

Proceeding Paper

Progress on Developing a Sustainable BESS Technical–Economic Model by Mapping the Latest Grid-Connected Installations in Bulgaria [†]

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Abstract

The rapid construction and commissioning of battery energy storage system (BESS) installations, both standalone and combined with photovoltaic power plants (PVPPs), is rapidly reshaping the energy market. Mapping these latest iterations in the energy infrastructure allows for a detailed analysis of the effects they have on the grid, in correlation with the already abundant operational PPV. This paper will provide a list of all BESS installations commissioned between 1 January and 30 September 2025. Taking into consideration their grid-connection power, and respective battery capacity, along with their geographical location and co-located (or lack thereof) PVPPs, the following-up analysis aims to answer several key questions: how do these installations compare to one another in terms of power, capacity and distribution across Bulgaria; how do they affect the availability of electric power from PVPP, co-located or not, to the end consumers; and how does that shift in availability affect the profits, both for the BESS and PVPP owners, based on the shifting price of electricity?

Keywords: energy storage; energy storage system; battery energy storage system; economics; photovoltaic power plants

1. Introduction

This study profiles grid-connected energy storage systems (ESSs), both standalone and co-located with PVPPs, based on a curated project list and an accompanying dataset [1]. All reviewed installations were commissioned before 30 September 2025. Methodologically, the workflow provides a reproducible pipeline for location normalization and unit harmonization suited to regulatory and planning analyses. Standardized location descriptors (region -> municipality -> settlement; parcel identifiers) and harmonized technical parameters add to the reproducibility. Eight nominally separate PVPP + ESS projects labeled 1 through 8 were aggregated into a single composite site, since they are located at the same site [2]. When ESS power is reported in kVA, values are converted to MW, assuming a power factor PF = 1; missing power and/or capacity are set to zero. These constraints notwithstanding, the dataset offers a transparent baseline for follow-on geospatial, techno-economic, and grid-impact assessments.



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This publication explores the current state of the integration process regarding battery energy storage systems (later referred to as BESSs or ESSs) in Bulgaria's electrical grid. There is an interactive map of the country with the location, power, and capacity of these systems. The objectives are threefold. First, to characterize the techno-geographic profile of the current project portfolio, including the distribution of ESS power and capacity across administrative units and by project type (PVPP + ESS vs. standalone ESS). Second, to quantify storage "duration" (hours), defined as the ratio of usable capacity to connection power (MWh/MW), for projects with complete metrics, thereby illuminating typical operational envelopes relevant to PV integration and peak management. Third, to identify patterns of scale—for example, the prevalence of repeated mid-scale configurations versus singular large installations—that may reflect permitting practices, interconnection constraints, or developer strategies.

Across $N = 19$ unique projects, the portfolio comprises a total ESS connection power of 379.73 MW and a total storage capacity of 981.35 MWh. Projects with both metrics explicitly available exhibit a capacity-weighted mean storage duration of around 3.53 h (range 2.05 to 4.00 h; median 2.70 h). The sample mixes PVPP + ESS (9/19) and standalone ESS (10/19), including one large two-stage installation (124 MW/496 MWh) and a repeated "mid-scale" motif around 5 MW/13.4 MWh and 10 MW/27 MWh. Geographically, the projects are distributed across multiple municipalities and regions, with cadastral parcel identifiers enabling precise spatial traceability for subsequent mapping and regional aggregation (Figure 1). Each site is represented with a number, referenced in Table 1.

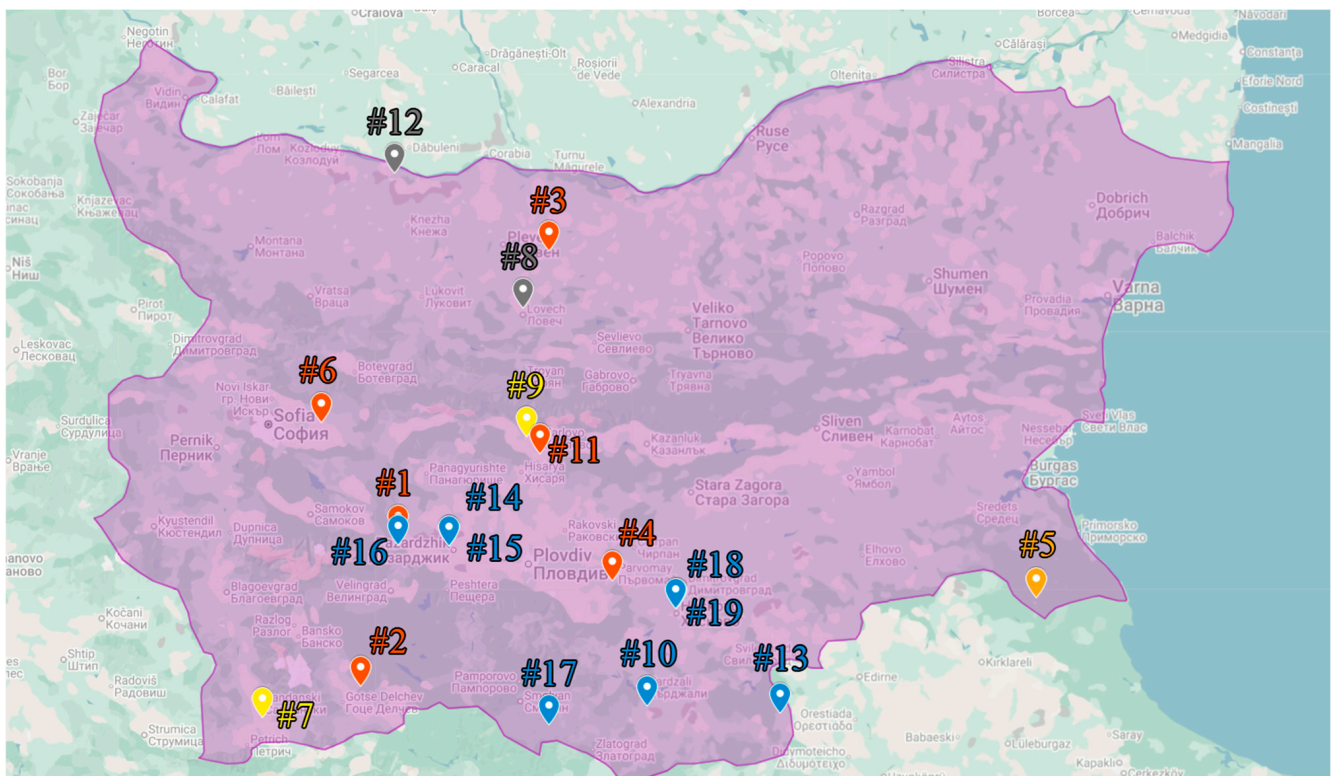


Figure 1. Interactive map of Bulgaria with all of the sites marked on it. Sites in red represent missing values (power, storage, or both). Sites in gray are the large-scale installations. Sites in blue are the later discussed 10 MW/27 MWh motif and sites in yellow and orange fall in none of the above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

Table 1. A list of all the BESS sites commissioned in Bulgaria between 1 January and 30 September 2025.

