BESS Sizing for Industrial Prosumers: A Grid-Dependency-Oriented Comparison of Combination-Based and Target-Oriented Approaches

Ahmet Korkmaz
Institute of Science)
Karamanoglu Mehmetbey University
Karaman, Türkiye
korkmaza956@gmail.com

Ümit Cetinkaya
Turkish Electricity Transmission
Ankara, Türkiye
u.cetinkaya28@gmail.com

Seda Kul
Electrical and Electronics Engineering
Karamanoglu Mehmetbey University
Karaman, Türkiye
sedakul@kmu.edu.tr

Ramazan Bayindir
Electrical and Electronics Engineering
Faculty of Technology
Gazi University
Ankara, Türkiye
bayindir@gazi.edu.tr

***Abstract*—This study investigates the sizing of a battery energy storage system (BESS) for a photovoltaic (PV)-integrated industrial facility using two complementary approaches, driven by one year of real-world hourly consumption and generation data. Initially, a combination-based approach evaluates battery power ratings and 2–4 hour duration capacities based on the annual hourly distribution of surplus generation exported to the grid. These predefined capacities are subsequently analyzed using a goal-oriented, rule-based, iterative energy-balancing model. In the iterative approach, the upper bound of the battery's energy capacity is defined to maximize the self-consumption of excess solar generation, thereby mitigating grid feed-in. The analysis reveals that grid dependency, which is 50.59% in the reference case without storage, is reduced to 12.28% under the optimal combination-based configuration (600 kW / 2400 kWh), while the self-sufficiency rate increases to 87.72%. Furthermore, the solar self-consumption rate demonstrates significant improvement over the 15.90% baseline observed without storage. Conversely, the iterative approach reveals that an energy capacity of approximately 436.8 MWh is required to achieve zero grid export, demonstrating that targeting complete surplus energy recovery in industrial prosumers with high PV generation can lead to severe system oversizing. Ultimately, these findings quantitatively illustrate diminishing returns across all evaluated configurations, highlighting that optimal BESS sizing must holistically balance minimal grid dependency with capacity feasibility, self-sufficiency, and marginal utility.**

Keywords*—*BESS sizing, solar energy system, industrial prosumer, grid dependency, self-sufficiency, rule-based operation, residual load analysis.

I. Introduction

With the growing interest in renewable energy sources and ongoing cost reductions, photovoltaic (PV) systems have become a pivotal tool for industrial consumers seeking to reduce energy costs and limit grid reliance [1]. However, the intermittent and time-dependent nature of PV generation leads to a temporal mismatch between production and load profiles at the hourly level. This structural mismatch renders standalone PV investments insufficient to ensure complete grid independence [2], [3]. This paradox is particularly pronounced in industrial facilities where total annual solar power generation significantly exceeds consumption: the facility is forced to export surplus generation to the grid while simultaneously drawing power from the grid during non-generation hours. Battery energy storage systems (BESS) directly address this temporal mismatch by storing surplus PV generation and shifting it to periods of energy deficit, thereby reducing grid imports and enhancing both self-consumption and self-sufficiency [4], [5]. Nevertheless, realizing these benefits heavily depends on selecting the optimal power rating and energy capacity. An undersized BESS fails to adequately capture surplus generation, whereas an oversized BESS yields diminishing marginal technical contributions, rendering it economically and operationally inefficient [1], [6]. Described in the literature as the diminishing returns effect, it is well documented that the additional utility beyond a specific capacity threshold systematically declines, irrespective of load profile characteristics [7], [8].

Research on BESS sizing has predominantly evolved around two methodological paradigms. Optimization-based approaches utilize mathematical programming methods such as mixed-integer linear programming (MILP), distributionally robust optimization (DRO), genetic algorithms (GA), and particle swarm optimization (PSO). For instance, the study in [1] developed a MILP-based total cost of ownership (TCO) minimization model for low-voltage grids in South Africa, demonstrating that optimal sizing could reduce grid imports by up to 30% and mitigate renewable energy curtailment by 15%. The authors of [2] determined the optimal BESS capacity for distribution systems, considering wind and PV uncertainties via a DRO approach; similarly, [9] demonstrated that systematic energy management can be achieved utilizing linear decision rules. Furthermore, [9] investigated BESS sizing via MILP across various electricity market structures and ownership models, revealing that market dynamics directly govern optimal capacity. Providing foundational design guidelines, [10] compiled specifications for Li-ion

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battery systems across diverse grid applications, establishing a key reference point in the field.

