.

Task 2. Sensitivity analysis to RRV. Determining the profitability threshold and intensity of ESS use depending on the cost of the residual resource. For an isolated study on the impact of endogenous hardware wear on the feasible region, MSRC values are taken equal to zero. This allows us to determine the "pure" threshold of economic efficiency of the energy transfer cycle relative to the current usable capacity.

The search for the global maximum of the mixed-integer quadratic programming problem was carried out using the corresponding algorithms from the Frontline Solver software module (USA) in the Microsoft Excel environment (USA).

5. Results of investigating the process of planning optimal schedules for energy storage systems

5. 1. Formalization of the objective function and the system of constraints for the mathematical model

The formalized representation of the problem is based on a systems approach, according to which ESS is considered as a cyber-physical control object. The proposed concept is built on the decomposition of control influences and parameterization of the model by time-varying characteristics of price signals and the residual resource of ESS. The mathematical model is formed on the basis of the following principles and assumptions.

Decomposition of control variables and separation of control channels. Instead of the alternating power value, two independent control vectors are introduced: purchase (identified with the charging mode) and sale (identified with the discharging mode) of electricity. This approach provided the opportunity to differentially formalize the asymmetry of price signals, tariff surcharges, and structural losses under different modes.

Additivity of costs. All components of operating costs (including market payments, depreciation, maintenance) are defined as additive and reduced to a single calculation unit – the specific cost of energy supplied.

Formalization of MSRC. Inclusion of MSRC in the structure of the objective function in the form of linear allowances provided the construction of an additional adaptive filter. The filter operation contributed to the narrowing of the region of admissible solutions by screening out economically inexpedient strategies in comparison with the idealized simulation of price arbitrage only by DAM price signals.

Dynamic modeling of RTE. Unlike [17], the efficiency of energy conversion is formalized as a dynamic characteristic through endogenous functions of energy losses in the system of recurrent equations for controlling the balances of energy accumulated in ESS.

Parameterization of RRV and operating costs. Variable costs for degradation and maintenance are given as a function of the dynamic cost of the energy storage service. Bringing these costs to a unit of usable output allowed us to regulate the intensity of asset use [18] within the framework of the cost-effective exploitation of ESS resources.

Quasi-stationarity of wear parameters. Given the significant resource of modern ESSs (5000–7000 cycles), the degree of wear within one day (1–2 cycles) was inadvertently recognized as small and not taken into account. The procedure for specifying the degree of degradation was transferred to the stage of interdaily iterative model updating.

Monitoring-based update. To take into account the hardware wear of ESS over significant periods of operation (months), iterative updating of model parameters (usable capacity, loss functions, RRV) based on retrospective monitoring data is provided before the start of the planning session.

Discretization of time domains. The time domain of the model is consistent with the DAM regulations: discretization step (calculation period) $h = 1$ h, planning horizon $D = 24$ h (day). The regulatory rules of trading in DAM are reflected by a separable objective function with an additive representation of each calculation period. This provided the opportunity to apply linear or quasi-linear programming methods to find the optimal vector of control variables within each interval while observing the global connected system constraints.

Determinism of input data. The DAM price signals on the planning horizon of one day were considered as known (forecasted) values. The issue of stochastic uncertainty of forecasts was taken beyond the scope of the constructed model.

Power approximation. The power values during the hour were assumed to be constant (stepwise approximation). This allowed us to establish a numerical equivalence between the instantaneous power (MW) and the amount of energy (MWh) for the calculation period interval h.

Ignoring transients. The duration of transients in power electronics was taken to be negligibly small compared to the time scale discretization step.

Energy invariance. The volumes of self-discharge and fixed costs for auxiliary power consumption (BMS, cooling) were determined to be negligibly small relative to the usable capacity and were considered as invariant to the operating mode of ESS during the day. Their cost assessment was carried out at the average daily price and was not taken into account directly in the optimization model.

