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Digital twin of a hybrid power supply system for scenario optimisation of battery storage unit modes

Andrii Povsheniuk*
Senior Lecturer
National University of Water and Environmental Engineering
33028, 11 Soborna Str., Rivne, Ukraine
https://orcid.org/0009-0000-7789-6181

Abstract. The purpose of the study was to determine how different approaches to battery module management affect the energy and economic characteristics of a local solar power system considering the actual consumption schedule, set charge limits, and tariff scheme. The method of scenario modelling of battery storage operating modes based on a digital twin was applied. It was found that the battery storage management parameters affect the import of electricity from the grid, the loss of solar generation, the relative cost of electricity, and the level of autonomy of the hybrid power supply system. The actual operating mode, basic control logic, minimum charge reserve, charging time, tariff structure, and battery storage capacity were compared. Based on the results of scenario modelling, it was found that changing the battery storage management mode affects the import of electricity from the grid, the loss of solar generation, the relative cost of electricity, and the energy self-sufficiency rate. In actual operating mode, imports from the network amounted to 25 kWh, the relative cost was 15.68 c.u., and the energy self-sufficiency rate – 49.91%. The basic modelling reduced the import to 20.88 kWh and the relative cost to 12.19 c.u., increasing self-sufficiency to 58.17%. The best economic result was obtained in the scenario with a decrease in the minimum battery reserve: imports decreased to 17.37 kWh, relative cost – to 8.69 c.u., and self-sufficiency increased to 65.19%. Increasing the battery capacity to 20 kWh provided the lowest losses of solar generation – 7.6 kWh and the highest self-consumption rate – 81.39%. The tariff-oriented regime showed that the economic effect depends not only on the volume of imports, but also on the time of electricity consumption from the grid. Practical significance lies in the possibility of using the results by designers and operators of local solar systems with a battery to choose rational settings for the charge reserve, charging time, tariff consumption, and the feasibility of increasing the storage capacity

Keywords: minimum charge reserve; delayed charging; two-zone tariff; solar generation losses; relative electricity cost; self-consumption rate; energy self-sufficiency

INTRODUCTION

The decentralisation of electricity supply, the spread of photovoltaic installations in households, and the growing role of battery-powered energy storage systems are changing the logic of the functioning of local power systems. In such conditions, hybrid power supply systems become one of the practical solutions for combining generation, accumulation, and controlled consumption of electricity at the level of an individual consumer. However, the efficiency of such systems is determined not only by the parameters of the equipment, but also by the operating modes of the battery storage system, the time structure of consumption, and tariff conditions. Poor battery management can lead to an increase in electricity imports from the grid, losses of solar generation due to forced restrictions, and an increase in total electricity costs.

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*Corresponding author (andrii_povsheniuk@outlook.com)

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Existing research has confirmed that the digital twin is a promising tool for modelling, monitoring, and optimising hybrid power systems. L. Chalal *et al.* (2023) showed that combining a digital twin with an Internet of Things (IoT) infrastructure allows reproducing the state of a hybrid power grid in real time and using a digital model to adjust control actions. The digital twin is considered not as a static design scheme, but as a dynamic model that can support the choice of system operating modes depending on the current state of generation, load, and storage. For photovoltaic installations, the potential of digital twins was summarised in the study by D.D. Angelova *et al.* (2024). The researchers found that digital twins of photovoltaic (PV) systems can improve the accuracy of generation prediction, facilitate the detection of deviations in equipment operation, and support the optimisation of power consumption and generation modes. For hybrid battery-powered systems, this conclusion is fundamental, since the efficiency of such a system depends on the correspondence of solar generation, load profile, and battery charge status over time.

The problem of time data granularity can be traced by C. Rus-Casas *et al.* (2024). The researchers found that the results of battery capacity optimisation and energy efficiency estimation depend on the discreteness of input data: excessive averaging can hide short-term consumption peaks, battery saturation moments, and solar generation losses. This justifies the need to use highly detailed time series in a digital twin, since they allow correctly reproducing the real modes of charging and discharging the battery. The economic aspect of storage system management was revealed by Z. Zeng *et al.* (2023). The findings showed that in systems with solar generation and battery storage, minimising the import of electricity from the grid does not always provide the lowest costs, since the economic result depends on the tariff zone and time of electricity consumption. This means that battery life should be evaluated not only by the energy balance, but also by the economic effect of transferring consumption between time intervals.

The possibility of using a digital twin specifically for scenario analysis of energy systems was confirmed by M. Deakin *et al.* (2023). A digital copy of the power grid allows comparing alternative control modes without interfering with the physical infrastructure and assessing the impact of such decisions on the operation of the system. This demonstrates that optimising battery modes also involves checking several scenarios in the digital model before forming practical recommendations.

