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Efficiency Assessment of Grid-Connected PVPPs and BESS in Bulgaria †

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Abstract

This study aims to demonstrate that, in the context of the energy transition and with solar generation playing a dominant role in the energy mix, key technical parameters of energy infrastructure should be re-evaluated and taken into account, as changes in these parameters affect operational processes and energy-loss calculation mechanisms. Data from newly installed battery energy storage systems (BESSs) connected to the power grid and photovoltaic power plants (PVPPs) in Bulgaria are used to establish a portfolio-level baseline for installed capacity, storage duration, geographic distribution, and preliminary economic indicators. By analyzing annual consumption and generation for 2024, 2025, and the first three months of 2026, the seasonal and cyclical nature of these variables and their dynamics of change are observed. The monthly data distribution allows for an in-depth study of load dynamics and the identification of key factors. The analysis identifies three typical seasonal cycles—winter, summer, and transitional—each of them differing in terms of specific consumption and generation profiles; the operation of PVPPs, BESS, and power transformers exhibits specific characteristics. The results show how changes in power quality indicators, specific technical parameters, and operational values directly or indirectly affect losses during power generation and distribution, and consequently also impact operating, maintenance, and repair costs.

Keywords: battery energy storage system; photovoltaic integration; Capital Expenditures (CAPEX); Operational Expenditures (OPEX); Levelized Costs Of Storage (LCOS); round-trip efficiency; transformer losses

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1. Introduction

Our energy system is currently undergoing a period of energy transformation. This transition is characterized by the rapid deployment of large decentralized renewable generation capacities, most commonly photovoltaic power plants (PVPPs), alongside the early-stage development of energy storage systems (ESSs). Both processes are taking place without a prior forecast-based assessment of grid-connection capacity and load distribution. Over the years, no comprehensive analysis has been carried out regarding the difference between net generation and net consumption, and there is also a lack of forecast analysis of low-voltage-side consumption. The way forward from this seemingly unusual

phenomenon lies in the study of active low-voltage microgrids and medium-voltage networks, the analysis of challenges related to the connection of PVPPs, the assessment of opportunities for integrating systems capable of storing energy "surpluses," and the implementation of load-side management. Bulgaria's increasing need for energy storage, driven by the accelerating integration of various renewable generation (particularly photovoltaic power plants) into a power system that must maintain reliability, flexibility, and economic efficiency under changing generation patterns [1,2]. Solar generation is concentrated in daylight hours, often peaking when demand is comparatively low, creating periods of excess production, potential reduction in generation by the outright disconnection of entire power plants from the grid, and downward pressure on market prices, while evening demand remains dependent on dispatchable generation or imports from neighboring countries. This mismatch strengthens the case for grid-connected energy storage systems capable of shifting surplus renewable energy from midday to peak-demand periods, smoothing rapid generation fluctuations, supporting balancing services, and reducing stress on both the transmission (400, 220 and 110 kV) and distribution (20 kV) infrastructure. In the Bulgarian context, the emergence of newly commissioned BESS and PVPPs+BESS projects shows that storage is already becoming part of the national energy transition, but the installed portfolio remains uneven in scale, location, duration, and data completeness. The previously mapped BESS portfolio demonstrates that Bulgaria has begun developing meaningful short-to-mid duration storage capacity, yet this capacity must now be assessed not only by installed MW and MWh, but also by its economic viability, operational efficiency, and ability to provide real grid value under Bulgarian market conditions [3]. The process of BESS integration into the Bulgarian power grid remains highly dynamic. These are the three key aspects that need to be monitored. The first thing that has to be determined is the distribution of power and capacity by administrative unit and by project type—PVPPs+BESS vs. stand-alone BESS (based on the techno-geographical profile). Secondly, the storage duration (hours), defined as the ratio of usable capacity to connection power (MWh/MW), also has to be quantitatively determined. And finally, the models of integration into the power grid have to be identified. A visual representation on an interactive map showing the location, power, and capacity of these systems as of September 2025 (Figure 1) provides an overview.

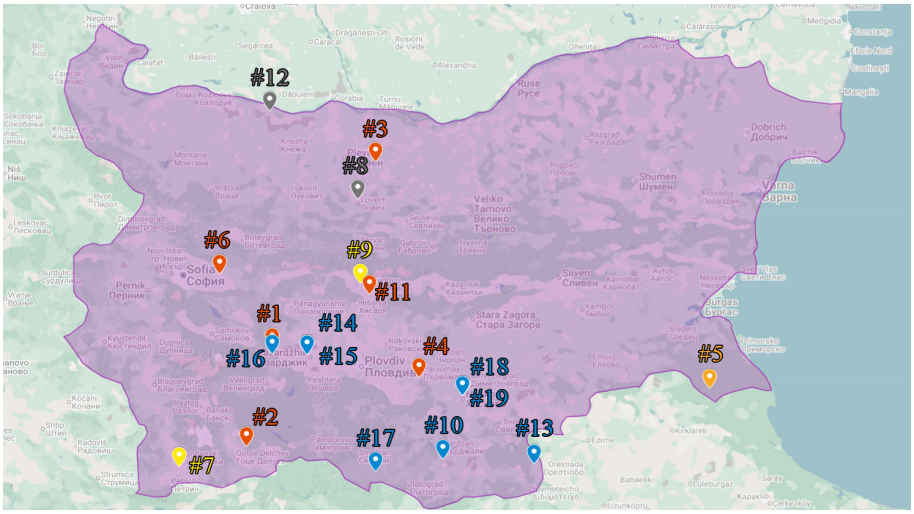


Figure 1. Interactive map of Bulgaria with all of the sites marked on it, with each site being represented with a number. Sites in red represent missing values (power, storage or both). Sites in gray are large-scale installations. Sites in blue are the later discussed 10 MW/27 MWh motif, and sites in yellow and orange fall in none of the above categories.

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There are 19 projects that comprise a total BESS capacity of 379.73 MW and a total storage capacity of 981.35 MWh. The average storage duration is approximately 3.53 h. The models that are presented include combinations of PVPP + BESS (9 out of 19) and standalone BESS (10 out of 19). This includes one large two-stage installation (124 MW/496 MWh) and recurring "mid-scale" models of approximately 5 MW/13.4 MWh and 10 MW/27 MWh [3].