The generalized objective function NFR(D) of maximizing the economic efficiency of ESS operation during the operating day D was represented by an additive model. It integrated deterministic market indicators based on the results of price arbitrage, MSRC, and RRV. This led to the transformation of the price arbitrage problem into the problem of maximizing the net financial result

$$\mathrm{Max}\left(\mathrm{NFR}\left(D\right)\right)=\mathrm{Sell}^{\mathrm{DAM}}\left(D\right)-\mathrm{Pur}^{\mathrm{DAM}}\left(D\right)-$$
$$-\mathrm{I}^{\mathrm{MSO}}\left(D\right)-\mathrm{Cost}_{\mathrm{op}}^{\mathrm{ESS}}\left(D\right), \quad (1)$$

where $\mathrm{Sell}^{\mathrm{DAM}}(D)$ – income from the sale of electricity (discharging mode), m.u.; $\mathrm{Pur}^{\mathrm{DAM}}(D)$ – costs of purchasing electricity (charging mode), m.u.; $\mathrm{I}^{\mathrm{MSO}}(\mathrm{D})$ – total MSRC, m.u.; $\mathrm{Cost}_{\mathrm{op}}^{\mathrm{ESS}}(D)$ – costs of wear and degradation of ESS, m.u.

The structural and logical diagram of ESS mode simulation model is shown in Fig. 1.

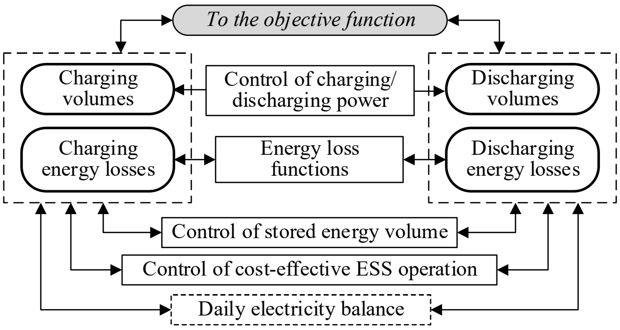


Fig. 1. Structural and logical diagram of the simulation model of energy storage system modes

The model was built on the basis of the detailing of technical characteristics associated with the occurrence of non-zero charging and discharging flows in ESS. Integration of flows with energy loss functions provided recurrent control over the storage state. Systems for controlling cost-effective operation and daily balance allowed us to monitor ESS operating modes on the daily planning horizon. The above constraint systems determined the region of technically feasible solutions, and the selection of the optimal one was carried out according to the criteria of the objective function (1).

The state space of the model at each calculation step $h \in D$ was identified through the control vectors of the amounts of charging and discharging energy, which acted as endogenous optimization parameters. The feasible region is determined by a system of linear constraints

$$\left\{0\le V_{\mathrm{ch},h}^{\mathrm{ESS}}\le V_{\mathrm{ch,max}}^{\mathrm{ESS}}\right\}\cup\left\{0\le V_{\mathrm{dch},h}^{\mathrm{ESS}}\le V_{\mathrm{dch,max}}^{\mathrm{ESS}}\right\}:\forall h\in D, \quad (2)$$

where $V_{\mathrm{ch},h}^{\mathrm{ESS}}$, $V_{\mathrm{dch},h}^{\mathrm{ESS}}$ – optimization variables, energy volumes, respectively, of charging and discharging for period h, MWh; $V_{\mathrm{ch,max}}^{\mathrm{ESS}}$, $V_{\mathrm{dch,max}}^{\mathrm{ESS}}$ – hardware limitations of maximum power, respectively, of charging and discharging for period h, MWh.

If necessary, the system of constraints (2) can be supplemented with terminal conditions of the capacity of energy import/export channels.