For the Ukrainian context, the issue of battery-powered energy storage systems is related not only to the integration of renewable generation, but also to increasing the flexibility and sustainability of the energy system. I. Prytyskach *et al.* (2024) found that energy storage devices can perform several functions in the electricity market, in particular, provide a reserve for maintaining frequency and reduce the load on conventional balancing mechanisms. The performance of the battery system depends on the strategy of managing the average charge level, the number of charge-discharge cycles, and consideration of battery degradation. At the household level, the aspect of introducing battery storage systems in Ukraine was revealed in the paper by G. Trypolska *et al.* (2024). The researchers found that the development of domestic photovoltaic installations creates prerequisites for wider use of home battery systems, since they can partially cover household demand and reduce the balancing problems of the power grid. This approach means that the spread of such systems requires organisational and economic incentives, because without appropriate financial mechanisms, the cost of installing storage systems remains a significant barrier for consumers. O. Diachenko (2025) considered battery storage systems as one of the means of increasing the energy independence and survivability of the Ukrainian energy system in conditions of damage to centralised generation and network infrastructure. The paper emphasised that such systems can support the operation of local micro-networks, provide electricity to critical consumers, and promote deeper integration of renewable energy sources. A local system with solar generation and a battery should be considered not only as a source of savings, but also as an element of increasing the autonomy and stability of the power supply.

Despite the existence of research on digital twins of energy systems, optimisation of photovoltaic installations with storage devices and tariff-oriented management, the applied aspect of combining these approaches within one local hybrid power supply system remains less developed. In particular, it is necessary to clarify how changing the operating modes of the battery storage system affects the import of electricity from the network, the loss of solar generation, the relative cost of electricity, and the level of autonomy of the system, provided that actual highly detailed time data is used. Thus, the purpose of the study was to assess the impact of various battery module control algorithms on the energy and economic performance of the local solar power system considering the actual consumption profile, charge restrictions, and tariff structure. To achieve this goal, the following tasks were set: based on scenario modelling, to assess the impact of battery management parameters on the import of electricity from the grid, solar generation losses, the relative cost of electricity, and the level of system autonomy; based on the results of comparing scenarios, to formulate practical recommendations for choosing rational battery modes.

MATERIALS AND METHODS

The study was conducted as an empirical and modelling analysis of the operation of a hybrid power supply

system for a private household. The research was based on the actual operational data of the system, which included a photovoltaic station, a battery storage device, an inverter, and a connection to the electrical network. Based on this data, a digital twin was built that reproduces energy flows between solar generation, consumer load, battery storage and the network. As part of this study, the digital twin was considered as a virtual reproduction of the actual telemetry system based on time series, designed for scenario analysis, rather than for continuous online control of a physical object. The study did not involve changing a physical object, but rather scenario modelling of battery storage modes. The actual mode was used as a basic reference for comparison, and then alternative disk management modes were tested. This allowed assessing the impact of the minimum charge reserve, delayed charging, tariff-oriented management, and increased battery capacity on the import of electricity from the grid, the loss of solar generation, the relative cost of electricity, and the energy self-sufficiency rate of the system.

The modelling was performed for a hybrid power supply system of a private household with a photovoltaic station with an installed capacity of 15.6 kW, a battery storage device with a capacity of 15 kWh, and an inverter with a rated capacity of 12 kW. Calculations were made based on actual operational data for the period from 01.06.2025 to 07.06.2025 inclusive, which corresponds to 7 days of telemetry observations. With a time, resolution of 5 minutes, 2,016 consecutive time intervals were used in the modelling. The selected period belonged to the summer season and was used as a representative sample of the system's actual operation, as it was characterised by high levels of photovoltaic generation, daily fluctuations in domestic load, and active use of the battery storage system. All telemetry time series were reduced to a single time scale in 5-minute increments. Time-synchronised values of power consumption, photovoltaic generation, network exchange, battery power, and battery charge status were used for each interval. The energy values for each step were defined as the product of the average power for the corresponding interval and the duration of the modelling step $\Delta t = 5/60$ h. To assess the system's performance, the actual operating mode and alternative battery management scenarios were compared. The comparison was based on the following indicators: the volume of electricity imports from the grid, losses of solar generation due to its restriction, the relative cost of electricity, the self-consumption rate of solar energy, and the energy self-sufficiency rate. This detail allowed considering short-term changes in the load, the dynamics of charging and discharging the battery, and the moments of limiting solar generation. The main parameters of the system under study are shown in Table 1.

Table 1. Output parameters for modelling a hybrid power supply system

Parameter	Value
Installed capacity of the photovoltaic station	15.6 kW
Basic battery capacity	15 kWh
Alternative battery capacity in one scenario	20 kWh
Rated power of the inverter	12 kW
Maximum battery unit charging power	5 kW
Maximum battery discharge power	5 kW
Minimum charge level in basic mode	35%
Maximum charge level in basic mode	100%
Charging efficiency factor	0.96
Discharge efficiency ratio	0.96
Relative daily tariff ratio	1
Relative night rate ratio	0.5
Night tariff period	23:00-07:00
Modelling step	5 min

Source: compiled by the author based on the initial parameters of the hybrid power supply system under study

The parameters of the photovoltaic power station, the battery storage system, and the inverter were used as the actual output characteristics of the system. The choice of indicators for comparing scenarios was conditioned by the need to comprehensively evaluate the operation of the battery storage system in a hybrid power supply system. The volume of electricity imports from the grid reflected the dependence of the system on external power supply, losses due to the restriction of solar generation characterised the efficiency of using the potential of a photovoltaic station, and the relative cost of electricity allowed comparing scenarios by economic criterion. Indicators of solar energy self-consumption and energy self-sufficiency were used to estimate the share of own generation in load coverage and the dependence of the system on electricity imports from the grid. The charging and discharging efficiency coefficients of the battery were accepted as the initial technical parameters of the model. As part of the current study, the export of excess electricity to the grid

was not considered. Excess solar generation that could not be used to cover the load or charge the battery was accounted for as losses due to generation limitations.