The previous study [3] established a structured baseline of Bulgaria's emerging grid-connected BESS sector by mapping newly commissioned standalone BESS and PVPPs+BESS installations, harmonizing their reported power and storage-capacity values, and organizing them by project type, location, duration, and technical completeness. It showed that the national portfolio is already large enough to influence discussions on PV integration, curtailment reduction, and short-duration flexibility, while also revealing important limitations in public project data, including missing capacity values, ambiguity between planned and commissioned stages, and inconsistent reporting of technical parameters. However, that work primarily answered the question of where BESS capacity is installed and at what technical scale. It did not fully address whether these systems are economically competitive, how sensitive their value is to CAPEX, OPEX, cycling frequency, efficiency, and degradation, or how BESS compares with other storage technologies suitable for Bulgaria. This creates the research gap addressed in the present follow-up study: moving from a descriptive inventory of installed storage assets toward a techno-economic assessment of their practical performance, cost of delivered energy, and efficiency-related limitations under Bulgarian grid and market conditions. This study is therefore positioned as an applied engineering assessment rather than a purely theoretical storage-cost model, aiming to connect BESS techno-economic evaluation with practical operating conditions observed in the Bulgarian power system, including PV-driven generation variability, transformer loading, power-quality disturbances and efficiency losses at the grid interface.

This follow-up study's main objective is to develop an applied techno-economic and efficiency-oriented assessment framework for grid-connected BESS in Bulgaria, with emphasis on engineering applicability under real grid operating conditions rather than on abstract cost modeling alone. The framework estimates representative CAPEX and OPEX ranges, accounting for battery modules, power conversion systems, transformers, grid connection, auxiliary systems, operation, maintenance, and system management. It then calculates the LCOS under the previously established cycling motifs, while incorporating key assumptions related to round-trip efficiency, utilization rate, and project lifetime. Beyond conventional cost modeling, the paper also examines practical sources of efficiency loss during charge and discharge, particularly transformer-related losses and repeated alternating current/direct current (AC/DC) conversion stages. Finally, it introduces supra-harmonics as an emerging power-quality concern in BESS-grid interfaces, highlighting the need to consider high-frequency distortion, transformer stress, and conversion-chain losses when evaluating the long-term performance and grid value of battery storage systems.

2. Materials and Methods

A realistic assessment of BESS deployment in Bulgaria requires a cost framework that separates upfront investment costs from long-term operating costs and relates both to delivered energy over the system lifetime. While installed power (MW) and capacity (MWh) indicate technical scale, they do not by themselves determine whether a storage project is economically viable or not. For this reason, CAPEX and OPEX must be clearly defined before calculating LCOS and comparing BESS with alternative storage technologies.

2.1. CAPEX Components of Cost Framework for BESS in Bulgaria

The CAPEX of a grid-connected BESS includes the battery modules, battery racks, battery management system (BMS), containerized enclosures, thermal management, and the more complex—energy management system (EMS). Together, they determine usable storage capacity, degradation behavior, and overall lifetime. A second major cost group includes the power conversion system (PCS), inverters/converters, transformers, switchgears, protection relays, metering, Supervisory Control and Data Acquisition (SCADA) interfaces, cabling, and grid-connection equipment, all of which determine how efficiently and reliably the system charges from and discharges to the grid. Additional investment costs include civil works, land preparation, foundations, fencing, roads, engineering, permitting, commissioning, grid studies, legal services, and financing-related expenses, which can vary significantly depending on project size, connection voltage, distance to the nearest substation, and whether the BESS is standalone or co-located with a PVPP.

2.2. OPEX Components of Cost Framework for BESS in Bulgaria

The OPEX of a BESS includes fixed operation and maintenance costs related to routine inspection, monitoring, software operation, insurance, site security, and compliance with grid, fire-safety and environmental requirements. It also includes variable operating costs such as auxiliary electricity consumption for thermal management/control systems, and stand-by operation, which reduce the net energy delivered to the grid. Over the lifetime of the project, additional expenses may arise from battery degradation management, module augmentation, component replacement, inverter/converter maintenance, and recalibration of the energy management system. In the Bulgarian context, OPEX may also depend on grid-access charges, balancing-market participation costs, land lease conditions, local service availability, and the operational strategy used to cycle the system.

2.3. Cost Uncertainty in the Bulgarian Context

Bulgaria-specific BESS economics may differ from generic European Union assumptions because project costs and revenue opportunities are both shaped by the national grid-connection rules [4,5], permitting procedures, local construction conditions, and the maturity of storage participation in electricity markets. Grid-connection costs can vary significantly depending on whether the project connects to the distribution (20 kV) or transmission (110, 220 or even 400 kV) networks. Along with that, the distance to available capacity, required reinforcement works, and the technical requirements imposed by the network operator take a toll. Permitting timelines and administrative procedures also affect total project cost since delays can increase financing expenses, equipment-price exposure, and development risk. Local construction costs, land availability, civil works, overall labor, transformer procurement, and medium-voltage (MV) infrastructure can further shift the final CAPEX relative to generalized EU benchmarks. On the revenue side, Bulgarian BESS projects are highly sensitive to electricity-price volatility, balancing-market access, and the ability to monetize multiple services beyond simple energy arbitrage. PV curtailment risk is also important, since storage becomes more valuable when midday renewable overgeneration creates low-price or curtailed energy that can be shifted toward evening peak demand (Figure 2). Therefore, LCOS and profitability should be assessed using Bulgaria-specific assumptions wherever possible, rather than relying only on broad European cost averages.

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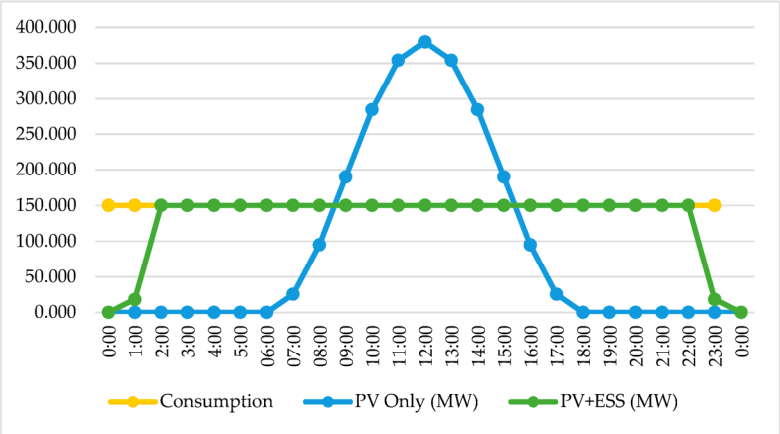


Figure 2. The graph visualizes the interval after 00:00 of the general cosine profile of the hourly grid availability in MW of PV generation without (PV only) and with ESS installations, with the ESS installations being already charged the day before.