Site	Town, Province	Power	Storage	Type
#1	Akandzhievo, Pazardzhik	3 MW	N/A	PVPP + BESS
#2	Leshten, Blagoevgrad	N/A	N/A	PVPP + BESS
#3	Pordim, Pleven	N/A	N/A	PVPP + BESS
#4	Debar, Plovdiv	10 MW	N/A	PVPP + BESS
#5	Malko Tarnovo, Burgas	110 MW	130 MWh	PVPP + BESS
#6	Stolnik, Sofia-Province	N/A	N/A	PVPP + BESS
#7	Novo Delchevo, Blagoevgrad	1.25 MW	3.7 MWh	BESS
#8	Lovech, Lovech	124 MW	496 MWh	BESS
#9	Sopot, Plovdiv	1.48 MW	1.65 MWh	PVPP + BESS
#10	Momchilgrad, Kardzhali	10 MW	27 MWh	BESS
#11	Dabene, Plovdiv	N/A	N/A	PVPP + BESS
#12	Selanovtsi, Vratsa	40 MW	107 MWh	PVPP + BESS
#13	Ivaylovgrad, Haskovo	10 MW	27 MWh	BESS
#14	Pazardzhik, Pazardzhik	10 MW	27 MWh	BESS
#15	Pazardzhik, Pazardzhik	10 MW	27 MWh	BESS
#16	Belovo, Pazardzhik	10 MW	27 MWh	BESS
#17	Rudozem, Smolyan	10 MW	27 MWh	BESS
#18	Haskovo, Haskovo	10 MW	27 MWh	BESS
#19	Haskovo, Haskovo	10 MW	27 MWh	BESS

The rapid expansion of photovoltaic generation amplifies the need for flexible resources capable of mitigating variability, aligning supply with demand, and supporting distribution and transmission-level reliability. Grid-connected energy storage systems (ESSs) address these needs by providing short-to-mid-duration services such as peak shaving, intra-day energy shifting, ramp-rate control, and reserve provision [3,4]. When co-located with PVPPs (PVPP + ESS), storage can also enable higher self-consumption and improve the economic efficiency of interconnection assets. Against this backdrop, a transparent, location-aware inventory of ESS projects is essential for planning studies, regulatory oversight, and investment appraisal. In Bulgaria, as in many European power systems, the accelerating deployment of PPV and the emergence of battery storage projects heighten the importance of consistent siting, permitting, and compliance practices. Publicly available project descriptions—often prepared for administrative and regulatory processes—contain rich but heterogeneous information on technical parameters and geography (for example, installed or connection power, usable capacity, cadastral parcel identifiers, municipality and region). Converting these narrative records into a harmonized analytical dataset enables reproducible assessments of technology mix, scale, and spatial distribution. It also facilitates traceability from aggregate statistics back to the underlying projects, a prerequisite for robust policy and grid-impact analysis [5,6].

This study develops such a dataset by systematizing a curated list of ESS projects, comprising both standalone installations and systems co-located with PVPPs. We standardize these descriptors into an administrative path (region -> municipality -> settlement) and extract cadastral identifiers (parcel numbers, RPI/PI) where available, supporting precise spatial referencing. On the technical side, we harmonize ESS connection power (MW) and energy capacity (MWh); when power is reported in kVA, we convert to MW, assuming power factor PF = 1 in the absence of explicit specifications. Missing power or capacity values are retained as zeros to preserve the completeness of the project list while transparently signaling data gaps. Eight nominally separate PV projects labeled 1 through 8, located at the same site, are aggregated into a single composite site for analysis.

2. Regulatory and Institutional Framework

2.1. Construction and Siting

In Bulgaria, the design, construction, and lawful use of PVPPs and energy storage systems (ESSs) are governed by the Spatial Development Act (SDA) and overseen by the National Construction Control Directorate (NCCD). The NCCD exercises legality control over construction, may suspend or order removal of unlawful works, and supervises compliance at commissioning and use stages—functions explicitly framed as SDA enforcement.

2.2. Energy-Sector Definition

The Energy Act recognizes storage facilities as part of the electricity system and (via its Additional Provisions) provides a legal definition of an “energy storage facility,” clarifying the distinction between grid-oriented storage and assets used solely for self-consumption that do not inject to the grid. The NCCD has circulated guidance reflecting this definition; more recent amendments also define “co-located storage” with generation. These definitional elements matter for permitting pathways and market roles.

2.3. Grid Connection

Technical and procedural rules for connecting consumption, generation, and storage to electricity networks are set by Ordinance №6 of 28 March 2024 [2], which superseded the earlier 2014 ordinance and was promulgated in State Gazette №28 on 2 April 2024. The ordinance expressly covers storage connections and amendments to existing connections. Sector commentary notes a concurrent alignment of connection thresholds (projects over 10 MW to the transmission grid operated by ESO; under or up to 10 MW to distribution grids) and transitional arrangements for projects holding pre-13 October 2023 grid agreements.

2.4. EU Context

Bulgaria’s framework is shaped by the EU Clean Energy Package. Directive (EU) 2019/944 establishes market rules and restricts DSO/TSO ownership of storage, allowing narrowly tailored exceptions subject to regulatory approval; Regulation (EU) 2019/943 sets internal-market principles affecting dispatch, balancing, and capacity mechanisms. The revised Renewable Energy Directive (EU) 2023/2413 (RED III) raises the 2030 RES target (min. 42.5%), reinforcing the system’s need for storage to integrate variable renewables [2,7]. These instruments provide the backdrop against which national definitions, ownership restrictions, and connection procedures are transposed and applied.

3. Materials and Methods

3.1. Data Sources and Scope

The analysis draws on two inputs:

- A curated project list describing PVPPs co-located with ESSs and standalone ESSs.
- A companion dataset (Table 2), containing project names and location descriptors. The unit of observation is the site. Per the research brief, eight nominally separate PV projects labeled 1 through 8 are aggregated into a single composite site, based on their location.

Table 2. Cosine profile of the hourly production of PV generation, based on which we have the hourly real PV + BESS generation (MW), proxy PV generation (MW), and total PVPP generation (MW), starting at 05:00 and ending at 19:00.

Hour	Cosine Profile	PV + ESS (MW)	Proxy PV (MW)	Total (MW)
05:00	0.000	0.000	0.000	0.000
06:00	0.000	0.000	0.000	0.000
07:00	0.067	14.420	11.020	25.442
08:00	0.250	53.810	41.120	94.933
09:00	0.500	107.620	82.240	189.865
10:00	0.750	161.440	123.360	284.798
11:00	0.933	200.830	153.460	354.288
12:00	1.000	215.250	164.480	379.730
13:00	0.933	200.830	153.460	354.288
14:00	0.750	161.440	123.360	284.798
15:00	0.500	107.620	82.240	189.865
16:00	0.250	53.810	41.120	94.933
17:00	0.067	14.420	11.020	25.442
18:00	0.000	0.000	0.000	0.000
19:00	0.000	0.000	0.000	0.000

3.2. Inclusion Criteria and Unit Conventions

Projects are included if they (a) contain an ESS (standalone or PVPP + ESS) and (b) report at least one of ESS connection power (kW/kVA/MW) or usable capacity (kWh/MWh). Power is expressed in MW, capacity in MWh. PV installed power (kWp) is recorded only for context and is not used in ESS power/capacity metrics.