The second paradigm, comprising simulation and rule-based approaches, offers a transparent and interpretable framework grounded in hourly energy balancing models [11]. Beck et al. investigated the impact of different temporal resolutions on PV-BESS sizing and self-consumption calculations, concluding that hourly profiles provide sufficient accuracy for sizing analyses [8]. Alpízar-Castillo et al. developed an open-source model that quantifies energy flows in PV-BESS configurations for peak shaving and self-consumption enhancement, validating its utility as a reference tool during the design phase [11]. Ciocia et al. examined the interaction among grid export constraints, self-sufficiency, and BESS capacity; corroborating this, Rana et al. demonstrated that marginal utility systematically decreases beyond a certain threshold, providing a comprehensive evidence base for the diminishing returns effect [7]. Furthermore, Rana et al. developed the Semi-Linear Iterative Formula (SLIF) method for peak-shaving applications in regional distribution networks, demonstrating that this analytical approach yields superior results with a lower computational burden than GA, PSO, and MILP techniques [6]. Kesküla et al. compared heuristic, profile-based, and hourly simulation models for export-restricted Estonian residential buildings within a multi-criteria decision analysis framework, demonstrating the superior reliability of simulation-based approaches [12]. Martins et al. addressed BESS peak shaving sizing using real industrial load profiles via linear programming, emphasizing that hourly energy balance simulations strike an effective compromise between computational efficiency and accuracy [13]. Spaeth et al. established the methodological foundations of the PV-BESS combinatorial scanning method for balcony-scale PV systems [14]. Finally, Oudalov et al. presented one of the pioneering studies in this domain by optimizing BESS sizing and operating strategies employing the dynamic programming method [15].

A review of the existing literature reveals a lack of comprehensive BESS sizing frameworks tailored to industrial prosumers in which annual PV generation significantly exceeds consumption. In such configurations, the primary design metrics are grid dependence, self-sufficiency, and recovery of surplus generation. However, determining a practical capacity range and quantitatively demonstrating the risk of oversizing remain critical research gaps. This study addresses these gaps through the following original contributions:

(i) residual load profile analysis and baseline scenario characterization utilizing one year of real-world hourly data;

(ii) a systematic evaluation of various BESS power and energy combinations regarding Grid Dependence (GD), Self-Sufficiency (SS), Excess Recovery Rate (ERR), and Self-Consumption Rate (SCR) indicators via an hourly rule-based energy balancing simulation;

(iii) the determination of the theoretical upper capacity limit and the explicit quantification of oversizing risks through an iterative approach aimed at a zero-export target; and

(iv) the quantitative demonstration of the diminishing returns effect across all evaluated configurations.

II. Data Definition and Methodology

A. Dataset and Residual Load Definition

This study utilizes empirical data spanning a full year (8760 hours) with an hourly resolution, representing the consumption and PV generation profiles of a PV-integrated industrial facility. The hourly load profile is denoted by L_t (kWh), and the simultaneous PV generation is denoted by PV_t (kWh). As demonstrated by Beck et al., an hourly temporal resolution provides sufficient accuracy for sizing analyses in PV-BESS applications [8]. The hourly difference between PV generation and load demand is defined as the residual load, R_t:

$$R_t = L_t - PV_t \tag{1}$$

During periods when $R_t > 0$\$, the facility experiences an energy deficit and draws power from the grid. Conversely, when $R_t < 0$, PV generation exceeds the load demand; this surplus energy can either be stored in the BESS or exported to the grid [11]. A systematic analysis of the load profile on both a monthly and daily basis provides the foundation for identifying viable BESS power and energy capacity candidates. Through this preliminary analysis, the periods of concentrated PV surplus, typical charging power requirements, and key power-energy combinations are determined.

B. Performance Metrics

Four key technical performance metrics are evaluated for each BESS configuration. These indicators align with the analytical framework established by Ciocia et al. regarding self-consumption and self-sufficiency [7], as well as the PV-BESS energy flow model formulated by Alpízar-Castillo et al. [11].