The parameterization of RTE was implemented through technological loss functions [3]. To increase the adequacy of the model, a quadratic approximation of losses was applied, the coefficients of which were updated based on monitoring data before the start of the planning procedure:

$$K_{\varDelta\mathrm{ch}}^{\mathrm{ESS}}=\frac{\varDelta V_{\mathrm{ch,max}}^{\mathrm{ESS}}}{\left(V_{\mathrm{ch,max}}^{\mathrm{ESS}}\right)^2};$$

$$K_{\varDelta\mathrm{dch}}^{\mathrm{ESS}}=\frac{\varDelta V_{\mathrm{dch,max}}^{\mathrm{ESS}}}{\left(V_{\mathrm{dch,max}}^{\mathrm{ESS}}\right)^2}, \quad (3)$$

where $\varDelta V_{\mathrm{ch,max}}^{\mathrm{ESS}}$, $\varDelta V_{\mathrm{dch,max}}^{\mathrm{ESS}}$ – electricity losses at maximum power, respectively, of charging and discharging at time interval h, MWh.

The energy loss functions for period h were formalized as strictly convex quadratic functions of the current values of control variables:

$$\begin{cases}\Delta W_{\mathrm{ch},h}^{\mathrm{ESS}}\left(V_{\mathrm{ch},h}^{\mathrm{ESS}}\right)=K_{\Delta\mathrm{ch}}^{\mathrm{ESS}}\cdot\left(V_{\mathrm{ch},h}^{\mathrm{ESS}}\right)^2\\ \Delta W_{\mathrm{dch},h}^{\mathrm{ESS}}\left(V_{\mathrm{dch},h}^{\mathrm{ESS}}\right)=K_{\Delta\mathrm{dch}}^{\mathrm{ESS}}\cdot\left(V_{\mathrm{dch},h}^{\mathrm{ESS}}\right)^2\end{cases}:\forall h\in D. \quad (4)$$

The positivity of the constant coefficients (3) in quadratic terms and the constraint of the domain for determining the optimization variables to non-negative values (2) cause the strict convexity of the functions (4). This became the basis for the conclusion about the strict concavity of the objective function (1), which, according to the optimization theory [19], indicates the existence of a single global maximum.

The use of the value of quadratic losses as a penalty in the objective function allowed us to solve the problem of the multiplicity of equally optimal solutions for periods with identical price signals [3], which is typical for linear programming problems.

The dynamics of the state of the energy stored in ESS at the end of each calculation period h were described by the recurrent transition equation

$$W_h^{\mathrm{ESS}}=W_{\mathrm{beg}}^{\mathrm{ESS}}+$$
$$+\sum_{k=1}^{h}\begin{pmatrix}V_{\mathrm{ch},k}^{\mathrm{ESS}}-V_{\mathrm{dch},k}^{\mathrm{ESS}}-K_{\varDelta\mathrm{ch}}^{\mathrm{ESS}}\cdot\left(V_{\mathrm{ch},k}^{\mathrm{ESS}}\right)^2-\\ -K_{\text{Ädch}}^{\mathrm{ESS}}\cdot\left(V_{\mathrm{dch},k}^{\mathrm{ESS}}\right)^2\end{pmatrix}:\forall h\in D, \quad (5)$$

where $W_{\mathrm{beg}}^{\mathrm{ESS}}$ is the amount of energy stored in ESS at the beginning of the operating cycle, MWh.

Then control over the amount of energy stored in ESS for each billing period is ensured by a system of constraints

$$0\le W_h^{\mathrm{ESS}}\le W_{\mathrm{work}}^{\mathrm{ESS}}:\forall h\in D,$$

where $W_{\mathrm{work}}^{\mathrm{ESS}}$ – available capacity of ESS, calculated before the start of the optimization procedure according to monitoring data, MWh.