3.3. Variable Definitions

- ESS connection power (MW): the rated AC power at the point of connection;
- ESS capacity (MWh): usable energy at the AC side (when ambiguous, the stated capacity is taken verbatim);
- Storage duration (h): $h = \text{MWh}/\text{MW}$, calculated only where both metrics are present;
- Project type: PVPP + ESS vs. standalone ESS;
- Administrative path: region -> municipality -> settlement; supplemented with parcel identifiers (PI/RPI) when present.

3.4. Data Standardization

Unit harmonization: kW to MW; kWh to MWh; kVA to MW, using $\text{PF} = 1$ when power factor is not provided (conservative, transparent assumption).

- Inverter-based power statements: When power is specified via inverter counts (for example—48 inverters x 110 kW per stage, two stages), the site power is the sum of inverter ratings across stages, converted to MW;
- Staged projects: If stages are additive and explicitly quantified, stage values are summed; otherwise, the clearly reported stage is retained and the remainder is documented as missing;
- Missing values: Absent power and/or capacity are set to 0 by design to signal data gaps while preserving the site in aggregates. Zeros therefore denote “unknown,” not physical zero.

3.5. Aggregations and Derived Indicators

- Site-level: original records are consolidated at site level; for the 1–8 group, entries are collapsed into one composite site and their location descriptors concatenated (deduplicated);

- Portfolio-level: totals of ESS power (MW) and capacity (MWh); counts by project type; and distributions of storage duration (h) for sites with complete metrics;
- Geographic: sums of MW and MWh by municipality and region using the standardized administrative path.

3.6. Statistical Treatment and Presentation

We report descriptive statistics (count, min-max, median) for MW, MWh, and duration (h); portfolio totals; and type shares (PVPP + ESS vs. standalone ESS). Where visualizations are used (bar charts by region, histograms of MW/MWh, duration distributions), axes and units are explicitly labeled, and one metric is shown per figure to avoid overplotting. All rounding is to two decimals unless transparency requires full precision (for example, cumulative totals)

3.7. Limitations and Sensitivity

Results are constrained by incomplete reporting (zeros as placeholders), the $PF = 1$ assumption for kVA \rightarrow MW, and ambiguity in whether stated capacities are usable AC values. Sensitivity checks can be performed by varying PF (0.9–1.0) and recalculating totals and durations; staged builds can be bracketed by “as-built” vs. “fully built” scenarios when documentation becomes available.

3.8. Reproducibility

The standardized location table is provided in Table 1, enabling re-calculation of all portfolio and geographic aggregates and straightforward revision if improved site specifications are supplied.

3.9. Proxy PV Capacity

To reflect the reality that numerous PV plants are already in operation but fall outside this study’s empirical dataset due to unknown counts and ratings, we introduce a proxy PV capacity used solely for scenario and balance checks. The proxy assumes that the aggregate AC capacity of the out-of-sample PV fleet equals the aggregate AC connection power of the standalone ESS—for example, those not co-located with PV plants within our dataset. The purpose of this construct is to provide a transparent, conservative baseline for counterfactual reasoning (e.g., PV-backstopping thought experiments) without altering the primary, observation-based results. It serves as a balancing proxy—a placeholder for the “background” solar generation plausibly available in the real system, while avoiding double-counting with the PVPP + ESS sites already present in the dataset. The scope and constraints of it include aggregation and no spatial redistribution across regions or municipalities. It also represents power only (MW), not energy (MWh), and does not encode seasonal/diurnal variability, availability, or export limits. Finally, it does not modify site-level metrics, type shares, or duration statistics derived from observed data. Results derived with this proxy should be read as illustrative system-level bounds rather than as an inventory of specific PVPPs, where improved information on the existing operating PV fleet becomes available with specific counts, AC ratings, and geography. The proxy can be replaced by empirically grounded PV aggregates and, if desired, distributed geographically to enable network-aware analyses.

4. Results

4.1. Portfolio Overview

The consolidated sample comprises $N = 19$ sites (including the aggregated PV projects 1–8 as a single site). Across the portfolio, the total ESS connection power is 379.73 MW

and the total storage capacity is 981.35 MWh. The mix includes PV + ESS (9/19 sites) and standalone ESS (10/19 sites). Standalone ESS accounts for 215.25 MW (56.7%) and 742.70 MWh (75.7%), while PVPP + ESS accounts for 164.48 MW (43.3%) and 238.65 MWh (24.8%). Several PV + ESS entries report ESS association without complete metrics; per protocol, missing values are retained as zeros and excluded from calculations. The portfolio is dominated by one large, two-stage installation (124 MW/496 MWh), which contributes 32.7% of total power and 50.5% of total capacity. The aggregated PV 1–8 composite site (40 MW/107.2 MWh) contributes 10.5% of power and 10.9% of capacity. Two mid-scale patterns are visible: 10 MW/27 MWh (23.7%/24.8%) and around 10.56 MW/21.672 MWh (2.8%/2.2%). A smaller standalone unit (1 MW/3.7 MWh) contributes 0.39%/0.17%.

4.2. Storage Duration

For the thirteen sites with both metrics reported, the fleet-average duration (calculated as total MWh divided by total MW) is around 2.68 h. The median duration is 2.70 h, with a range from around 2.04 h (21.672 MWh/10.56 MW) to 4.00 h (496.392 MWh/124.098 MW). The aggregated PV 1–8 site exhibits around 2.68 h (107.2 MWh/40 MW), and the 10 MW/27 MWh site exhibits 2.70 h. Overall, durations cluster in the 2 to 4 h band, consistent with short-to-mid-duration applications (intra-day shifting, peak shaving, ramp-rate control).

4.3. Composition by Project Type

- PVPP + ESS (9 sites):

Contribute 164.48 MW/238.65 MWh, largely driven by the aggregated 1–8 composite (40 MW/107.2 MWh). Several PV-co-located entries lack explicit ESS capacity and therefore do not affect duration statistics. One PV + ESS entry contributes around 4.8 MW based on AC equipment (3×1600 kVA, PF = 1), with no stated energy capacity.

- Standalone ESS (10 sites):

Contribute 215.25 MW/742.7 MWh, including the large two-stage installation (124 MW/496 MWh) and two mid-scale motifs (10 MW/27 MWh; around 10.56 MW/21.672 MWh).

4.4. Proxy PV Capacity

To reflect solar generation that exists in reality but lies outside the empirical dataset, we adopt a proxy PV capacity set equal to the aggregate AC connection power of the standalone ESS subset—215.25 MW.

4.5. Data Completeness and Traceability

Zeros mark missing power/capacity by design and are excluded from duration aggregates. Location standardization yields an administrative path (region -> municipality -> settlement) and captures parcel identifiers (RPI/PI) where present; each standardized record preserves the original location text to maintain auditability. These features enable direct roll-ups by administrative unit and straightforward verification against source descriptions.

5. Analysis

5.1. Portfolio Structure and Concentration

The sample exhibits a heavy-tailed size distribution: one two-stage standalone installation (124 MW/496 MWh) supplies around 33% of total ESS power and around 50% of total capacity. This concentration shapes portfolio indicators and suggests that incremental additions to this large node (for example staging and augmentation) would materially shift system-level statistics. The aggregated PV composite (1–8; 40 MW/107.2 MWh) accounts for a further 10% of power and nearly 11% of capacity, indicating a secondary pole of influence. Excluding the largest

installation yields a portfolio-average duration of around 1.9 h (485 MWh/255 MW), while excluding instead the aggregated PV composite yields around 2.57 h (874 MWh/339 MW). Excluding both produces around 1.75 h (378 MWh/216 MW). These sensitivity checks underline how a few high-impact sites drive apparent “system averages.”