2.4. Definition of LCOS

The levelized costs of storage (LCOS) represent the discounted lifetime cost of storing and delivering one unit of electrical energy, usually expressed in EUR/MWh discharged. Unlike the levelized cost of electricity generation, which evaluates the cost of producing electricity, LCOS evaluates the cost of converting purchased or otherwise available electricity into stored energy and later returning it to the grid. For BESS applications, this makes LCOS a suitable indicator for comparing different storage durations, cycling strategies, efficiency assumptions, and cost structures, Equasion (1).

$$\mathrm{LCOS} = \frac{\sum_{t=0}^{n} \frac{CAPEX_t + OPEX_t + C_{charge,t} + C_{replacement,t}}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_{discharged,t}}{(1+r)^t}} \quad (1)$$

The general LCOS expression can be written as such, where

- $CAPEX_t$ represents expenditures;
- $OPEX_t$ represents annual operating expenditures;
- $C_{charge,t}$ is the cost of electricity used for charging;
- $C_{replacement,t}$ includes battery augmentation or replacement cost where applicable;
- $E_{discharged,t}$ is the useful electrical energy discharged to the grid;
- r is the discount rate;
- n is the project lifetime in years.

A more simplified form of the same concept can be expressed as, Equasion (2).

$$\mathrm{LCOS} = \frac{CAPEX \times CRF + OPEX_{annual} + C_{charge,annual}}{E_{discharged,annual}} \quad (2)$$

CRF represents the capital recovery factor used to annualize the initial investment over the project lifetime. The denominator must refer to discharged energy rather than charged energy, because only the energy delivered back to the grid can generate useful service or market revenue. Therefore, round-trip efficiency, transformer losses, auxiliary consumption, availability, degradation, and cycling frequency directly affect LCOS by reducing the amount of saleable energy over the lifetime of the asset. Lower delivered energy increases LCOS even if the initial CAPEX remains unchanged, which is why efficiency and utilization are central to the economic evaluation of BESS.

2.5. Financial Assumptions

The LCOS calculation depends mainly on the financial assumptions used to distribute investment and operating costs over the project lifetime. In this study, the discount rate represents the cost of capital and investment risk associated with BESS deployment, with higher discount rates increasing the annualized cost of CAPEX and therefore raising the LCOS. The project lifetime defines the period over which the storage asset is evaluated, while the battery lifetime may be shorter than the full project lifetime due to degradation, cycle aging and calendar aging. Residual value may be included if major components, land rights, grid-connection assets, transformers, or remaining battery capacity retain economic value at the end of the assessment period. Annual degradation is treated as a gradual reduction in usable storage capacity and delivered energy, directly increasing the LCOS (unless compensated through system oversizing), reduced depth of discharge, or battery augmentation. Replacement or augmentation assumptions are therefore important, especially for projects expected to operate beyond the effective life of the original battery modules. These costs may include module replacement, additional battery racks, inverter upgrades, or control system modernization. The availability factor accounts for the share of time during which the BESS is technically capable of operation after considering maintenance, forced outages, grid restrictions, and operational limitations. A lower availability factor reduces annual discharged energy and increases the LCOS, even if CAPEX and OPEX remain constant. Combined, the discount rate, lifetime assumptions, degradation profile, replacement strategy, residual value, and availability factor determine how the upfront investment is converted into the long-term cost per MWh delivered to the grid.

2.6. Technical Assumptions

The technical assumptions define how much of the installed storage capacity can be converted into useful discharged energy over the project lifetime. Round-trip efficiency (RTE) is one of the most important parameters, since it captures the combined losses occurring during charging, storage, and discharging. The lower efficiency increases the amount of input energy required for each MWh delivered to the grid and therefore raises the LCOS. Depth of discharge and usable capacity further determine the practical energy window of the BESS, because the nominal installed capacity is not always fully available for operation due to battery protection limits, degradation management, reserve margins, and warranty conditions. The charge and discharge power limits define how quickly the system can absorb or deliver energy and therefore determine the effective storage duration together with usable capacity. The number of equivalent full cycles per year is also critical, because higher utilization spreads fixed CAPEX and OPEX over a larger amount of discharged energy, while lower utilization increases the cost per delivered MWh. Transformer and power conversion losses must also be included, since grid-connected BESS operation requires repeated transformation between voltage levels and conversion between AC and DC. These losses occur in transformers, inverters/converters, filters, auxiliary power systems, and control equipment, meaning that the energy available at the grid connection point is lower than the energy stored within the battery modules.

3. Results

3.1. Round-Trip Efficiency (RTE) and Conversion-Chain Losses

Round-trip efficiency describes the share of electrical energy charged into a BESS that can later be delivered back to the grid after all storage and conversion losses are considered. In Lithium Iron Phosphate (LFP) based systems, battery-cell efficiency is generally high, but the final delivered energy is reduced by losses in the bidirectional inverter, DC/AC and AC/DC conversion stages, transformers, filters, cabling and protection equipment.