For the correct completion of the daily cycle and preparation of the system for the next planning period, a terminal condition is introduced

$$W_{\mathrm{end}}^{\mathrm{ESS}}=W_{\mathrm{beg}}^{\mathrm{ESS}}+\sum_{h\in D}\begin{pmatrix}V_{\mathrm{ch},h}^{\mathrm{ESS}}-V_{\mathrm{dch},h}^{\mathrm{ESS}}-K_{\varDelta\mathrm{ch}}^{\mathrm{ESS}}\cdot\left(V_{\mathrm{ch},h}^{\mathrm{ESS}}\right)^2-\\ -K_{\text{Ädch}}^{\mathrm{ESS}}\cdot\left(V_{\mathrm{dch},h}^{\mathrm{ESS}}\right)^2\end{pmatrix}, \quad (6)$$

where $W_{\mathrm{end}}^{\mathrm{ESS}}$ is the target value of the amount of energy stored in ESS at the end of the day, set by the operator or the upper-level algorithm, MWh.

Thanks to the formalization of the arguments and the system of constraints, the transition to the cost assessment of ESS operating modes was performed and the structure of the objective function (1) was detailed. The goal was to form a management strategy to maximize the net financial result from arbitrage operations in DAM, taking into account the total costs.

The criterion for the effectiveness of price arbitrage in (1) is formed as the difference between income from the sale of energy and the costs of its purchase

$$\mathrm{Sell}^{\mathrm{DAM}}(D)-\mathrm{Pur}^{\mathrm{DAM}}(D)= \\ =\sum_{h\in D}\left(C_h^{\mathrm{DAM}}\cdot V_{\mathrm{dch},h}^{\mathrm{ESS}}\right)-\sum_{h\in D}\left(C_h^{\mathrm{DAM}}\cdot V_{\mathrm{ch},h}^{\mathrm{ESS}}\right), \qquad (7)$$

where C_h^{DAM} is the predicted market price of DAM over period h, m.u./MWh.

To increase the adequacy of the model, MSRC were taken into account as linear allowances for adjusting the values of marginal efficiency of operations. Specific market costs are formalized as

$$\Delta C^{\mathrm{AMSO}}=T^{\mathrm{MO}}+T^{\mathrm{TSO}}+T^{\mathrm{DSO}}, \qquad (8)$$

where T^{MO} is the market operator's tariff for electricity purchase/sale transactions, m.u./MWh; T^{TSO}, T^{DSO} are tariffs for electricity transmission and distribution, respectively, m.u./MWh.

In structure (1), MSRC is used as a mechanism for soft screening of unprofitable solutions by narrowing the area of their economic feasibility

$$\mathrm{I}^{\mathrm{MSO}}(D)=\Delta C^{\mathrm{AMSO}}\cdot\sum_{h\in D}\left(V_{\mathrm{ch},h}^{\mathrm{ESS}}+V_{\mathrm{dch},h}^{\mathrm{ESS}}\right). \qquad (9)$$

Within the scope of our paper, a symmetric soft screen (9) is formed for the conditions of participation of ESS operator only in DAM. When modeling the activities of ESS operator on several trading platforms (for example, in DAM and on the balancing market), the MSRC is characterized by asymmetry

$$\mathrm{I}^{\mathrm{MSO}}(D)=\sum_{h\in D}\left(\Delta C_{\mathrm{ch},h}^{\mathrm{AMSO}}\cdot V_{\mathrm{ch},h}^{\mathrm{ESS}}+\Delta C_{\mathrm{dch},h}^{\mathrm{AMSO}}\cdot V_{\mathrm{dch},h}^{\mathrm{ESS}}\right),$$

where $\Delta C_{\mathrm{ch},h}^{\mathrm{AMSO}}$, $\Delta C_{\mathrm{dch},h}^{\mathrm{AMSO}}$ – specific aggregate MSRC for transactions, respectively, of electricity purchase and sale on different trading platforms in the settlement hour h, m.u./MWh.