5.2. Storage Duration and Operational Envelope

Among sites with complete metrics (thirteen cases), durations cluster in the 2 to 4 h band, with a median of 2.7 h and a capacity-weighted mean of around 3.53 h. This range is consistent with short-to-mid-duration use cases such as PV ramp-rate smoothing, midday-to-evening shifting, and peak shaving at distribution level. The repeated 5 MW/near 13.4 MWh motif (1–8 composite) and the 10 MW/27 MWh configuration point to templated designs, likely aligned to interconnection, equipment sizing, and site-specific load or market objectives. The large standalone system at around 4 h suggests a strategy oriented toward deeper intra-day arbitrage, reserve stacking, or more stringent ramp control.

5.3. Type Mix and Data Completeness

While standalone ESS entries outnumber PVPP + ESS, the latter contribute a smaller share of aggregate MWh due to incomplete reporting for several PV-co-located sites.

5.4. Geographic Traceability and Planning Implications

The standardized administrative paths (region -> municipality -> settlement) and extracted parcel identifiers (RPI/PI) enable reproducible roll-ups by jurisdiction and straightforward cross-checking with permitting records. Even without coordinates, parcel-level references provide sufficient precision for follow-on geocoding, proximity analysis to substations, and assessment of likely interconnection voltage levels. From a planning perspective, the observed clustering around 5–10 MW and around 2–3 h suggests designs tailored to distribution-level constraints, PV self-consumption/curtailment mitigation, and peak management. The dominance of an over 100 MW asset indicates parallel activity at transmission-relevant scales and underscores the need to consider both DSO and TSO interfaces in scenario work.

5.5. Interpreting the Proxy PV Capacity

We use the proxy PV capacity—set equal to the aggregate AC connection power of the standalone ESS subset (215.25 MW)—as an interpretive device for power sufficiency, without altering observation-based metrics. Analytically, the proxy benchmarks whether a background fleet of operating, yet unobserved PV plants could meet the charging-power constraint of the standalone batteries. As a sanity check, applying the previously established capacity-weighted mean duration of around 3.53 h to 215.25 MW implies around 759.83 MWh of energy for a full daily cycle. This is close to, but not a substitute for, the observed standalone aggregate of 742.7 MWh. The 2.3% gap reflects rounding and compositional differences and is purely a consistency check. Actual energy adequacy still depends on realized PV energy, including PR, DC/AC ratio, irradiance, and seasonality, and on operational limits like the battery C-rate, interconnection and export constraints, and round-trip efficiency. The proxy avoids double-counting with PVPP + ESS sites and serves as a system-level benchmark and not as an inventory claim, nor a guarantee of seasonal adequacy.

5.6. Cosine-Bell PV Variants with vs. Without ESS

In Table 2 and Figure 2 below we establish a simple cosine profile of the hourly production of PV generation, based on which we will run scenarios for real PVPP + BESS generation (excl. the BESS component) and imaginary proxy PV generation, before in-

roducing ESS installations into the mix. We will also establish a constant value for the demand for power in order to explore particular cases of wasted generation of PV power plants due to over-generation during the early afternoon and how ESS installations can be used to correct that.

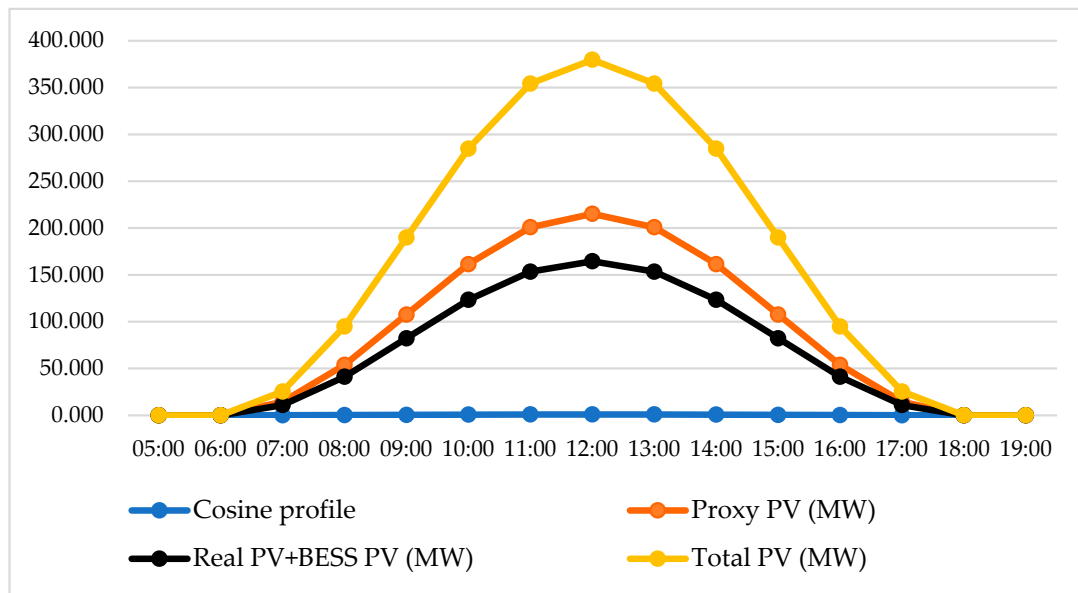


Figure 2. The graph visualizes the established in Table 2 cosine profile the hourly (between 05:00 and 19:00) production of PV generation, along with PVPP + BESS generation, proxy PV generation, and total PVPP generation.

If we export this to the grid as produced and establish the aforementioned constant value for the demand for power at 200 MW across the entire grid, we can see that between 09:00 and 15:00, the PVPPs generate electricity that we cannot utilize. That equals to a little over 1.6 GWh of unutilized energy daily or over 605 GWh wasted on a yearly basis. The demand can no longer be met solely by PV generation for the next 18 h, between 15:00 and 09:00. In the case (Table 3 and Figure 3) we will look at the total PV generation (MW), this time with the newly installed ESS sites in Bulgaria, meant to even-out the curve by gathering the electrical energy unutilized during peak hours. For that, we will need to visually introduce constant energy consumption and establish the state-of-charge (SOC) of the ESS and the energy output to the grid (MW).

Table 3. The hour of the day, total consumption (MW), total generation from PV power plants (MW), and the state-of-charge (SOC) of all grid-connected ESS installations and the availability of energy on the grid (MW).