Additional losses arise from auxiliary consumption including battery management systems, monitoring equipment, communication systems, stand-by operation and fire-safety systems. Thermal management is also important since heating, ventilation and cooling systems consume energy to keep battery modules within safe and efficient operating temperature ranges. Control-system losses and operational constraints further reduce practical efficiency, especially when the BESS operates at partial load, maintains reserve margins or follows grid-support commands rather than a simple full charge–discharge cycle. Therefore, round-trip efficiency should be treated not as a fixed battery-cell parameter but as a system-level indicator that reflects the combined performance of the battery, power electronics, transformer interface, auxiliary systems and operating strategy. In [2], prepared by ESO, the condition of the national power grid is analyzed. The 110 kV network is considered the most heavily loaded part of the system. The analysis is carried out on the basis of the expected maximum load in the electric power system for an average working day, referred to as the average winter operating regime. This regime is used as the baseline for determining a scenario with minimum power losses in the power system. The general load-flow analysis performed for the average winter regime shows that a load of 7130 MW is supplied by generation sources distributed as follows: Losses from transmission, distribution, and transformation amount to approximately 142 MW. The 110 kV grid operates predominantly in a closed-ring configuration, and the main electrical load of the power system, equal to 6505 MW, is connected to it. Of this load, nearly 32% is supplied directly by power plants, while the remaining part is transformed from the 220 kV and 400 kV grids. In areas with concentrated renewable energy generation, and under certain operating regimes, transformation from medium voltage to high voltage takes place. In local active grids, during periods of photovoltaic overgeneration, a sharp change in the quasi-stationary operating mode of the network can be observed. As a result of switching powerful equipment on or off during emergency overloads, or in the presence of long overhead lines, switching overvoltages may occur. These are oscillatory transient processes with amplitudes two to three times higher than the phase voltage and with high frequencies, reaching up to several hundred kHz. The cause of these overvoltages is the interaction between the residual magnetic flux in the transformer core and the capacitive-inductive parameters of the network at the moment the phenomenon occurs. The reliable operation of power substations and the transmission network depends to a large extent on the adequate management of these switching transients. Since the end of March this year, ESO has introduced internal rules for relay-protection settings aimed at limiting the operation of renewable energy sources whose output exceeds the contractually agreed connection capacity. An increase in generated power of more than 10% within a 60 s interval is not permitted. In practice, however, this requirement is not always fulfilled. Cases of incorrectly configured inverters are frequent, where maximum current and power are not properly regulated. This leads to disconnections and overvoltages with undesirable consequences, including changes in frequency, voltage, and capacitive current during the switching-off process. There are real operating situations in which the high-voltage winding of a power transformer is directly connected to the electric power system. Older inverter models are often unable to compensate for the transformer inductance. In other cases, substations have significant photovoltaic generation connected through direct or mixed feeders, where generation exceeds the local load by more than a factor of two. This initiates a process of so-called reverse generation, often referred to as islanding operation. In such cases, it is important to prevent unintended islanding. When photovoltaic power plants are operating, the load should participate in voltage regulation at the point of connection, with the ability to supply or consume reactive power Q in the range from −28% to +34% of the gross contractually connected power. Switching overvoltages associated with the connection or disconnection

of large inductive elements, such as transformers, and large capacitive elements, such as cable lines, are assessed differently depending on the grounding arrangement of the star-point neutral.

We analyze the trends in electricity generation and consumption in Bulgaria for the years 2024, 2025, and the first quarter of 2026. The goal is to identify the patterns that emerge and the changes in trends. Their correct determination is important for optimizing and ensuring good forecastability of loads and the planned development of the electricity distribution and transmission infrastructures. As expected, seasonality and cyclicality are observed in the consumption profile. Three periods are identified (winter, summer, and transitional), each with its own distinctive features. The highest electricity consumption values are recorded during the winter period, which is a direct consequence of the increased need for heating in the residential and industrial sectors. During this period, peak levels of energy consumption are reached (Figure 3). Solar power plants reach a seasonal minimum during this period due to the shorter duration of daylight hours and the low intensity of sunlight.

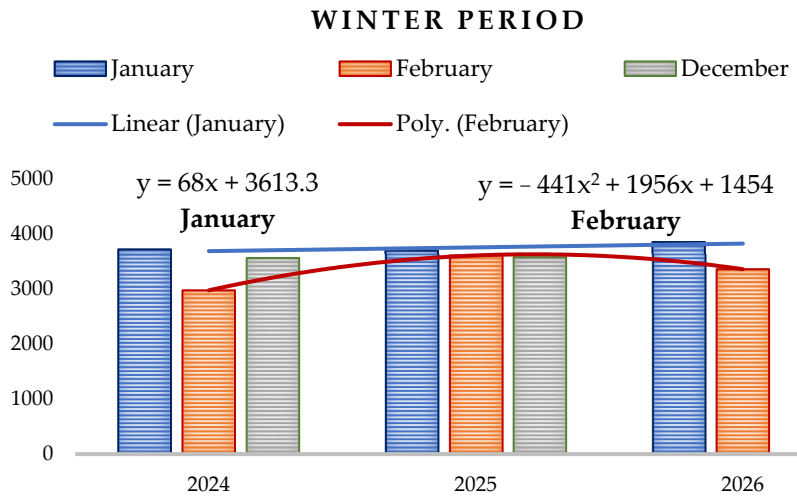


Figure 3. Winter period demand profile [GWh], trend lines for January and February of 2024, 2025, and 2026.

The transition period covers almost six months (March–November) and is marked by significant fluctuations. It is characterized by a gradual reduction in overall consumption compared to winter peaks, as weather conditions become more moderate and energy consumption decreases. Photovoltaic capacity shows a distinct increase in generation due to longer daylight hours and more favorable sunshine. The load profile illustrates the balance between stable consumption and the growing share of solar energy (Figure 4).

The summer quarter (June–August) is marked by a secondary peak in consumption. However, alongside the increased load, this is also the time of maximum efficiency for PVPPs. Due to the long days and strong solar radiation, PVPPs reach their annual production peaks, helping to cover the summer energy peak in the system (Figure 5).

The analysis highlights the increased significance and influence of PVPPs and solar generation on the national energy mix. Although this generation is determined by the weather, they represent a critical factor in diversifying energy sources and reducing the use of conventional fuels. Approximately 13–13.2% of the energy generated by Renewable Energy Sources (RES) must be stored to ensure the necessary reserve to cover peak consumption [6]. The distribution by typical periods is presented in Table 1.

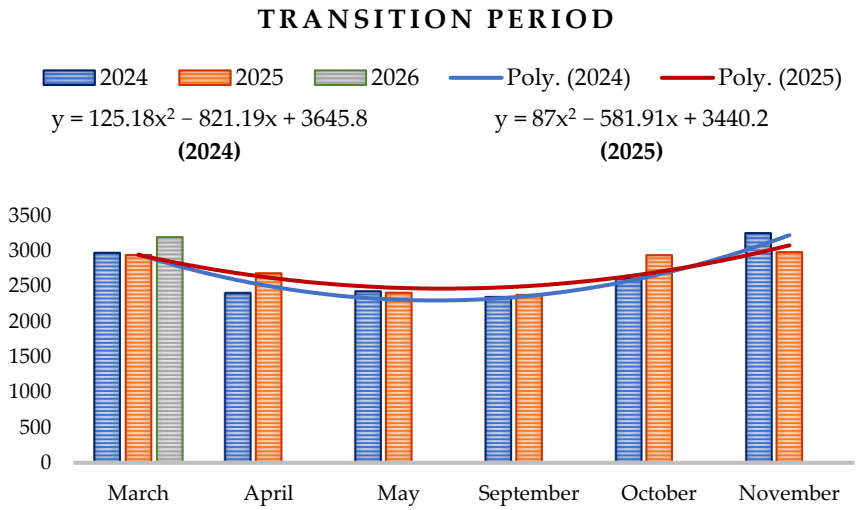


Figure 4. Transition period demand profile [GWh], trend line for transition demand of 2024 and 2025.