The digital twin of a hybrid power supply system was built as a discrete model of energy balance. The time horizon of the modelling was divided into consecutive intervals in increments of $\Delta t = 5/60$ h. For each time point t, the model considered the power consumption, the potential power of photovoltaic generation, the electricity tariff, and the state of charge of the battery. The potential power of photovoltaic generation was determined from the telemetry data of the inverter as the available power of the photovoltaic station at the corresponding time step. In cases where, after covering the current load and possibly charging the battery, part of the solar generation could not be used by the system, the difference between the potential, and actually used generation was considered as losses due to the limitation of solar generation. The controlled variables were the charging and discharging capacity of the battery, the power of importing electricity from the grid, and losses due to limited solar generation. The state of the battery was described in terms of its energy reserve (Anderson *et al.*, 2021). The charge dynamics at each time step was defined as:

$$E_{bat}(t + \Delta t) = E_{bat}(t) + (\eta_{ch} \times P^{ch}_{bat}(t) - P^{dis}_{bat}(t)/\eta dis) \times \Delta t, \quad (1)$$

where E_{bat} (t) – energy reserve in the battery at time t, kWh; η_{ch} – charge efficiency coefficient; η_{dis} – discharge efficiency coefficient, kW; $P^{ch}_{bat}(t)$ – battery charging power, kW; $P^{dis}_{bat}(t)$ – battery charging capacity; Δt – duration of the modelling time step, h.

A 5-minute step corresponds to $\Delta t=5/60$ h. The charging and discharging capacities were considered as non-negative values. The state of charge of the battery storage device as a percentage was determined as the ratio of the current energy reserve to the nominal capacity of the battery storage device:

$$SOC(t) = E_{bat}(t)/C_{bat} \times 100\%, \quad (2)$$

where C_{bat} – rated battery capacity; $E_{bat}(t)$ – energy reserve in the battery at time t.

At each time point, the model performed an energy balance between the load, photovoltaic generation, battery storage, and electrical network (Bloch *et al.*, 2019):

$$P_{load}(t) + P^{ch}_{bat}(t) = P^{use}_{pv}(t) + P^{dis}_{bat}(t) + P^{import}_{grid}(t), \quad (3)$$

where $P_{load}(t)$ – power consumption at time t, kW; $P^{use}_{pv}(t)$ – actually used photovoltaic power at time t, kW; $P^{dis}_{bat}(t)$ – battery storage discharge power at time t, kW; $P^{import}_{grid}(t)$ – power of electricity imports from the grid at time t, kW; $P^{ch}_{bat}(t)$- battery storage charging power at time t, kW.

In this form of balance, charging the battery was considered as an additional load, and discharging the battery, using solar power and importing from the network were considered as sources of its coverage. The actual solar generation used was defined as the difference between potential generation and losses due to its limitation (O'Shaughnessy *et al.*, 2021):

$$P^{use}_{pv}(t) = P^{pot}_{pv}(t) - P_{curt}(t), \quad (4)$$

where $P^{use}_{pv}(t)$ – actually used photovoltaic power at time t, kW; $P^{pot}_{pv}(t)$ – potential power of photovoltaic generation at time t, kW; $P_{curt}(t)$ – losses resulting from the restriction of solar generation at time t, kW.

If the battery storage unit reaches the upper charge limit and the current load is lower than the available solar generation, some of the potential generation cannot be used by the system to cover the load or charge the battery. In this case, it was considered as losses due to limited solar generation. To assess the efficiency of battery storage modes, scenarios were compared in terms of energy and economic indicators, in particular, the relative cost of imported electricity and losses of unused solar generation;

$$Cgrid = \Sigma t(P^{import}_{grid}(t) \times Tariff(t) \times \Delta t); \quad (5)$$

$$E_{curt} = \Sigma t(P_{curt}(t) \times \Delta t), \quad (6)$$

where Cgrid – relative cost of electricity imported from the grid, c.u.; $P^{import}_{grid}(t)$ – power of electricity imports from the network at time t, kW; Tariff(t) – tariff coefficient at time t; Δt – modelling time step, H; E_{curt} – amount of curtailed solar generation, kWh; $P_{curt}(t)$ – curtailed solar generation power at time t, kW.

In the calculations, a 5-minute step corresponds to $\Delta t = 5/60$ hours. This approach allowed comparing the operating modes of the battery storage system in terms of economic effect and efficiency of using potential solar generation.