Hour	Consumption (MW)	PV Generation (MW)	SOC (MWh)	Grid (MW)
05:00	200.000	0.000	0.000	0.000
06:00	200.000	0.000	0.000	0.000
07:00	200.000	25.442	0.000	25.442
08:00	200.000	94.933	0.000	94.933
09:00	200.000	189.865	0.000	189.865
10:00	200.000	284.798	84.798	200.000
11:00	200.000	354.288	239.086	200.000
12:00	200.000	379.730	418.816	200.000
13:00	200.000	354.288	573.104	200.000
14:00	200.000	284.798	657.901	200.000
15:00	200.000	189.865	647.766	200.000
16:00	200.000	94.933	542.699	200.000

Table 3. *Cont.*

Hour	Consumption (MW)	PV Generation (MW)	SOC (MWh)	Grid (MW)
17:00	200.000	25.442	368.141	200.000
18:00	200.000	0.000	168.141	168.141
19:00	200.000	0.000	0.000	0.000

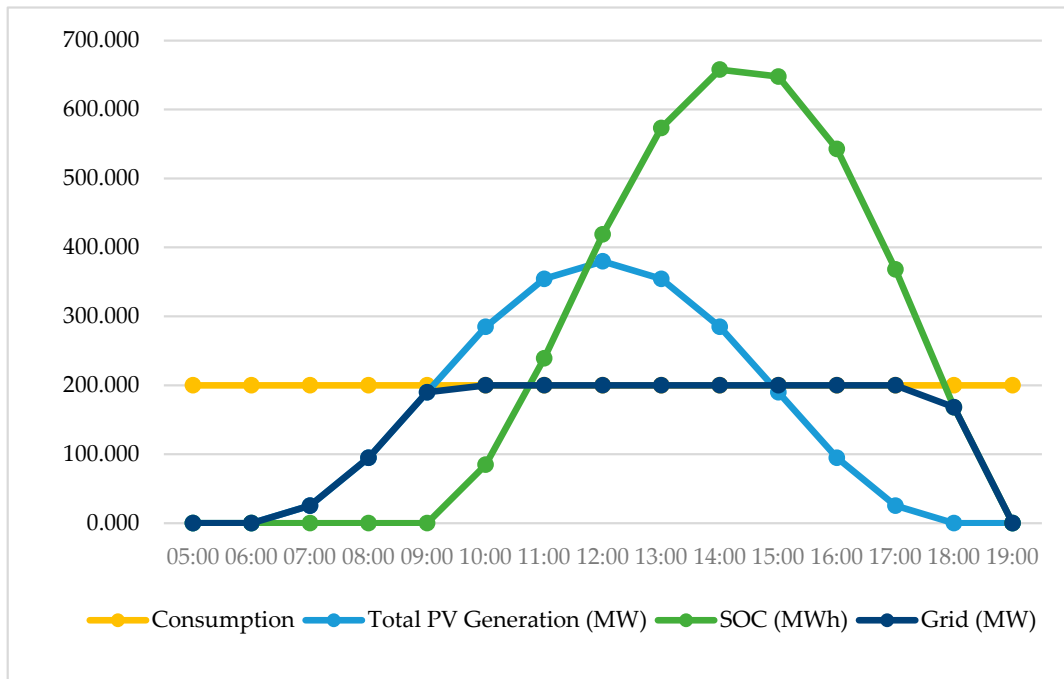


Figure 3. The graph visualizes the cosine profile established in Table 3 of the hourly (between 05:00 and 19:00) production of PV generation, along with PV + BESS generation, proxy PV generation, and total PV power generation.

As we can see, the introduced ESS installations significantly expand the availability of renewable energy to the grid throughout the day by flattening the curve. This case in particular revolves around the immediate discharge of energy stored within the same day. In order to compare the grid availability of PV energy with and without ESS installations, we will study a case where the excess energy generated from PV plants the previous day (657.901 MWh) is retained within the ESS and discharged evenly throughout the next day, meeting the demand for consumption as best as possible. On top, we will overlay the curve of PV generation without any ESS installations.

As we can see from Table 4 and Figure 4, the ESS installation significantly spreads-out the available renewable energy generated by PV plants that would otherwise be wasted. An interesting thing to note is that the ESS installations can never reach a fully charged state, because the constant consumption outweighs generation significantly.

Table 4. The hour of the day, total grid consumption (MW), total grid availability from PV power plants without ESSs (MW), total grid availability from PVPPs with ESS installations charged the day before, and the state-of-charge (SOC) of ESS installations paired with PVPPs (MWh).

Hour	Consumption (MW)	PV Only (MW)	PV + ESS (MW)	ESS SOC (MWh)
03:00	200.000	0.000	0.000	657.901
04:00	200.000	0.000	0.000	657.901
05:00	200.000	0.000	168.141	489.761
06:00	200.000	0.000	200.000	289.761

Table 4. *Cont.*

Hour	Consumption (MW)	PV Only (MW)	PV + ESS (MW)	ESS SOC (MWh)
07:00	200.000	25.442	200.000	115.202
08:00	200.000	94.933	200.000	10.135
09:00	200.000	189.865	200.000	0.000
10:00	200.000	284.798	200.000	84.797
11:00	200.000	354.288	200.000	239.086
12:00	200.000	379.730	200.000	418.816
13:00	200.000	354.288	200.000	573.104
14:00	200.000	284.798	200.000	657.901
15:00	200.000	189.865	200.000	647.766
16:00	200.000	94.933	200.000	542.699
17:00	200.000	25.442	200.000	368.141
18:00	200.000	0.000	168.141	168.141
19:00	200.000	0.000	0.000	0.000
20:00	200.000	0.000	0.000	0.000
21:00	200.000	0.000	0.000	0.000

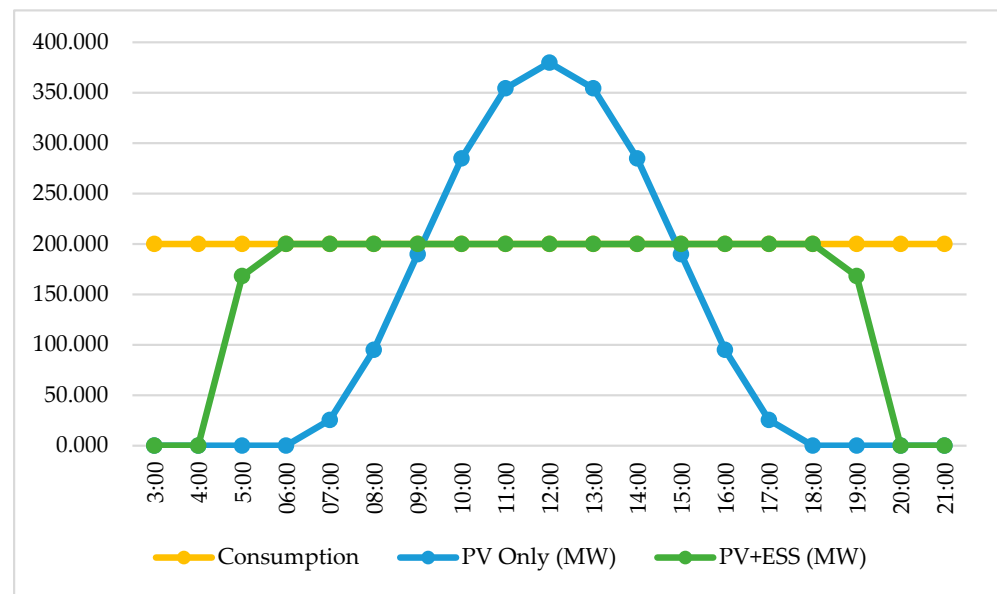


Figure 4. The graph visualizes the cosine profile established in Table 4 of the hourly grid availability in MW of PV generation without and with ESS installations, with the ESS installations having already been charged the day before (the SOC from Table 4 excluded).