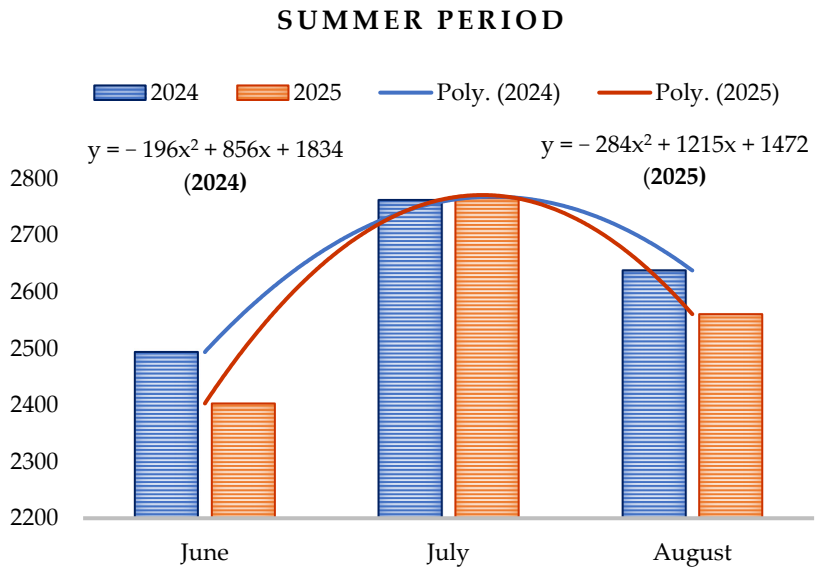


Figure 5. Summer period demand profile [GWh], trend line for summer demand of 2024 and 2025.

Table 1. Energy to be stored during each of the periods under consideration [GWh].

Period	Energy for Storage [GWh]		
	2024	2025	2026
Winter period	1331	1412	936
Transition period	2083	2124	No data available
Summer period	1026	1005	No data available

The summer season is marked by peak demand and peak solar generation, as well as periods of overgeneration. How does this affect energy infrastructure while these processes are occurring? We decided to investigate the "damage and consequences" for the energy grid by monitoring the quality of electricity and other "hidden" but highly influential factors.

The issues associated with power quality indicators and reverse power generation first emerge in low voltage (LV) active microgrids. Due to the bidirectional exchange of energy flows through MV distribution grids and power transformers, energy losses cannot be determined precisely. They are a cumulative value formed by the impact of many

factors. For this reason, we investigate an active low-voltage microgrid and monitor key operational variables and parameters.

The object of analysis is the operation of an active microgrid with a connected PVPP of 198 kWp. The consumer connection scheme is Terra Neutral Combined system (TN-C). At the point of connection of the photovoltaic power plant, the following electrical quantities are monitored: voltages in the three phases U_A, U_B, U_C and the neutral U_N; currents in the three phases and the neutral I_A, I_B, I_C, I_N; frequency f; power factor PF; and total harmonic distortion at maximum current in each phase and in the neutral, expressed as Total Demand Distortion, TDD%, for I_1, I_2, I_3, I_N. The TDD% of the currents I_1, I_2, I_3, I_N is observed because this indicator measures the harmonic current of each phase of the power-supply network as a percentage of the maximum consumer current, thereby serving as an indicator of harmonic distortion. In this way, the loading conditions of the active microgrid are taken into account. This indicator is more useful than total harmonic distortion, THD, which uses the fundamental current as a reference value. TDD% is considered a key indicator for ensuring compliance with power-quality standards. The selected measurement period is from 13 June to 3 July 2025 (the summer period, marked by overgeneration from PVPPs), with measurements taken at 10 min intervals, corresponding to a period of the year characterized by maximum solar-generation intensity. The percentage exceedance of phase voltages above permissible values during periods of overgeneration is presented for the individual phases in Figure 6.

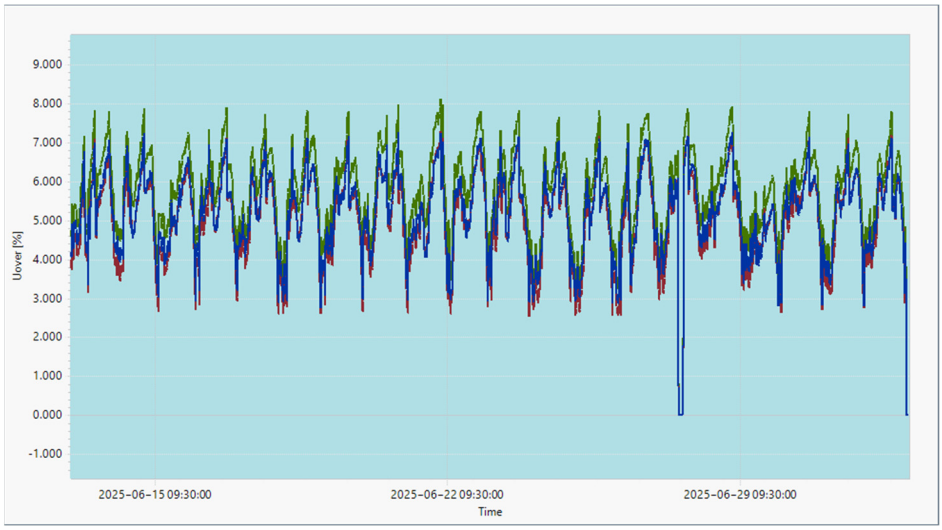


Figure 6. Percentage exceedance of phase voltages above permissible values: U_{OVER1}, U_{OVER2}, U_{OVER3}.