- Grid Dependence (GD): Defines the ratio of total annual energy imported from the grid to the total annual load demand. A lower GD value signifies enhanced grid independence:

$$GD = \frac{\sum_t E_t^{grid-import}}{\sum_t L_t} \times 100 \tag{2}$$

- Self-Sufficiency Ratio (SS): Indicates the proportion of the total load demand satisfied by on-site resources (i.e., direct PV generation and BESS discharge). It serves as the complement to Grid Dependence:

$$SS = 100 - GD \tag{3}$$

- Excess Recovery Rate (ERR): Demonstrates the fraction of surplus PV generation—which would otherwise be exported to the grid in the baseline scenario—that is successfully captured and utilized on-site via the BESS. Here, E_{base}^{export} represents the total energy exported without storage, and E_{BESS}^{export} denotes the residual export after BESS integration:

$$ERR = \frac{E_{base}^{export} - E_{BESS}^{export}}{E_{base}^{export}} \times 100 \quad (4)$$

- Self-Consumption Rate (SCR): Represents the share of total PV generation that is utilized on-site, serving as a complementary metric that quantifies the temporal synchrony between generation and load profiles. Specifically, it accounts for the PV energy consumed directly without grid export during periods when $PV_t \leq L_t$

$$SCR_{base} = \frac{86{,}648.52}{544{,}801.56} \times 100 = 15.90\% \quad (5)$$

C. BESS Sizing Approaches

Two complementary BESS sizing methodologies are employed in this study. Drawing upon the findings from the preliminary load analysis, power ratings of 400 kW, 500 kW, and 600 kW, paired with storage durations of 2, 3, and 4 hours, are identified as the primary capacity candidates. Consequently, nine distinct configurations are formulated within the combinatorial screening approach [13], [14], an established methodology for PV-BESS sizing in the literature. The BESS energy capacity E_{BESS} is calculated as follows:

$$E_{BESS} = P_{BESS} \times h \quad (6)$$

- Approach 1: Combinatorial Screening-Based Sizing: Each of the nine BESS power-energy configurations is independently evaluated through an 8760-hour annual simulation, utilizing the rule-based operational model detailed in Section D. By testing all configurations under identical operational rules and datasets, this method ensures a robust and unbiased comparative analysis regarding both technical performance and practical feasibility. This approach rigorously aligns with the methodological frameworks established by Spaeth et al. [14] and Martins et al. [13].

- Approach 2: Goal-Oriented Iterative Sizing: To achieve a strict zero-export target (i.e., completely eliminating the grid feed-in of surplus PV generation), the BESS capacity is iteratively expanded. An annual simulation is executed with an initial capacity; the residual grid export is then evaluated. If the target is not satisfied, the process iterates by incrementally increasing the power rating or energy capacity. It should be noted that this approach is not intended to yield a practical system design; rather, it is implemented to explicitly reveal the theoretical upper bound of the required capacity and to quantitatively illustrate the risks associated with severe system oversizing.

D. Rule-Based BESS Operation Model

Both sizing approaches employ the rule-based energy balancing operational strategy outlined by Alpízar-Castillo et al. [11] and Rana et al. [6]. The hourly energy balance is governed by the following equation:

$$L_t = PV_t + E_t^{BESS} + E_t^{grid} \quad (7)$$

The charging and discharging operational rules are formulated as follows:

- Charging Rule: During periods when $PV_t > L_t$ ($R_t < 0$), the surplus PV generation charges the BESS. The charging power is constrained by the maximum BESS power rating (P_{BESS}) and the available capacity within the State of Charge (SoC) limit.
- Discharging Rule: During periods when $L_t > PV_t$ ($R_t > 0$), the BESS discharges to compensate for the energy deficit. The discharging power is similarly constrained by P_{BESS} and the available energy down to the minimum SoC limit.
- SoC Constraints: The operational limits are set at SOC_{min} = 5% and SOC_{max} = 95%. These boundaries are established to prevent deep discharging and overcharging states, thereby mitigating capacity degradation and preserving the cycle life of the Li-ion battery [10].

Based on these operational states, the hourly grid import (energy drawn) and grid export (energy fed in) are computed using the subsequent equations:

$$E_t^{grid-import} = \max(0, L_t - PV_t - E_{BESS}^{discharge}) \quad (8)$$

$$E_t^{grid-expoer} = \max(0, PV_t - L_t - E_{BESS}^{charge}) \quad (9)$$

Compared to mathematical optimization techniques, this rule-based operational approach significantly reduces computational complexity while yielding transparent and verifiable outcomes under real-world industrial load profiles [11]. The annual performance metrics, GD, SS, ERR, and SCR, are subsequently evaluated iteratively across the full 8760-hour simulation horizon using the defined equations.

III. Results

This section presents a comparative analysis of the two proposed BESS sizing methodologies, evaluating their respective impacts on the industrial prosumer's Grid Dependence (GD), Self-Sufficiency (SS), Excess Recovery Rate (ERR), and Self-Consumption Rate (SCR).