The next case we look at is if PV production were to remain the same (379.73 MWp). The ESS matches the grid-connection AC power of the PV production (379.73 MW—both real and aux.), the total installed ESS capacity remains at 981.35 MWh, but the consumption is cut by 50%, being at a constant 150 MW. This will generate a total excess of 947,766 MWh from the day prior to the studied time interval, as evident in Table 5.

Table 5. Spans across two days’ worth of PV generation and respective ESS storage, taking into consideration the hour of the day, total grid consumption (MW), total grid availability from PV power plants without ESSs (MW), total grid availability from PV power plants with ESS installations charged the day before, and the state-of-charge (SOC) of ESS installations paired with PVPPs (MWh).

Hour	Consumption (MW)	PV Only (MW)	PV + ESS (MW)	ESS SOC (MWh)
05:00	150.000	0.000	0.000	0.000
06:00	150.000	0.000	0.000	0.000
07:00	150.000	25.442	25.442	0.000
08:00	150.000	94.933	94.933	0.000

Table 5. Cont.

Hour	Consumption (MW)	PV Only (MW)	PV + ESS (MW)	ESS SOC (MWh)
09:00	150.000	189.865	189.865	0.000
10:00	150.000	284.798	284.798	134.798
11:00	150.000	354.288	354.288	339.086
12:00	150.000	379.730	379.730	568.816
13:00	150.000	354.288	354.288	773.104
14:00	150.000	284.798	284.798	907.901
15:00	150.000	189.865	189.865	947.766
16:00	150.000	94.933	94.933	947.766
17:00	150.000	25.442	25.442	947.766
18:00	150.000	0.000	0.000	947.766
19:00	150.000	0.000	0.000	947.766
20:00	150.000	0.000	0.000	947.766
21:00	150.000	0.000	0.000	947.766
22:00	150.000	0.000	0.000	947.766
23:00	150.000	0.000	0.000	947.766
00:00	150.000	0.000	0.000	947.766
01:00	150.000	0.000	18.141	929.625
02:00	150.000	0.000	150.000	779.625
03:00	150.000	0.000	150.000	629.625
04:00	150.000	0.000	150.000	479.625
05:00	150.000	0.000	150.000	329.625
06:00	150.000	0.000	150.000	179.625
07:00	150.000	25.442	150.000	55.067
08:00	150.000	94.933	150.000	0.000
09:00	150.000	189.865	150.000	39.865
10:00	150.000	284.798	150.000	174.662
11:00	150.000	354.288	150.000	378.950
12:00	150.000	379.730	150.000	608.680
13:00	150.000	354.288	150.000	812.968
14:00	150.000	284.798	150.000	947.766
15:00	150.000	189.865	150.000	987.631
16:00	150.000	94.933	150.000	932.563
17:00	150.000	25.442	150.000	808.005
18:00	150.000	0.000	150.000	658.005
19:00	150.000	0.000	150.000	508.005
20:00	150.000	0.000	150.000	358.005
21:00	150.000	0.000	150.000	208.005
22:00	150.000	0.000	150.000	58.005
23:00	150.000	0.000	18.141	39.864
00:00	150.000	0.000	0.000	39.864

With the concept proven, we will pair it with real data taken from the Bulgaria's state-owned grid operator, ESO. The following chart is generated based on open-source data taken from their website and represents the real energy consumption in Bulgaria on 30 September 2025. With the real consumption data at hand, spreading across an entire day, we will overlay the PV generation and BESS storage data from Figure 5 over the data from Figure 6, visualizing the rift between the currently installed BESS capacity, charged by PV generation, and the real demand for electric power. As we can see, the installed ESS capacity within the scope of this study (~380 MW) can barely account for 10.6% of the lowest consumption (3582 MW) at 01:00 and even less, 7.5%, of the peak consumption (5054 MW) at 19:00 (Figure 7).

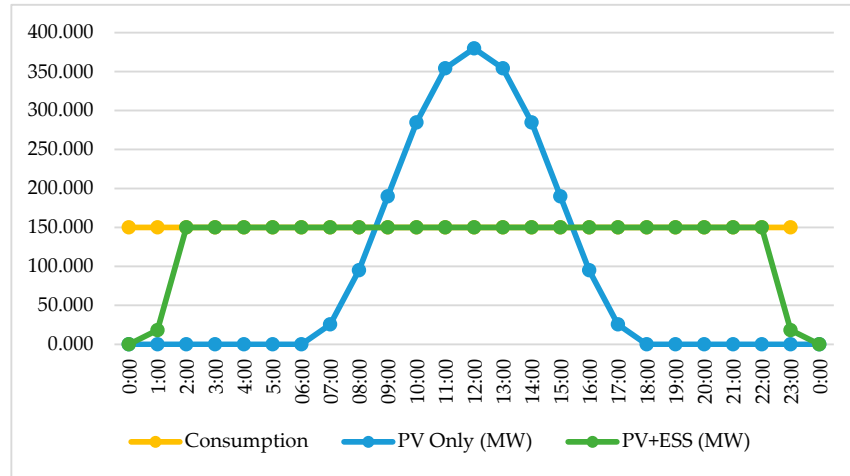


Figure 5. The graph visualizes the interval after 00:00 of the second day of the cosine profile established in Table 5 of the hourly grid availability in MW of PV generation without (PV only) and with ESS installations, with the ESS installations having already been charged the day before (the SOC from Table 5 excluded).

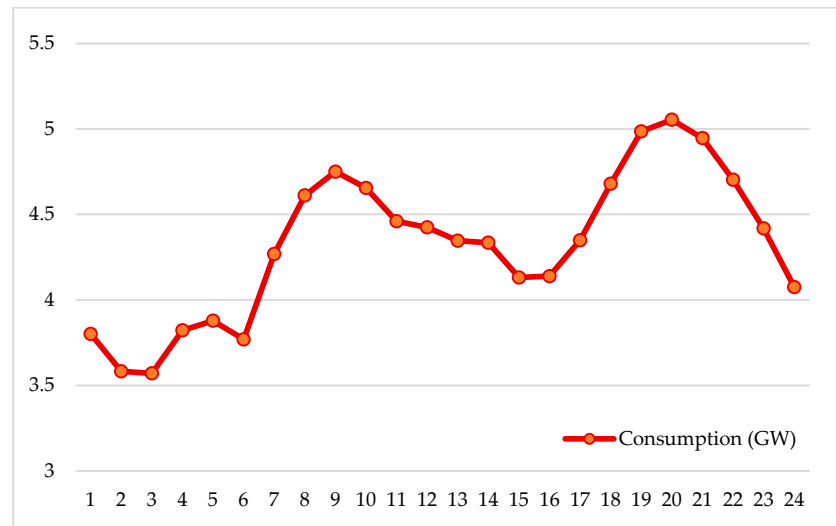


Figure 6. The graph visualizes the real measured grid consumption on 30 September 2025 across the entire grid in Bulgaria, represented in GW.