Total Demand Distortion (TDD%) defines the harmonic distortion of current in an electrical system as a percentage of the full-load current, Equation (3). It is a power-quality index that relates the harmonic content of the current to the maximum current that the system can accommodate. Therefore, TDD% is a distortion measure that reflects the overall impact on the system, especially under varying load conditions. This differs from Total Harmonic Distortion (THD), which is expressed as a ratio relative to the fundamental current component and may vary significantly depending on the load.

$$\mathrm{TDD} = \sqrt{\sum_{h=2}^{\infty} \left[\frac{I_h^2}{I_L^2} \right]} \cdot 100\%, \tag{3}$$

- h—is the harmonic order;

- I_h— is the amplitude of the current harmonic of order h;
- I_L—is the maximum load current;

The connection between TDD and THD is, Equation (4)

$$\text{TDD} = \text{THD} \cdot \frac{I_1}{I_L} \tag{4}$$

As can be seen from (3), Total Demand Distortion (TDD%) evaluates the harmonic content of currents between the end user and the energy source; in other words, it indicates the impact of harmonic distortion within the active microgrid. For example, if a system shows high THD values but low consumption, the impact of harmonic distortion on the system may be insignificant. Under full-load conditions, however, the THD value for current harmonics is equal to TDD, which may have a negative impact on the active microgrid and all equipment connected to it. TDD% can provide insight into current distortion as a percentage of full-load current and is the most suitable power-quality index for explaining current harmonics at the end of the consumer circuit. In the active microgrid under consideration, the current harmonic distortion as a percentage of I_L, expressed as TDD%, for the individual phases is presented in Figure 7.

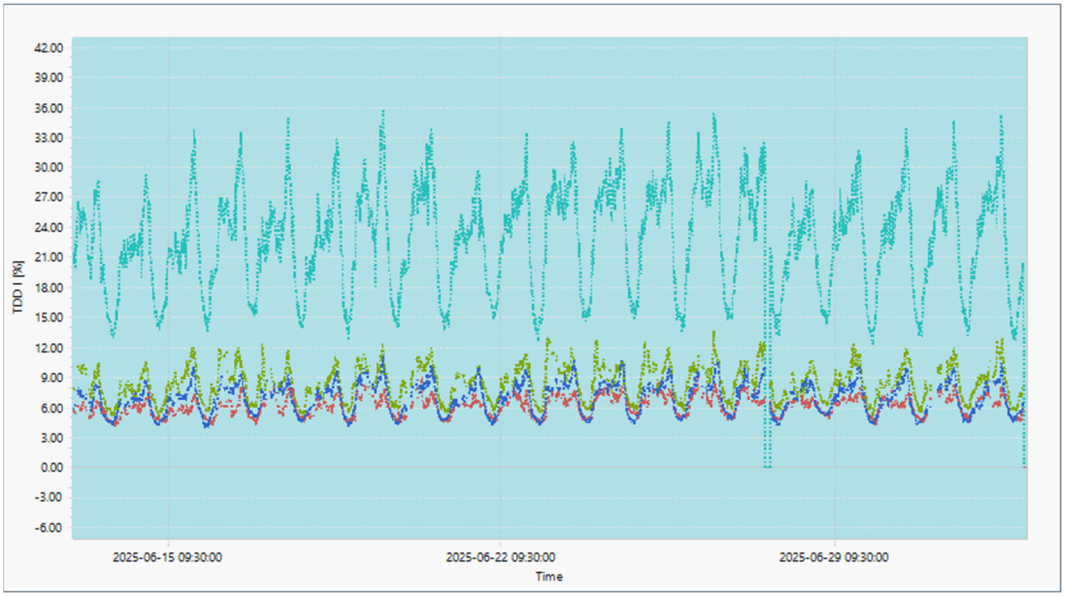


Figure 7. Current harmonic distortion as a percentage of full-load current, TDD: I_1, I_2, I_3, I_N.

Voltage harmonic distortion in the common distribution system, which determines electricity consumption quality, depends on current harmonics and the system impedance at different harmonic frequencies. Electricity consumers are connected to the power system at the point of common coupling (PCC). The Short-Circuit Ratio (SCR) defines the system impedance and is important because impedance is influenced and limited by the short-circuit current of the system. SCR describes the extent to which voltage harmonics affect power quality in the system as a result of current harmonics produced by the consumer. SCR can be expressed as Equation (5):

$$\text{SCR} = \frac{I_{SC}}{I_L}, \tag{5}$$

Lower SCR values indicate that the short-circuit current is very low. Such a ratio results in lower current harmonics and, therefore, lower TDD. IEEE Standard 519–2014 relates to and regulates TDD and SCR values [7]. The responsibility for maintaining current

harmonics and TDD below the recommended limits lies with electricity consumers. To encourage compliance, some electricity distribution companies have proposed penalties for customers who exceed the TDD limits at the PCC. Activities and measures aimed at eliminating harmonics are important for the quality of electricity generation and distribution. As long as consumers comply with these standards, power systems can operate with relatively lower harmonic pollution in electricity-supply networks. In order to obtain a reasonable and realistic understanding of current harmonics, the Total Demand Distortion index, TDD, is the most suitable power-quality index that can be used.

3.2. Supraharmonics and Transformer Stress

At present, PVPPs operate for voltage and, respectively, power control, rather than for coordinated operation with the transformer. There is a lack of research on adequate thermal-aware On-Load Tap Changer (OLTC) control and aging-based transformer loading limits, and consequently on aging-based PV curtailment. This is of exceptional importance for the proper operation of power-system equipment. There are hidden aging effects in the insulation of power transformers caused by current overloading under seemingly low-load conditions, as well as false operation of protection devices. The main cause of this is supraharmonics, considered in two frequency bands: 2–9 kHz and 9–150 kHz. These are simply not "seen" by many network analyzers and measuring devices, because such instruments typically measure only up to the 50th harmonic. Each supraharmonic represents an equivalent additional load for the transformer, increasing the root-mean-square value of the current and, consequently, the thermal loading of the windings. This leads to insulation aging, insulation breakdown, and related failures, despite the predefined inverter settings of the photovoltaic power plants, as shown in Figure 6. The observed supraharmonics are in the 2–9 kHz range (Figure 8). The highest level is observed in the second phase, L2. The red bars represent the 10 min average values observed in accordance with BDS EN 50160:2010, replaced by BDS EN 50160:2023 [8], while the blue bars represent the 200 ms maximum values occurring within those 10 min intervals.