The digital twin of the hybrid power supply system is implemented in the Python software environment. The Pandas library was used for processing time series, NumPy – for numerical calculations, and Matplotlib – for plotting and visualising results. Calculations were performed sequentially for each time step of the modelling. Initially, the available solar generation was directed to cover the current load. In the presence of excess generation, it was used to charge the battery considering the current state of charge, power limits, and rules of the corresponding scenario. If its own generation was not enough, the model determined the possibility of discharging the battery to cover the shortage. In the event of insufficient energy in the battery, the residual load was covered by importing electricity from the grid. If unused solar power remained after covering the load and charging the battery, it was

recorded as a loss due to the generation limit. For all scenarios, the same calculated energy balance logic was applied, and the differences between scenarios were set using parameters or rules for controlling the battery. The consistency of the basic modelling with the actual mode was checked by comparing the main integral indicators with the same initial parameters of the system: the amount of electricity consumed from the network, losses due to limited solar generation, the relative cost of electricity, the self-consumption rate of solar energy and self-sufficiency rate. For each indicator, the absolute deviation between the basic modelling and the actual mode, and the relative deviation as a percentage of the actual value, were determined. Absolute deviation was defined as the difference between the indicator value in the basic modelling and the actual mode, and relative deviation was defined as the ratio of the absolute deviation to the actual indicator value.

For scenario modelling, six variants of the system operation were selected, which allowed assessing the impact of key factors on the efficiency of the battery storage system: the actual operating mode, basic control logic, minimum charge reserve, charging time, tariff structure, and capacity of the battery storage system. The actual mode and basic modelling were used as a reference base for comparison, while other scenarios reflected possible areas for changing the battery mode or system configuration. The actual mode reproduced the actual operation of the system based on telemetry data. The basic modelling was used to test the operation of the digital model with the same equipment configuration and standard battery management logic. The scenario of reducing the minimum charge reserve allowed estimating the effect of the available usable capacity of the battery on covering the evening load and reducing the import of electricity from the grid. The delayed charging scenario was used to test the assumption that filling the battery too early can lead to losses in solar generation during the daytime. The tariff-oriented scenario allowed assessing the impact of the two-zone tariff model on the economic result of the system. The scenario of increasing the battery storage capacity to 20 kWh was included to test the effect of hardware changes in the system, i.e., increasing its storage capacity.

The effectiveness of scenarios was evaluated by energy and economic indicators. Energy indicators included the amount of electricity consumed from the grid, losses due to limited solar generation, the self-consumption rate of solar energy, and the energy self-sufficiency rate. The economic indicator was the relative cost of electricity, calculated based on the two-zone tariff structure. The self-consumption rate of solar energy characterised the proportion of potential solar generation that was actually used by the system to cover the load or charge the battery storage system. The energy self-sufficiency rate reflected the share of total electricity demand covered by its own generation and battery storage without importing from the grid. Losses due to limited solar generation were used as an indicator of the efficiency of using the potential of a photovoltaic plant. The relative cost of electricity was used to compare scenarios based on an economic criterion without reference to the absolute price of electricity in UAH. This set of criteria allowed evaluating the scenarios in a comprehensive way: in terms of the cost of electricity, dependence on the network, the use of solar generation, and the technical limitations of the battery storage system.

The methodological provisions of the study were consistent with international standards concerning digital twins, monitoring of photovoltaic systems and electricity storage systems. The terminology framework of the digital twin was based on ISO/IEC 30173:2023 (2023), the approach to the use of time series of generation, load, and system status – IEC 61724-1:2021 (2021), and the terminology regarding the battery storage system and its operating modes – IEC 62933-1:2024 (2024). The model considered the main technical limits that determine the permissible modes of operation of a hybrid power supply system: the minimum and maximum charge levels of the battery storage system, the maximum power of its charging and discharging, the rated power of the inverter, and the impossibility of full use of excess solar generation in the absence of free storage capacity. For basic mode, the minimum battery storage system charge level was assumed to be 35%, and the maximum was assumed to be 100%. This means that part of the storage capacity was stored as a reserve and was not used to cover the load. Changing the minimum charge reserve was considered as one of the control scenarios, since it directly affects the available usable storage capacity. If the solar generation exceeded the current load and the ability to charge the battery, the unused part of the generation was recorded as a loss due to its limitation. A limitation of the study is the use of actual data from a single object and a specific configuration of the hybrid power supply system. The scenarios did not include the capital costs of increasing the battery capacity, so the option with a 20 kWh storage system requires a separate economic substantiation. The results obtained may vary for other seasons, tariff models, or consumption profiles.

RESULTS AND DISCUSSION

The results of scenario modelling showed that the battery storage system control modes affect both the energy and economic performance of the hybrid power supply system. Changes in the minimum charge reserve, the use of tariff-oriented management and an increase in battery storage capacity have different effects on the amount of electricity consumed from the

network, the loss of solar generation, the relative cost of electricity, the self-consumption rate of solar energy and the energy self-sufficiency rate. Calculations were performed based on a discrete model of energy balance according to equations (1-6), and the self-consumption rate of solar energy and the energy self-sufficiency rate were determined as generalised integral indicators based on the results of modelling all 5-minute intervals. The results of the scenario comparison are summarised in Table 2.