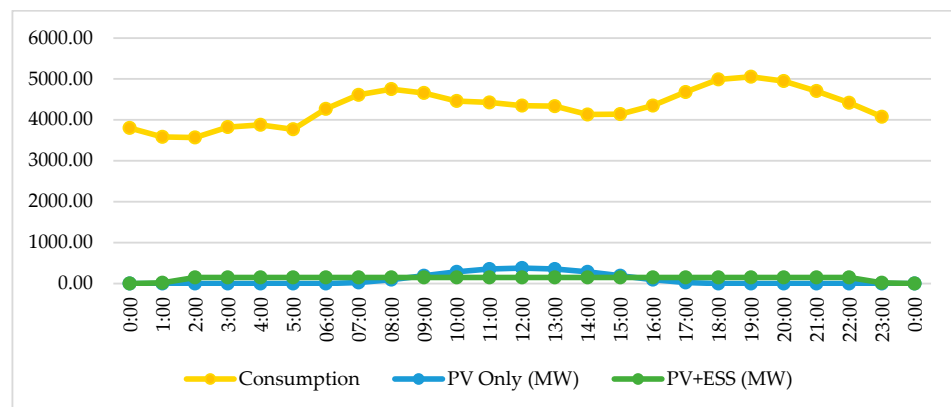


Figure 7. The graph visualizes the real measured consumption on 30 September 2025, across the entire grid in Bulgaria, represented in MW. Below we can see the data from Figure 5.

5.7. Uncertainties and Paths to Refinement

Based on the case examined in Figure 5, we can conclude that as a concept, matching PV generation with ESS installations of identical AC power can help match demand and extend the availability of almost 2.3 GWh, all of which would otherwise be wasted, by a total of 12 h, significantly before (and beyond) the time the sun is no longer shining.

The main uncertainties arise from missing ESS metrics for several PV-co-located projects, reliance on PF = 1 for kVA → MW conversion in the absence of specified power factors, and occasional ambiguity over whether reported capacities are usable (AC-side) values. These can be progressively reduced by requesting explicit ESS AC connection power, usable MWh, and power factor (or inverter apparent-power ratings with PF) data. Where projects are staged, distinguishing “as-built” versus “fully built” states would clarify temporal comparability. Finally, adding coordinates (centroids or parcel vertices) would enable spatial accessibility analyses (for example, distance to 20/110 kV nodes) and loss modeling, improving the fidelity of geospatial and grid-impact assessments.

5.8. Economic Model

The data provided shows that during periods of high solar generation, particularly between 10:00 and 16:00 when excess energy is produced, the BESS can capture and store this surplus. For instance, if excess energy is estimated to reach over 1.6 GWh daily, this would otherwise be wasted without storage. By smoothing out the output and discharging the stored energy during peak consumption periods (like 18:00 to 20:00 when generation declines), the ESS effectively flattens the energy generation curve, meeting grid demand more consistently and reducing reliance on fossil fuels during these high-demand hours. Operationally, the observed characteristics such as storage duration clustering around 2 to 4 h imply that these systems are well-suited for applications like intraday shifting and peak shaving—qualities that can be monetized through improved market participation. However, potential misattributions of generation between PV and ESS subsystems, along with incomplete reporting for certain co-located projects, underscore the need for refinement in the metrics used to assess performance and economic returns.

The financial metrics show a net presented value as a function of the benefits minus costs in a year divided by the discount rate (assuming usually 8–10% depending on the risk assessment). This perspective makes it difficult to structure a transparent sensitivity and scenario analysis due to the significant deviation of crucial parameters such as electricity prices and the charge/discharge approach based on them. The model could become more simplified if the storage systems use pre-defined prices based on long-term agreements, providing additional services for coordination and balance of the national grid that could improve stability and reliability by maintaining the technical parameters. ENTSO-E is providing additional possibilities in this direction in the context of the 2026 TYNDP [8,9].

We now look at the leveled cost of storage delivered (LCOS), representing long-run average cost per MWh discharged by including capital recovery, O&M, and the cost of buying charging energy. Taking 30 September 2025 as a sample, we are looking at data from IBEX, including the prices and volume of energy being traded.

As stated above, the drop in price is noticeable between 10:00 and 16:00, when PVPPs are generating an abundance of electrical power. The price ranges between EUR 54.20 and 146.80/MWh, or at an average of EUR 89.82 /MWh. On the contrary, between 07:00 and 09:00, as well as in the interval between 18:00 and 21:00, the price of electricity rises to the range between EUR 92.03 and 367.91/MWh, or EUR 232.62/MWh on average.

This price difference allows us to charge the entire 981.35 MWh portfolio for an average of EUR 88,144.86 while selling it at both peak times for an average of EUR 228,281.64,

reaching a profit margin of up to EUR 140,136.78, or the equivalent of 61%. This excludes any transmission and distribution fees, taxes, and other expenses (Figure 8).

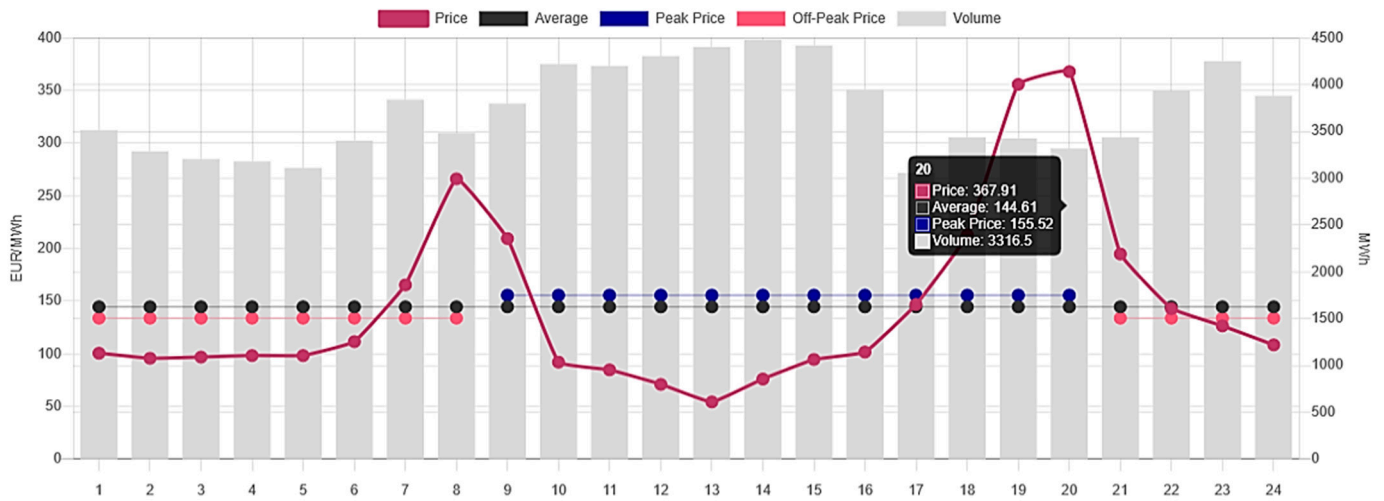


Figure 8. The graph represents the volume (MWh) and price (EUR/MWh) of traded electrical energy on 30 September 2025 over at IBEX.

In order for the LCOS to be properly calculated, we must first take into consideration the round-trip efficiency $\eta_{rt} = 0.88$, the CAPEX of EUR 250 per MW and additional EUR 250 per MWh duration, the fixed operations and maintenance FOM = 1.5% of CAPEX per year with a lifetime of 15 years, a discount of 8% (CRF), 95% availability of the system, and one full discharge per day. This results in three possible outcomes, considering the 2–4 h motif of the overviewed BESS installations. At a 2 h rate, the LCOS lays at 244.64/MWh, losing 12.02/MWh. Keeping to the one cycle per day and 95% availability, the entire portfolio’s loss is nearly EUR 4,100,000 per year. At the 3 and 4 h rate, the LCOS is priced at EUR 228.80 and 220.88/MWh, respectively, earning a margin of EUR 3.82 and 11.74/MWh. With a single cycle per day, the portfolio-level gross margin is at EUR 1,300,000 per year for the 3 h and the much more impressive EUR 4,000,000 per year for the 4 h.