According to the optimization principles [19], the calculation model takes into account only variable costs directly related to the operation of ESS. Unlike [9], such costs are reduced to a unit of usable electricity output through the mechanism of interday updating of the model. The specific residual cost of resource degradation is determined based on the residual book value and the predicted number of cycles according to the following principle [10]

$$C_{\mathrm{f,dch}}^{\mathrm{ESS}}=\frac{Cost_{\mathrm{full}}^{\mathrm{ESS}}}{W_{\mathrm{work}}^{\mathrm{ESS}}\cdot N_{\mathrm{rem}}^{\mathrm{ESS}}}, \qquad (10)$$

where $Cost_{\mathrm{full}}^{\mathrm{ESS}}$ – residual book value of ESS, m.u.; $W_{\mathrm{work}}^{\mathrm{ESS}}$ – actualized usable capacity of ESS (calculated according to monitoring data), MWh; $N_{\mathrm{rem}}^{\mathrm{ESS}}$ – residual resource of char-ging/discharging cycles (integer number of cycles).

For (1), RRV is reduced to the volumes of usable output

$$\mathrm{Cost}_{\mathrm{op}}^{\mathrm{ESS}}(D)=C_{\mathrm{f,dch}}^{\mathrm{ESS}}\cdot\sum_{h\in D}V_{\mathrm{dch},h}^{\mathrm{ESS}}. \qquad (11)$$

Component (11) in the objective function (1) provided automatic formation of the "standby region" – states in which the market price spread is insufficient to cover hardware wear and tear, and the operation of ESS is not profitable. The proposed formalization allowed us to transform complex physicochemical degradation processes into an "economic screen" understandable for the optimization algorithm, which guarantees the long-term profitability of the facility.

In the cases of ESS integration into local systems (for example, microgrids), the RRV model could be adapted by replacing the price signals from DAM with indicators of the marginal costs of the system at the point of commercial accounting. In this case, it was assumed that the profitability condition would be preserved through the following constraints

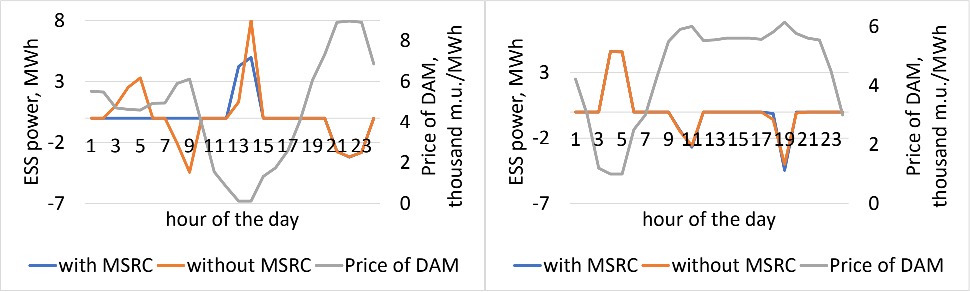
$$\sum_{h\in D}\left(C_h^{\mathrm{DAM}}-\Delta C^{\mathrm{AMSO}}-C_{\mathrm{f,dch}}^{\mathrm{ESS}}\right)\cdot V_{\mathrm{dch},h}^{\mathrm{ESS}}- \\ -\sum_{h\in D}\left(C_h^{\mathrm{DAM}}+\Delta C^{\mathrm{AMSO}}\right)\cdot V_{\mathrm{ch},h}^{\mathrm{ESS}}\geq 0. \qquad (12)$$

In our model, the consideration of efficiency losses was limited to charging and discharging modes. Methods and models for describing the self-discharge of ESS are considered in [20].

5. 2. Studying the influence of market and system-related charges on planning results

The results of assessing the influence of MSRC (9) on the control vectors of ESS regimes are shown in Fig. 2.