Table 2. Comparison of the results of scenario modelling of battery storage modes

Modelling scenario	Volume of electricity consumed from the grid, kWh	Losses due to limited solar generation, kWh	Relative cost of electricity, c.u.	Self-consumption rate of solar energy, %	Energy self-sufficiency rate, %
Actual mode	25	12.86	15.68	68.51	49.91
Basic modelling	20.88	10.98	12.19	73.1	58.17
Reduction of the minimum battery storage system charge reserve	17.37	8.74	8.69	78.61	65.19
Delayed charging of the battery storage unit	22.92	13.2	14.24	67.67	54.07
Tariff-oriented management mode	23.9	13.49	13.06	66.96	52.11
20 kWh battery storage unit	19.44	7.6	10.76	81.39	61.04

Source: compiled by the author based on the results of scenario modelling of battery storage modes based on a discrete model of energy balance according to equations (1-6); the self-consumption rate of solar energy and the energy self-sufficiency rate were generalised based on the results of modelling 5-minute intervals

Analysis of the 5-minute dynamics of the system showed that during the day, energy flows had a pronounced time unevenness. In the morning hours, the load was covered mainly due to the residual charge of the battery storage system and, if it was insufficient, the import of electricity from the network. With the growth of photovoltaic generation during the daytime, solar energy was first directed to cover the current load, and its excess – to charge the battery storage system. After reaching the upper charge limit, some of the potential solar generation could not be used by the system and was considered losses due to the generation limit. In the evening, when photovoltaic generation was reduced or absent, the battery was discharged to cover the load, and after reducing the state of charge to the permissible limit, the need for importing electricity from the grid increased. It is this daily sequence of charging, discharging, importing, and limiting generation that explains the differences between the scenarios: scenarios with a higher available usable storage capacity better covered the evening load, while scenarios with a higher storage capacity better accepted the daytime excess of solar generation.

A comparison of the scenarios showed that the differences between them are due not only to changes in the total amount of available energy, but also to the distribution of this energy over time. The scenario with a decrease in the minimum battery reserve provided a better result in terms of electricity import from the grid and relative cost, since it increased the available useful capacity of the storage system to cover the load in the evening. At this time, photovoltaic generation was reduced or absent, so the additional available energy reserve in the storage device directly reduces the need for import from the grid. Instead, the scenario of increasing the battery capacity to 20 kWh had the best effect on solar generation losses, as the larger capacity allowed for most of the daily excess generation. Therefore, the scenario with a decrease in the minimum charge reserve mainly improves the economic result and reduces dependence on the network, while increasing the storage capacity primarily increases the efficiency of using potential solar generation. Absolute and relative deviations of the main indicators were calculated to assess the compliance of the basic modelling with the actual mode. Compared to the actual mode, the basic modelling reduced the amount of electricity consumed from the grid by 4.12 kWh, or 16.48%, losses due to solar generation restrictions – by 1.88 kWh, or 14.62%, and the relative cost of electricity – by 3.49 c.u., or by 22.26%. Furthermore, the self-consumption rate of solar energy increased by 4.59 percentage points, and the energy self-sufficiency rate –by 8.26 percentage points. The deviations obtained show that the basic modelling does not fully reproduce the actual mode, but preserves the logic of the system's energy balance and can be used as a control calculation scenario for further comparison of alternative battery management modes.

The tariff-oriented management mode has shown that the economic efficiency of the system depends not only on the total volume of electricity imports from the grid, but also on its distribution between tariff periods. In this scenario, the total import volume was 23.9 kWh, and the relative cost of electricity was 13.06 c.u. Considering the daily tariff coefficient of 1 and the night coefficient of 0.5, it was calculated that the estimated volume of imports during the night period was 21.68 kWh, and during the day – 2.22 kWh. This

explains why the tariff-oriented scenario did not provide a minimum volume of imports from the network, but gave a lower relative cost compared to the actual mode: the main part of network consumption occurred during the period with a lower tariff coefficient. In the delayed battery charging scenario, the main performance of the system worsened compared to the basic modelling: electricity imports from the grid increased from 20.88 to 22.92 kWh, losses due to solar generation restrictions – from 10.98 to 13.2 kWh, and the self-consumption rate of solar energy decreased from 73.1 to 67.67%. The relative cost of electricity also increased from 12.19 to 14.24 c.u. Therefore, in the framework of the modelling, the transfer of charging to a later time did not provide an improvement in energy or economic indicators. This result can be explained by the fact that the selected time limits for delayed charging were not sufficiently consistent with the actual dynamics of solar generation and loading. Limiting charging during the daytime reduced the battery's ability to receive excess solar power exactly when it was available. As a result, part of the potential generation was not accumulated, but was accounted for as losses due to restrictions. However, in the evening period, the energy reserve in the storage device was insufficient to fully cover the load, which increased the need to import electricity from the grid. Therefore, the reason for the lower efficiency of this scenario was not the delayed charging principle itself, but the discrepancy between the specified charging mode and the actual generation profile, load and state of charge of the battery.