The LCOS changes drastically when we utilize the BESS installations twice per day, however. The 2 h LCOS rate is at EUR 173.35/MWh, leaving a margin of EUR 59.27/MWh or a EUR 40,340,000/year portfolio gross margin. The 3 and 4 h LCOS is EUR 165.43 and 161.47/MWh, with a margin of 67.19 and 71.15/MWh, respectively. On a yearly basis, the gross margin goes up to EUR 45,730,000 yearly for the 3 h, and 48,420,000 gross margin for the 4 h LCOS, since doubling the cycles halves the CAPEX/FOM component per MWh, dropping LCOS materially, while the energy-cost term stays at the average price paid to charge over the round-trip efficiency (P_{charge}/η).

6. Limitations of the Study

6.1. Data Completeness and Representativeness

The dataset comprises $N = 19$ sites assembled from project descriptions and an accompanying spreadsheet. It is not a statistically sampled frame; therefore, results should be interpreted as descriptive for this portfolio rather than inferential for all ESS/PVPP + ESS projects in Bulgaria. Several entries lack either ESS power or capacity; by protocol, these are retained as zeros (placeholders), which preserves coverage but reduces the number of records eligible for duration analysis and may bias type-level shares.

6.2. Assumptions in Unit Harmonization

Where power is reported in kVA, conversion to MW assumes PF = 1 in the absence of an explicit power factor. Actual PF values (0.9–0.98) would scale the corresponding MW downward, altering aggregate indicators and duration (MWh/MW). Similarly, power derived from inverter counts may overstate interconnection-limited AC power if grid constraints, clipping, or control setpoints are binding.

6.3. Ambiguity in Capacity Definitions

Reported “capacity” is taken at face value; however, sources may alternately refer to DC nameplate, energy content at the battery terminals, or usable AC-side MWh after conversion and control limits. If values are DC or nominal rather than usable AC, duration estimates may be upwardly biased.

6.4. Treatment of Staged and Composite Projects

Staged projects are included as reported; where both stages are quantified, totals are summed, but where only one stage is explicit, the remainder is effectively missing. The deliberate aggregation of the eight PV-labeled projects (1–8) into a single composite site masks intra-group heterogeneity in siting and configuration.

6.5. Temporal Scope and Status Uncertainty

The analysis is a snapshot of project specifications at the time of data compilation. Project statuses (permitting, under construction, commissioned), equipment revisions, or grid-connection amendments that occur prior to 01 January 2025 and after 30 September 2025 are not reflected. For staged assets, “as-built” versus “fully built” distinctions may shift totals over time.

6.6. System Boundaries and Omitted Variables

The study focuses on nameplate MW and MWh. It does not model degradation, usable state-of-charge windows, round-trip efficiency, availability, or operational strategies (for example reserve stacking), all of which affect effective deliverable energy and system services. Cost metrics, market revenues, and network constraints are outside scope and thus not used to contextualize techno-economic viability.

6.7. Sensitivity of Portfolio Indicators to Large Sites

Aggregate metrics are sensitive to a small number of high-capacity entries (notably a 124.098 MW / 496.392 MWh installation). While sensitivity checks are provided in Section 5, any changes in the specification or status of these sites would materially shift portfolio averages and duration statistics.

6.8. Potential Misattribution Between PV and ESS Subsystems

For co-located assets, some AC ratings (for example, transformer MVA) may pertain primarily to the PV subsystem rather than the ESS. Where documentation is ambiguous, this can inflate apparent ESS connection power and depress computed duration.

6.9. Implications for Interpretation

Given these limitations, results should be read as a transparent baseline for the current portfolio, suitable for scoping, benchmarking, and planning dialog. Refinements should prioritize explicit ESS AC power and usable MWh, power factor specifications for kVA-reported entries, clear “as-built vs. planned” staging, and geocoded locations to enable network-aware analysis.

7. Conclusions

This study systematized a portfolio of 19 ESS sites—both standalone and co-located with PV—into a harmonized, traceable dataset. After standardizing location descriptors and technical metrics, the portfolio totals 379.73 MW of connection power and 981.35 MWh of storage capacity. Where both metrics are reported, storage durations cluster in the 2 to 4 h range (median 2.70 h; capacity-weighted mean around 3.53 h), consistent with short-to-mid-duration applications such as intra-day shifting, peak shaving, and ramp-rate control. The distribution is markedly heavy-tailed, with a single 124 MW/496 MWh installation driving most aggregate indicators and an aggregated PV composite (1–8, 40 MW/107.2 MWh) forming a secondary concentration. Repeated mid-scale templates (for example 10 MW/27 MWh, around 10.56 MW/21.672 MWh) further suggest standardized design and interconnection strategies.

Methodologically, the work delivers a reproducible pipeline for location normalization down to parcel identifiers (PI/RPI), unit harmonization (including transparent kVA to MW conversion with PF = 1 when unspecified), and principled handling of staged and composite projects. Retaining zeros for missing values preserves coverage while signaling data gaps, and keeping the original text fields ensures auditability from aggregate statistics back to source descriptions. The findings provide a transparent baseline for planning and policy dialog: the observed duration band aligns with current grid needs for PV integration, while the coexistence of distribution-scale clusters and a transmission-relevant outlier highlights the need to consider both DSO and TSO interfaces. Key priorities for refinement include explicit ESS AC connection power and usable MWh, stated power factor for kVA-reported sites, clear as-built vs. planned staging, and geocoded locations to enable network-aware assessments. With these enhancements, the dataset can underpin geospatial analyses, techno-economic appraisal, and grid-impact studies, supporting the evidence-based development of storage-enabled PV plants across regions and municipalities.

Finally, to acknowledge the existing but unobserved operating PV fleet, we report a proxy PV capacity equal to the aggregate AC connection power of the standalone ESS subset (215.25 MW). This proxy serves solely as a system-level benchmark for charging-power sufficiency—without modifying observation-based site metrics or portfolio totals—and should be replaced by empirically grounded PV aggregates when available to enable fuller, network-aware adequacy assessments. This volume of synthetic data allowed us to analyze scenarios that are beyond the currently available data, while still remaining grounded in reality. Matching existing PV generation with appropriate ESS installations extends the availability of renewable energy to consumers on the grid significantly beyond the point in which the sun has already set beyond the horizon.

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Abbreviations

The following abbreviations are used in this manuscript:

BESS	Battery energy storage system
PVPP	Photovoltaic power plant
EES	Energy storage system
RPI/PI	Regulated Parcel Identifier/Parcel Identifier
ENTSO-E	European Network of Transmission System Operators for Electricity
ESO	Electricity System Operator
NCCD	National Construction Control Directorate
SDA	Spatial Development Act
DSO/TSO	Distribution System Operator/Transmission System Operator
AC	Alternating current
DC	Direct current
PF	Power factor
LCOS	Levelized Cost of Storage
IBEX	Independent Bulgarian Energy Exchange
O&M	Operation and maintenance
CAPEX	Capital expenditures

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