The price spread of the summer season (Fig. 2, *a*) provided the possibility of forming two charging/discharging cycles of ESS on the daily planning horizon for idealized conditions. However, taking into account MSRC significantly affected the optimal schedule, causing a reduction in the intensity of operation to one cycle. For the characteristic profile of the winter period (Fig. 2, *b*), the influence of MSRC on ESS operation schedule turned out to be insignificant. This demonstrated the parametric insensitivity of the optimization model to the conditions of the winter price profile.



a

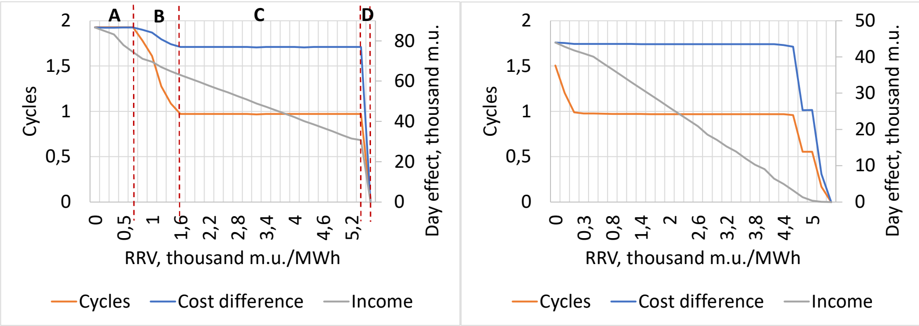
b

Fig. 2. Comparing the impact of market and system-related charges (9) on the operation schedules of an energy storage system: *a* – for the summer season; *b* – for the winter season

5. 3. Studying the influence of operating costs on the formation of optimal work schedules

The results of an experimental study on the influence of RRV (11) for typical profiles of the summer and winter seasons are shown in Fig. 3.

From the constructed optimal plots (Fig. 3), it is observed that the behavior of the model changes depending on the chosen strategy of cost formalization. In particular, areas of adaptive regulation are highlighted in which the intensity of price arbitrage decreases proportionally to the increase in the values of RRV. At the same time, the plots reveal regions of parametric insensitivity of the model, in which the variation of RRV values does not lead to a change in the intensity of system operation.



a *b*

Fig. 3. Representation of the economic effect from energy storage system operation depending on the residual value (11): *a* — for the summer season; *b* — for the winter season

6. Discussion of results based on modeling the operation schedules of energy storage systems

The results of solving the problem of assessing the impact of MSRC on the strategy of ESS operator's participation in the DAM auctions for the summer profile (Fig. 2, *a*) showed a significant shift in the results because of ignoring financial costs. Idealized conditions "Without MSRC" led to an excessively "aggressive" ESS operation strategy with two charging/discharging cycles on the daily planning horizon with a net profit of 70,274 m.u. In contrast, the results of calculations "With MSRC" demonstrated the convergence of the solution to the strategy of one charging/discharging cycle with a net profit of 51,842 m.u. That is, the idealization of the conditions for participation in the DAM auctions led to an overestimation of the expected profit by 35.6%. In this case, the MSRC component in (1) performed the role of a "soft screen" by eliminating economically inefficient scenarios outside the region of feasible solutions.

For the winter profile (Fig. 2, *b*), almost identical optimal plots were built, although the deviation in the objective function value between the models "without MSRC" and "with MSRC" was 91.6% (18,392 m.u. versus 35,234 m.u.). Such a high level of relative deviation is due to the low market price spread, at which fixed (8) became the dominant factor that leveled the marginal profit. On the other hand, our results from modeling the winter market price profile demonstrated the effect of the parametric insensitivity of the model to market price fluctuations.

The presence of regions of parametric insensitivity has been confirmed by the results from solving the problem of RRV sensitivity analysis.

For the summer market price profile (Fig. 3, *a*), three characteristic regime regions are distinguished:

– regions of parametric insensitivity (A and C). A sufficiently large marginal benefit of price arbitrage (7) ensured the insensitivity of the optimal strategy of ESS operation to the growth in RRV (11), despite the decrease in net profit (1);

– adaptive regulation regions (B and D). The growth in RRV (11) led to a proportional reduction in the amplitude of the cycle (the first for B and the second for D). In these regions, a soft cut-off mechanism was triggered, which gradually displaced operations with low margin;

– region of profitability loss (> 5360 m.u./MWh). The area reflected a standby region where the price signals from DAM did not ensure the profitable operation of ESS.