Based on the results of scenario modelling, it is possible to formulate practical recommendations for managing a battery storage system in a hybrid power supply system. It is advisable to determine the minimum charge reserve considering the actual consumption profile, since an excessively high reserve reduces the available useful storage capacity and increases the system's dependence on the network in the evening. Charging modes should be consistent with the daily dynamics of photovoltaic generation to avoid premature filling of the storage tank and subsequent losses of potential solar generation. Under the conditions of a two-zone tariff, it is advisable to consider not only the total volume of electricity imports from the grid, but also its distribution between tariff periods. Increasing the battery capacity can reduce the loss of solar generation and increase the self-consumption rate of solar energy, but this decision requires a separate economic substantiation based on the cost of additional capacity.

The results obtained are consistent with approaches in which the battery storage device is considered not only as a means of storing energy, but also as an active element for controlling the energy balance of a hybrid system. In particular, in the study by A. Sorour *et al.* (2021), predictive control of a photovoltaic system with a battery was used to increase the self-consumption rate of solar energy. A similar logic can be traced in the study by M.M. Alam *et al.* (2022), where the efficiency of a home micro-grid with photovoltaic generation and battery storage was related to optimal power management. As part of the current study, this conclusion is supported by the fact that changing the battery mode affected not only the use of solar power, but also the import of electricity from the grid and the relative cost of electricity. This was most clearly manifested in the scenario with a decrease in the minimum charge reserve, where the import of electricity from the grid decreased to 17.37 kWh, and the relative cost – to 8.69 c.u. Thus, the results not only confirm the general conclusion of previous studies about the importance of storage system management, but also concretise it at the level of comparing individual system operation scenarios.

The scenario with a decrease in the minimum battery storage system charge reserve gave the lowest import of electricity from the grid – 17.37 kWh and the lowest relative cost – 8.69 c.u. Compared to the actual regime, imports decreased from 25 to 17.37 kWh, and the self-consumption rate of solar energy increased to 78.61%. The improvement in performance was conditioned by a more complete use of the available battery capacity, rather than an increase in its capacity. This correlates with the study by Y. Wu *et al.* (2022), in which the energy management strategy and optimal battery capacity were considered for a flexible photovoltaic system with a battery under the conditions of a temporary tariff. In this formulation, the efficiency of the system depends not only on the parameters of the battery storage system, but also on the mode of its operation over time. A similar logic can be traced in the paper by X. Chen *et al.* (2023), where optimisation of battery storage capacity in a network photovoltaic system with a battery was presented as a multi-criteria problem with the consideration of the time rate. In the present study, this relationship was manifested due to the difference between scenarios. Increasing the battery capacity to 20 kWh gave the best result for using solar generation: losses due to generation restrictions decreased to 7.6 kWh, and the self-consumption rate of solar energy increased to 81.39%. However, in terms of the volume of imports from the network and the relative cost of electricity, this scenario was preferred, but the scenario with a decrease in the minimum battery charge reserve. This showed that increasing the capacity of the battery storage unit improves the use of excess solar generation, but the economic result and reducing dependence on the network may depend more strongly on the mode of use of existing capacity.

It is advisable to consider the scenario with an increase in the battery capacity to 20 kWh not as a universally preferred option, but as a scenario that primarily improves the use of excess solar generation.

The large storage unit capacity helped to reduce losses due to limited generation, but did not provide the lowest relative cost of electricity. This means that a technical increase in the cumulative capacity of the system does not in itself guarantee the economically best result. This conclusion can be compared with the study by M. Tostado-Véliz *et al*. (2021), in which the optimal size of a battery-powered photovoltaic system was determined based on network outages and demand management. H. Li *et al*. (2024) considered the issue of efficiency of distributed photovoltaic systems with battery storage through the correspondence between generation, consumption, and feasibility. In the present study, this correlation was manifested due to the difference between energy and economic indicators: a larger battery capacity reduced the loss of solar generation, but the scenario with a decrease in the minimum charge reserve remained economically better in terms of relative cost. The study by P. Jivaganont *et al*. (2024) was also related to this logic, since the design of a photovoltaic system with a battery in it was based on the load demand characteristic. For the results of this study, this means that it is advisable to evaluate the increase in battery capacity not separately, but together with the consumption profile, operating mode of the storage system and cost indicators.

In the tariff-oriented mode, the volume of electricity consumed from the grid was 23.9 kWh, that is, it was more than in the basic modelling – 20.88 kWh. The relative cost of electricity in this scenario was 13.06 c.u., which was lower than the actual mode with an indicator of 15.68 c.u. This showed that tariff-oriented management did not produce the best energy result, but reduced the cost of electricity compared to the actual regime. This correlates with the study by Z. Wang *et al*. (2024), in which the technical and economic performance of photovoltaic systems with a battery was analysed under various tariff policies. In this study, a similar relationship was manifested due to the fact that the economic indicator did not change in the same way as the volume of imports from the network: the tariff-oriented regime had more imports than the basic modelling, but a lower relative cost compared to the actual regime. F. Norouzi *et al*. (2025) considered the impact of different pricing on the example of a photovoltaic system with a battery in a residential micro-network. This corresponds to the results of this study, since the tariff scenario showed that the economic assessment of the system's operation depends not only on the amount of electricity consumed from the network, but also on the terms of its payment. C. Lorenz *et al*. (2026), based on simulations for 448 households, also analysed the impact of dynamic tariffs on the benefits of using photovoltaic systems with battery storage. In the current study, this aspect was manifested within the two-zone tariff: transferring consumption or imports to other time periods can reduce the relative cost of electricity, even when the volume of imports from the network itself is not minimal. Therefore, it is advisable to evaluate tariff-oriented management separately from purely energy indicators of the system.