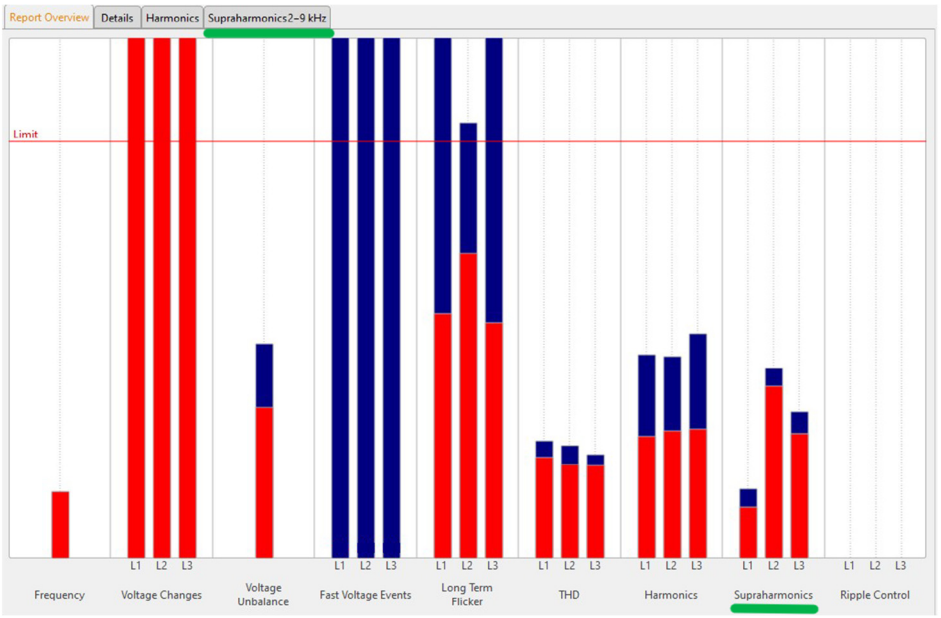


Figure 8. Phase and line voltage measurements in LV grid with a 198 kWp connected PVPP.

Supraharmonics from PV inverters and their impact on power transformers is a topic that dispatchers are already beginning to observe in practice, but asset-management methods still do not incorporate them quantitatively. Everything discussed so far demonstrates

the urgency of developing a methodology for supraharmonic-corrected aging-equivalent load. The authors consider this achievable by monitoring three quantities: the aging coefficient for the average/base load, K_{avg} which represents the average evening load, for example around 22:00; the load coefficient without supraharmonics, $K_{eq,A}$ representing the aging-equivalent load without supraharmonics, such as when only batteries are present; and the corresponding coefficient in the presence of supraharmonics, for example when several PVPPs are connected to a 20 kV grid, or when one large PVPP with many inverters is present, denoted a ${K_{eq,A}}^{SH}$. When ${K_{eq,A}}^{SH} > K_{limit}$ the BESS is charged and thereby "saves" the transformer. This research approach, on which the authors continue to work, establishes a link between power-quality indicators and their deterioration due to PVPP inverters, the investigation of premature and forced transformer aging, and intelligent PVPP+BESS control. In this way, an aging-based rule-based BESS control strategy can be achieved.

At present, these phenomena are still not regulated normatively. According to [9], the integration of photovoltaic systems into power grids presents notable power-quality challenges, especially regarding THD caused by power electronic converters, which may not comply with IEEE Standard for Harmonics Control in Electric Power Systems, IEEE 519 [10] and IEC 61000 series standards. Therefore, a regulatory gap exists Figure 9, as also discussed by [10]. As shown in the figure, the frequency range that remains without full regulatory coverage extends approximately from 2–3 kHz to 150 kHz. This frequency range is defined as supraharmonics [11–13]. Most power electronic converters used in energy equipment operate within this frequency band, particularly those containing Insulated-Gate Bipolar Transistor (IGBT), which are known to switch in the range of approximately 2–8 kHz and above. Another issue in this range is that most grid analyzers used to measure power-quality indices detect harmonics only up to the 50th harmonic, which corresponds to 2.5 kHz in a 50 Hz system and 3 kHz in a 60 Hz system. Consequently, they cannot detect high harmo nic levels in this frequency band, since these components are located above the 50-th harmonic.

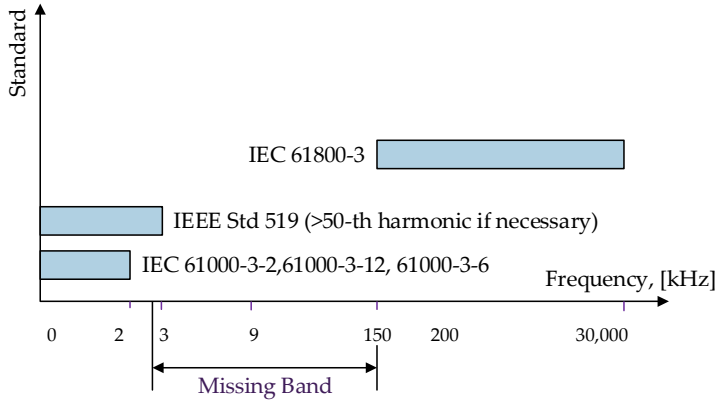


Figure 9. Frequency range regulated by the currently applicable standards with respect to harmonic components.

The standards IEC 61000-4-30 [14] and IEC 61000-4-7 are relevant in this context, although IEC 61000-4-7 covers spectral components only up to 9 kHz [14,15]. Therefore, it does not directly cover the entire supraharmonic range, but it remains important as the boundary of the classical harmonic-assessment approach.

IEC 61000-2-4:2024 relates to conducted disturbances in the frequency range from 2 kHz to 150 kHz [16,17]. It gives compatibility levels in differential mode Line-to-Line and Line-to-Neutral (L-L and L-N) for industrial locations, with a nominal voltage up to 35 kV and a nominal frequency of 50 Hz or 60 Hz. The implementation of this standard is currently ongoing. Compatibility levels at the point of common coupling (PCC) in public networks are specified in IEC 61000-2-2 for LV grids and IEC 61000-2-12 for MV grids [18,19].

According to [17], with the large-scale integration of new energy sources into power grids, the level of disturbances in new power systems has gradually increased. The disturbances in the 9–150 kHz frequency band may exceed the limit values of the electromagnetic compatibility in the IEC 61000-2-2 standard [17,18]. However, methods for measuring disturbances in this band are still under development. Currently, IEC SC77A/WG9 is developing a quasi-peak (QP) measurement method of disturbances in the 9–150 kHz band for the IEC 61000-4-30 standard [14,20].