For the winter market price profile (Fig. 3, *b*), the nature of model behavior is identical but the boundaries of phase transitions between regions are shifted to the left due to the narrowing of the price spread.

Identification of regions of adaptive regulation and parametric insensitivity opened up prospects for adjusting the strategy of ESS operator's participation in DAM, taking into account the given level of risks. Unlike the use of the normalized energy storage cost indicator in [9] and the static screen in [3], our structure (1) provides the ability to control the adaptive screen of MSRC and RRV components using additional weighting coefficients. Thus, a targeted search for the parametric insensitivity region allows one to obtain a "conservative" scenario for participation in DAM with minimizing the risks of economic losses due to the inaccuracy of the forecast of market signals. In contrast, obtaining a plan for participation in DAM in the adaptive regulation region allows one to implement "aggressive" arbitrage with maximizing profit under the conditions of the predicted daily price vector. However, the risks of economic losses due to the price forecast error increase.

The proposed model with a comprehensive adaptive screen of unprofitable operations provided a reliable mechanism to search for optimal price arbitrage strategies in the day-ahead market. The model was recognized as suitable for use in modern architecture of energy management systems. Its implementation was aimed at effective automation of the processes of preparing strategies for the participation of the operator of the energy storage system in the auctions.

Our studies are limited by a strict dependence on deterministic forecasts of market price signals for the calculated operating day. The results are stable and reproducible only under the condition of high accuracy of the input vector of DAM prices. Another limitation was the assumption of quasi-stationarity of wear within one day. This limited the application of the model to objects where the number of daily cycles is 1–2, and the degree of degradation over this period of time is indeed negligibly small. In addition, the input data ranges are limited by a stepwise approximation of the power (constant values during the calculation hour) with a sampling step of $h = 1$ h in accordance with DAM regulation. As a result, the model has become insensitive to intra-hour fluctuations.

The shortcomings of our study included investigating the impact of MSRC only for DAM. That did not make it possible to fully reveal the adaptive mechanism of the model under the condition of the simultaneous participation of ESS operator in different market segments (intraday or balancing markets). Another drawback of the study was ignoring the duration of transient processes, which limited the applicability of the model only to high-speed energy storage technologies. The elimination of these shortcomings is considered possible by switching to a sub-hourly (for example, 15-minute) modeling step and expanding the system of global coherent constraints for modeling simultaneous trading on several adjacent spot platforms.

Further advancement of our model is aimed at finding regions of parametric insensitivity. This should enable the design of an adaptive toolkit for ESS operator to choose a "conservative" or "aggressive" arbitrage strategy.

7. Conclusions

1. We have formalized the objective function and the system of constraints for a mathematical model as a mixed-integer quadratic programming problem. Its difference from analogs is the formalization of adaptive screens of admissible solutions for the comprehensive consideration of market charges, round-trip efficiency, as well as the cost of the residual resource. This allows the model to be used in the architecture of energy management systems to automate planning procedures.
2. The influence of market and system-related charges on the structure of the optimal operation schedule has been investigated. It was confirmed that the error in income estimation, due to the idealization of market conditions, reaches 91.6 percent in periods with a low price spread. For conditions of a low price spread, the effect of parametric insensitivity has been revealed, when changes in the structure of profits and expenses do not lead to a change in the optimal price arbitrage strategy.
3. The influence of operating costs on the intensity of equipment operation has been investigated through the assessment of the residual cost of the resource. The existence of regions of parametric insensitivity has been confirmed for both high and low market price spreads.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Oleksandr Havva: Conceptualization, Methodology, Writing, Investigation, Data curation; **Yevgene Parus:** Conceptualization, Methodology, Software, Writing; **Ihor Blinov:** Conceptualization, Writing, Validation, Formal analysis, Supervision; **Volodymyr Evdokimov:** Validation, Investigation, Supervision, Project administration, Data curation.

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