The results of this study showed that different regimens had different benefits. Reducing the minimum battery storage system reserve gave the lowest import from the network – 17.37 kWh and the lowest relative cost – 8.69 c.u. But the 20 kWh battery storage system provided the lowest losses of solar generation – 7.6 kWh and the highest self-consumption rate of solar energy – 81.39%. The tariff-oriented mode reduced the relative cost compared to the actual mode – 13.06 against 15.68 c.u., but it was not the best for importing from the network. This is consistent with the research by Y. Lin *et al*. (2024), in which an integrated photovoltaic system with a battery was evaluated under the conditions of temporary tariff formation in an industrial park. In this study, the time tariff also affected the cost indicator: the tariff-oriented mode reduced the relative cost of electricity compared to the actual mode, but did not provide the best energy indicators. F. Samm *et al*. (2025) considered the operation of a battery storage system through a combination of economic goals and parameters of interaction with the network at different tariffs for electricity consumption and supply. In the current study, a similar distinction was shown due to various advantages of scenarios: reducing the minimum charge reserve was better in terms of cost and import from the grid, while increasing the battery capacity was better in terms of using solar power. The study by D. Keles & J. Dehler-Holland (2022) concerned the evaluation of photovoltaic systems with storage devices in energy markets in conditions of uncertainty. For this study, this statement is close in terms of the economic assessment of the operation of the storage system: the choice of the mode of operation of the battery storage system depends on what indicator is taken as a basis – the cost of electricity, import from the network, or the use of solar generation.

It is advisable to compare the result obtained for delayed charging of the battery storage system with the study by C. Dai *et al*. (2025), in which increasing the energy flexibility of a building with a photovoltaic system and battery storage was considered through load forecasting and management. In the current study, a similar logical conclusion was obtained: the efficiency of the charging mode depends not on the fact of the charging shift in time, but on its compliance with the consumption profile, the dynamics of solar generation and the state of charge of the battery. K. Dharmaraj & P. Natarajan (2024) also linked energy management to demand response, uncertainty, and the use of renewable energy sources. In this context, the results of this study show that the battery mode of operation should be evaluated together with load, generation, and cost indicators. The result obtained in the current

study specifies the limits of the application of delayed charging: such a mode cannot be evaluated as effective only due to changes in the charging time, since its effectiveness depends on the actual correspondence of the charging time limits to the consumption profile and solar generation.

S.M. Ali *et al*. (2025) considered digital twins as an energy management tool for prosumers in smart grids using deep learning, deep reinforcement learning, and big data analytics techniques. For this study, the approach to using the digital model was close not as a static description of the system, but as a tool for checking and selecting its operating modes. In the scenario modelling, the digital twin was also used to assess how changing the battery management mode affects the import of electricity from the grid, the loss of solar generation, the relative cost of electricity, the self-consumption rate of solar energy, and the self-sufficiency rate. F.H. Aghdam *et al*. (2026) considered digital dual as the basis for real-time energy management for smart homes. In this study, the digital twin was not used for continuous operational control, but performed the analytical function of comparing alternative modes of operation of the battery storage system. F.M. Bashir *et al*. (2026) used operational digital twin to jointly optimise a photovoltaic system with a battery storage unit, building engineering systems, and time-dependent consumption rates. This approach correlates with the results of this study due to the multi-criteria nature of the assessment: the choice of battery management mode should consider not one individual indicator, but the ratio between the cost of electricity, import from the grid, the use of solar generation, and the energy self-sufficiency rate.

In the study by J.D. Mariano & J. Urbanetz Jr. (2022), the integration of an energy storage system was considered on the example of energy management of a photovoltaic system. For this study, it is close that the battery storage system is analysed not separately, but as part of the operating mode of the entire system. In the scenario modelling, this was reflected in the difference between the actual mode, the basic modelling, and the modified battery management modes: depending on the scenario, the import of electricity from the grid, the loss of solar generation, the relative cost of electricity, and the self-consumption rate of solar energy changed. H. Kang *et al*. (2023) investigated multi-criteria size determination and operational planning of battery storage in the energy community. This study also traced the multi-criteria nature of the choice of battery storage mode, although the problem was solved through scenario comparison. Different scenarios were successful according to different criteria: reducing the minimum charge Reserve was better in terms of electricity imports from the grid and relative cost, while increasing the battery capacity was better in terms of reducing solar generation losses and increasing the self-consumption rate of solar energy. The paper by M. Bird *et al*. (2025) conducted a financial assessment of the management of a photovoltaic system with a battery throughout the life cycle of a commercial building. This correlates with the results of this study due to the differentiation of energy and economic effects. Technical improvement of the system operation mode requires comparison with the economic result. D. Berrian *et al*. (2026) analysed the value of a grid photovoltaic system with a battery in conditions of over-generation and unfavourable price conditions. In this study, a similar problem was manifested due to losses due to limited solar generation. The use of additional battery storage capacity should be evaluated not only by reducing generation losses, but also by economic consequences. Therefore, the efficiency of a photovoltaic system with a battery storage system depends on the coordination of the storage system's operating mode with the consumption profile, solar generation, and tariff conditions. That is why scenario modelling is an appropriate tool for choosing a rational control mode.