4. Discussion

4.1. Economic Conditions for BESS Viability

BESS becomes economically justified in Bulgaria when the system is used frequently enough to spread CAPEX and fixed OPEX over a large volume of discharged energy while also capturing sufficient value from electricity-price differences and grid-support services. A storage asset operated only for occasional arbitrage may struggle to recover its investment, especially if price spreads are narrow, utilization is low or efficiency losses reduce the amount of saleable energy. By contrast, BESS viability improves when daily or near-daily cycling is possible, when midday PV overgeneration creates low-price charging opportunities and when evening demand creates higher-value discharge periods. The strongest economic case emerges when BESS is not limited to a single revenue stream. In addition to energy arbitrage, storage can provide balancing services, reserve provision, congestion relief, ramp-rate control and reduction in PV curtailment. Revenue stacking is therefore essential, since the same asset can increase its value by combining market participation with technical grid services when regulation, metering, dispatch rules and grid-operator requirements allow such participation. For co-located PVPP+BESS projects, economic value may also arise from increasing the usable share of solar generation, reducing export constraints, improving forecast compliance and shifting otherwise curtailed energy into higher-price hours. Under Bulgarian conditions, BESS profitability is therefore highly sensitive to utilization rate, price volatility, balancing-market access, grid-connection constraints and the treatment of curtailed renewable energy. Projects with high cycling frequency, favorable connection points, predictable PV surplus and access to multiple market products are more likely to achieve competitive LCOS and positive margins. Conversely, assets with limited dispatch opportunities, restricted market access, high connection costs or significant technical losses may remain valuable from a system-planning perspective but less attractive as private investments.

4.2. Role of BESS and Importance of Efficiency and Utilization in LCOS

BESS should be evaluated as a technology optimized for fast-response, short-to-mid-duration grid services rather than as a universal replacement for all forms of energy storage. Compared with alternatives like pumped hydro or hydrogen-based storage, BESS offers higher modularity, faster response, easier siting and stronger suitability for photovoltaic integration, peak shaving, frequency regulation, ramp-rate control and intraday energy shifting. However, alternative technologies may be more appropriate for long-duration, seasonal, or large-scale system balancing, especially where storage duration and lifetime

are more important than response speed or distributed deployment. Within this operational role, LCOS depends strongly on efficiency and utilization.

High RTE improves the amount of energy delivered back to the grid, while frequent cycling spreads CAPEX and fixed OPEX over a larger number of discharged MWh. Conversely, low utilization, degradation, auxiliary consumption, transformer losses, and conversion losses increase LCOS by reducing the useful energy output of the system. Therefore, a BESS project may appear technically attractive based on installed MW and MWh, but its economic performance ultimately depends on how often it operates, how efficiently it converts stored energy into delivered energy, and whether its use case matches the time scale and service requirements of the Bulgarian power system.

4.3. Modelling and Technical Limitations

The main limitations of this study arise from the assumptions required to model BESS economics without complete project-specific cost and operating data. LCOS results are highly sensitive to the selected discount rate, project lifetime, battery lifetime, residual value, annual degradation, availability factor, electricity purchase price, number of equivalent full cycles per year and assumed RTE. Small changes in these parameters can significantly alter the calculated cost per discharged MWh, especially in cases where the BESS is underutilized or where electricity-price spreads are insufficient to justify frequent cycling. For this reason, the presented LCOS values should be interpreted as scenario-based estimates rather than fixed financial outcomes for all Bulgarian BESS projects. Further uncertainty comes from the lack of publicly available data on actual CAPEX, OPEX, grid-connection costs, balancing-market revenues, curtailment compensation and project-specific financing conditions. Generic European or literature-based cost assumptions may not fully reflect the Bulgarian context, where permitting timelines, transformer availability, medium-voltage infrastructure, land costs, construction conditions and grid-operator requirements can differ significantly between projects. In addition, simplified models often assume regular cycling and stable efficiency, while real BESS operation may be irregular, constrained by dispatch signals, market rules, grid limitations, battery warranties and operational reserves.

The technical part of the analysis is also limited by the current state of BESS technology and by the availability of measured field data. LFP-based BESS offers high efficiency and fast response but still experiences calendar aging, cycle degradation, temperature sensitivity, auxiliary consumption, inverter losses, transformer losses and reduced usable capacity over time. Transformer-related losses, harmonic and supraharmonic effects and aging-equivalent loading are discussed conceptually, but a precise quantitative assessment would require site-specific measurements, including inverter switching behavior, transformer loading, thermal profiles, harmonic and supraharmonic spectra, local grid impedance and protection-system response. Therefore, the study provides a framework for incorporating these effects into future techno-economic assessments, while recognizing that detailed validation requires long-term operational data from actual Bulgarian BESS and PVPP+BESS installations.

5. Conclusions

BESS offers faster response, higher modularity, easier deployment, and stronger compatibility with daily PV shifting, peak shaving, ramp-rate control, balancing and reserve provision. These characteristics make it especially relevant for managing midday PV overgeneration, reducing curtailment and extending the availability of renewable electricity into evening demand periods. However, the economic viability of BESS cannot be determined by installed MW and MWh alone. Profitability depends strongly on utilization rate, round-trip efficiency, cycling frequency, electricity-price spreads, market access, grid-connection conditions and the ability to recover costs through multiple revenue streams. A BESS asset

that operates frequently and participates in arbitrage, balancing, reserve provision, congestion relief and curtailment reduction is more likely to achieve a competitive LCOS, while an underutilized asset may remain technically valuable but financially weak. The contribution of this study is primarily engineering-oriented: it translates BESS cost assessment into a practical framework that reflects how storage systems operate within PV-rich distribution and transmission environments.

The results also emphasize that future techno-economic models must move beyond simplified CAPEX, OPEX and LCOS calculations. A realistic assessment of BESS performance should include conversion-chain losses, transformer efficiency, auxiliary consumption, battery degradation, availability and power-quality effects. In particular, transformer-related losses, harmonic (and supraharmonic) emissions and aging-equivalent loading may influence both delivered energy and long-term asset reliability. Incorporating these factors into future Bulgarian BESS models will improve the accuracy of investment appraisal, grid-planning studies and control strategies for PVPPs+BESS integration.

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Abbreviations

The following abbreviations are used in this manuscript:

RES	Renewable Energy Sources
CAPEX	Capital Expenditures
OPEX	Operational Expenditures
LCOS	Levelized Costs Of Storage
BESS	Battery Energy Storage System
LFP	Lithium Iron Phosphate
PVPP	Photovoltaic Power Plant
ESS	Energy storage system
AC	Alternating Current
DC	Direct Current
BMS	Battery Management System
EMS	Energy Management System
PCS	Power Conversion System
RTE	Round-Trip Efficiency

TDD	Total Demand Distortion
THD	Total Harmonic Distortion
PCC	Point of Common Coupling

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