A. Baseline Scenario: Analysis Without Storage

In the baseline scenario without storage, PV generation primarily supplies the instantaneous load demand. Any generation exceeding the load is exported to the grid, whereas during periods of insufficient generation, the facility imports power from the grid. Under these conditions, the total annual load demand is recorded as E_{load} = 175,380.84 kWh, and the total annual PV generation stands at E_{PV} = 544,801.56 kWh. An analysis of the residual load profile, calculated via Equation (1), reveals that PV generation substantially exceeds load demand for a considerable portion of the 8760-hour horizon, resulting in systematically high export volumes. Specifically, the annual energy imported from the grid in the absence of a BESS is $E_{base}^{grid-import}$ = 88,732.32 kWh, while the surplus PV generation exported to the grid amounts to E_{base}^{export} = 458,153.04 kWh. Based on these energy flows, the baseline Grid Dependence (GD) and Self-Sufficiency (SS) rates are established as follows:

$$GD_{base} = \frac{88{,}732.32}{175{,}380.84} \times 100 = 50.59\%$$

$$SS_{base} = 100 - GD_{base} = 49.41\%$$

Consequently, the baseline Self-Consumption Rate (SCR) is calculated as:

$$SCR_{base} = \frac{86{,}648.52}{544{,}801.56} \times 100 = 15.90\%$$

This outcome reveals that only 15.90% of the generated PV energy is used on-site. Given that the total annual PV generation is approximately 3.1 times the annual load demand, this profound structural mismatch inherently drives massive grid export volumes, thereby underscoring a significant risk of BESS oversizing during the system design phase.

B. Combinatorial Sizing Results and Performance Evaluation

Drawing upon the power dynamics observed during periods of high surplus generation in the preliminary load analysis, BESS power ratings of 400, 500, and 600 kW were selected. These ratings were subsequently paired with storage durations of 2, 3, and 4 hours to formulate the nine distinct configurations detailed in Table I.

TABLE I. BESS POWER AND ENERGY CAPACITY COMBINATION MATRIX

Power Rating	2 hours	3 hours	4 hours
400 kW	800 kWh	1200 kWh	1600 kWh
500 kW	1000 kWh	1500 kWh	2000 kWh
600 kW	1200 kWh	1800 kWh	2400 kWh

For each configuration, a full 8760-hour annual simulation was executed independently, and the corresponding performance metrics were evaluated. The quantitative results of these simulations are summarized in Table II.

TABLE II. ANNUAL PERFORMANCE METRICS ACROSS EVALUATED BESS CONFIGURATIONS

Power (kW)	Period (h)	E_BESS (kWh)	GD (%)	SS (%)	Grid Import (kWh)	Grid Export (kWh)	ERR (%)	ΔGD (pp)
400	2	800	16,26	83,74	28.514,88	397.935,60	13,14	34,33
400	3	1200	14,11	85,89	24.754,44	394.175,16	13,96	36,48
400	4	1600	12,96	87,04	22.736,40	392.157,12	14,40	37,63
500	2	1000	15,11	84,89	26.493,72	395.914,44	13,58	35,48
500	3	1500	13,12	86,88	23.006,40	392.427,12	14,35	37,47
500	4	2000	12,51	87,49	21.947,04	391.367,76	14,58	38,08
600	2	1200	14,11	85,89	24.754,44	394.175,16	13,96	36,48
600	3	1800	12,72	87,28	22.307,04	391.727,76	14,50	37,87
600	**4**	**2400**	**12,28**	**87,72**	**21.530,28**	**390.951,00**	**14,67**	**38,31**

A comprehensive evaluation of Table II reveals three primary findings. First, the integration of a BESS demonstrates a profound reduction in grid dependence: the GD metric, which stood at 50.59% in the baseline scenario without storage, is reduced to 12.28%–16.26% across the evaluated configurations. This represents a substantial improvement of 34-38 percentage points (pp), irrespective of the specific combination.

Second, the Excess Recovery Rate (ERR) remains constrained to a narrow band of 13%–15%. This limitation is fundamentally driven by the system's structural imbalance, where annual PV generation (E_{PV}) equates to approximately 3.1 times the annual load demand (E_{load}). Consequently, the vast majority of the export volume fundamentally exceeds the storage capacity of any practically sized BESS. Therefore, improvements in GD and SS metrics must be evaluated independently of the ERR metric.

The third and most critical finding is the quantitative manifestation of the diminishing returns effect. The technical utility gained from incrementally increasing capacity is decidedly non-linear. This asymptotic behavior is consistently observed across all three power ratings. For instance, at the 400 kW power rating, increasing the storage duration from 2 to 3 hours yields a 2.15 pp improvement in GD, whereas the subsequent transition from 3 to 4 hours yields only a 1.15 pp gain. At 500 kW, these marginal gains shrink to 2.60 pp and 0.61 pp, respectively; and at 600 kW, they further diminish to 1.39 pp and 0.44 pp. Consequently, extending the storage duration yields progressively smaller marginal technical benefits at each step, a trend similarly mirrored when scaling the power capacity.