CONCLUSIONS

The results of the study showed that it is advisable to consider a battery storage device in a hybrid power supply system not only as a means of storing energy, but also as a controlled element of energy balance. A comparison of scenarios showed that the basic modelling improved the system performance compared to the actual mode, but the scenario with a decrease in the minimum battery charge reserve provided the greatest economic effect. It was this scenario that gave the lowest import of electricity from the grid and the lowest relative cost, which indicates the feasibility of more complete use of the available storage capacity during periods of increased consumption. The delayed charging scenario did not confirm the expected efficiency: the loss of solar generation in it was 13.2 kWh, and the relative cost of electricity was 14.24 c.u., that is, they were worse than in the basic modelling. This means that transferring charging to another time cannot be applied as a universal rule without considering the load profile, the actual dynamics of solar generation, and the state of charge of the battery. The tariff-oriented mode showed a different type of effect: when importing 23.9 kWh, the relative cost of electricity was 13.06 c.u., which was lower than in actual mode. Thus, the economic efficiency of the system is determined not only by the amount of electricity consumed from the network, but also by the time conditions of this consumption.

Increasing the battery capacity to 20 kWh best reduced the loss of solar generation and increased the self-consumption rate of solar energy, but did not become the most profitable scenario in terms of cost. Therefore, increasing the capacity of the battery storage unit requires a separate economic

substantiation considering the cost of additional capacity. The digital twin in the study helped to compare alternative modes of operation of the battery storage system according to a single system of indicators. In general, the choice of a rational control mode should be based on the ratio of the energy effect, the cost of electricity, losses of solar generation, the energy self-sufficiency rate, and technical limitations of the battery. Further research should focus on expanding the model for seasonal scenarios considering capital expenditures and battery degradation, and integrating generation and consumption forecasting for adaptive storage management.

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CONFLICT OF INTEREST

None

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Цифровий двійник гібридної системи електроживлення для сценарної оптимізації режимів роботи акумуляторного накопичувача

Андрій Повшенюк
Старший викладач
Національний університет водного господарства та природокористування
33028, вул. Соборна, 11, м. Рівне, Україна
https://orcid.org/0009-0000-7789-6181

Анотація. Метою дослідження було визначити, як різні підходи до керування батарейним модулем позначаються на енергетичних і економічних характеристиках локальної сонячної енергосистеми з урахуванням фактичного графіка споживання, заданих меж заряду та тарифної схеми. Застосовано метод сценарного моделювання режимів роботи акумуляторного накопичувача на основі цифрового двійника. Виявлено, що параметри керування акумуляторним накопичувачем впливають на імпорт електроенергії з мережі, втрати сонячної генерації, відносну вартість електроенергії та рівень автономності гібридної системи електроживлення. Було порівняно фактичний режим експлуатації, базової логіки керування, мінімального резерву заряду, часу заряджання, тарифної структури та ємності акумуляторного накопичувача. За результатами сценарного моделювання встановлено, що зміна режиму керування акумуляторним накопичувачем впливає на імпорт електроенергії з мережі, втрати сонячної генерації, відносну вартість електроенергії та рівень енергетичної самозабезпеченості. У фактичному режимі імпорт із мережі становив 25 кВт·год, відносна вартість – 15,68 ум. од., а рівень енергетичної самозабезпеченості – 49,91 %. Базова симуляція зменшила імпорт до 20,88 кВт·год і відносну вартість до 12,19 ум. од., підвищивши самозабезпеченість до 58,17 %. Найкращий економічний результат отримано у сценарії зі зменшенням мінімального резерву заряду акумулятора: імпорт знизився до 17,37 кВт·год, відносна вартість – до 8,69 ум. од., а самозабезпеченість зросла до 65,19 %. Збільшення ємності акумулятора до 20 кВт·год забезпечило найнижчі втрати сонячної генерації – 7,6 кВт·год і найвищий рівень самоспоживання – 81,39 %. Водночас тарифно-орієнтований режим показав, що економічний ефект залежить не лише від обсягу імпорту, а й від часу споживання електроенергії з мережі. Практична значимість полягає у можливості використання результатів проєктувальниками та операторами локальних сонячних систем із батареєю для вибору раціональних налаштувань резерву заряду, часу заряджання, тарифного споживання та доцільності збільшення ємності накопичувача

Ключові слова: мінімальний резерв заряду; відкладене заряджання; двозонний тариф; втрати сонячної генерації; відносна вартість електроенергії; рівень самоспоживання; енергетична самозабезпеченість