From a practical design perspective, the comparison between the maximum-capacity configuration (600 kW / 2400 kWh) and a mid-range configuration (400 kW / 1200 kWh) is particularly illuminating. Doubling the energy capacity from 1200 kWh to 2400 kWh mitigates grid dependence by a marginal 1.83 pp (from 14.11% to 12.28%). This profoundly modest enhancement seriously calls into question the economic viability and practical justification of deploying such an oversized system. Thus, the 400 kW / 1200 kWh configuration emerges as an optimal, pragmatic design candidate that strikes an effective balance between high technical performance and capacity feasibility.

These comparative insights are summarized in Table III.

TABLE III. COMPARATIVE ANALYSIS OF BASELINE, COMBINATORIAL, AND ITERATIVE SIZING APPROACHES

Scenerio	P_BESS (kW)	E_BESS (kWh)	GD (%)	SS (%)	ERR (%)	Grid Import (kWh)	Grid Export (kWh)
Baseline (ref)	0	0	50,59	49,41	0,00	88.732,32	458.153,04
Combination- best technique	**600**	**2.400**	**12,28**	**87,72**	**14,67**	**21.530,28**	**390.951,00**
Iterative rule-based approach	~410	~436.800	8,93	91,07	~100	15.669,96	~0

As detailed in Table III, the optimal combinatorial configuration (600 kW / 2400 kWh) reduces Grid Dependence (GD) to 12.28%, a substantial 38.31 percentage-point reduction relative to the baseline scenario. However, the annual grid export volume only decreases from 458,153.04 kWh to 390,951.00 kWh. This marginal reduction corresponds to an Excess Recovery Rate (ERR) of merely 14.67%. This constrained recovery highlights an unavoidable

limitation imposed by the structurally high PV-to-load ratio, demonstrating that significant enhancements in grid independence are achieved through operational mechanisms rather than by reducing bulk export.

Conversely, the findings derived from the goal-oriented iterative approach starkly illustrate the severe risks of system oversizing. To achieve a strict zero-export target, the required BESS energy capacity increases to approximately 436,800 kWh, exceeding the facility's total annual load demand (175,380.84 kWh) by a factor of 2.5. Such a capacity requirement is fundamentally unfeasible from both technical and economic standpoints. Consequently, this unequivocally proves that eliminating exports cannot serve as a primary sizing objective for industrial prosumers with high PV-to-load ratios. Ultimately, this study establishes a quantitative theoretical upper bound on BESS capacity in a PV-dominant industrial context, thereby conclusively validating the impracticality of zero-export design paradigms.

IV. Conclusion

This study investigated Battery Energy Storage System (BESS) sizing for an industrial prosumer whose annual PV generation significantly exceeds its load demand, using two complementary sizing methodologies. The primary conclusions are summarized as follows:

- Substantial Reduction in Grid Reliance: Grid Dependence (GD), which stood at 50.59% in the baseline scenario without storage, was successfully curtailed to 12.28% under the optimal combinatorial configuration (600 kW / 2400 kWh), concurrently elevating the Self-Sufficiency (SS) rate to 87.72%.
- Quantification of the Diminishing Returns Effect: A pronounced diminishing returns effect was observed across all evaluated configurations; the marginal technical utility derived from incremental capacity expansions systematically declined.
- Identification of a Pragmatic Design: The 400 kW / 1200 kWh configuration emerges as a highly pragmatic design candidate. Despite deploying only half the energy capacity of the maximum configuration, its GD performance lags by a mere 1.83 percentage points, striking an optimal balance between technical efficacy and economic feasibility.
- Impracticality of Zero-Export Targets: The goal-oriented iterative analysis demonstrated that an exorbitant capacity of approximately 437 MWh is required to achieve a complete zero-export state. This definitely proves that the complete elimination of exports is an infeasible primary sizing objective for industrial prosumers with significant generation surpluses.
- Structural Constraints on Export Recovery: The Excess Recovery Rate (ERR) remained tightly constrained between 13% and 15%, indicating that a structurally high PV-to-load ratio fundamentally restricts bulk export recovery, decoupling it from improvements in grid independence.

Future research should explore the generalizability of this framework by incorporating BESS capacity degradation models, dynamic electricity tariff structures, and a broader spectrum of industrial load profiles with varying PV-to-load ratios.

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