AI-Based Control Strategy And Systematic Review For Industrial Peak Shaving Using Hybrid Solar PV And Battery Energy Storage Systems (BESS) In Uzbekistan

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***Abstract*— Rapid industrialization and evolving energy policies in Uzbekistan require sustainable solutions to manage electricity demand, especially during peak periods. This study explores the potential of hybrid solar photovoltaic (PV) and battery energy storage systems (BESS) to implement effective peak shaving in large industrial plants. Through detailed statistical analysis of minute-by-minute load profiles, this study identifies key demand characteristics and develops an AI-based control strategy to optimize BESS operations. The proposed system integrates external factors such as solar radiation, temperature, and dynamic tariffs with internal operational parameters to enable intelligent scheduling of battery charging and discharging. The results demonstrate significant improvements in load management, including a 400 kWh reduction in daily peak-period consumption and a 44 % decrease in peak-hour electricity payments, compared with the base case. Furthermore, this study contributes to a replicable methodology for optimizing industrial energy in developing countries transitioning to decarbonization and renewable energy integration.**

Keywords—Battery Energy Storage System, Industrial Peak Shaving, Hybrid Systems, Demand Response, Artificial Intelligence, Load Profile Analysis, Dynamic Tariff, Smart Grid, Energy Management System, Uzbekistan Energy Strategy

I. Introduction

Due to the continuous growth of the global population's living standards and the rapid expansion of the industrial sector, a significant increase in electricity demand is projected worldwide. Electric load refers to the power consumption of electricity users. Based on their consumption characteristics, electricity consumers are typically categorized into industrial, construction, agricultural, transportation, and residential sectors. By 2040, global electricity demand is expected to grow annually by approximately 2.1%, with around 90% of total consumption predicted to be attributed to the industrial and construction sectors [1].

To meet this rising demand, increased reliance on non-renewable energy sources could result in severe environmental degradation. Consequently, energy systems across the globe are undergoing a profound transition toward low-emission and renewable energy sources. Studies show that a 1% increase in electricity generation from renewable sources can reduce CO_2 emissions by approximately 0.35% [2].

Specifically, Uzbekistan has committed to reducing climate-related emissions by 45% by 2030 and achieving net-zero emissions by 2050, in alignment with the Paris Agreement. In this regard, the national "Energy Supply Concept for 2019–2030" outlines strategies to ensure energy sustainability, security, and equity through the integration of renewable energy sources [1,3]. According to the concept, the target is to generate 11.8 GW of electricity from renewable sources by 2030.

However, to ensure a successful energy transition, grid operators must be equipped with enhanced network management capabilities. Traditionally, these operators relied on the integration of additional units in thermal power plants to balance load fluctuations. Nevertheless, in electricity grids with a high share of renewable energy sources, novel approaches to enhance network flexibility become crucial.

Among the major sectors comprising the electric load, industrial enterprises remain the largest energy consumers and offer the greatest potential for load balancing. Many researchers have emphasized that implementing demand response programs within industrial facilities can significantly optimize energy consumption, thereby contributing meaningfully to reducing overall grid load levels .Industrial demand-side management is typically implemented through various strategies, the main strategies of load management are listed below [4].

Peak shaving – reducing electricity consumption during periods of maximum demand to lower peak load and avoid high tariff charges.

Load shifting – transferring energy-intensive operations from peak to off-peak periods when tariffs are lower.

Valley filling – increasing consumption during off-peak periods to maintain a stable load profile.

Load leveling – smoothing demand over time by combining peak shaving and valley filling to minimize fluctuations.

Demand response (DR) – adjusting or curtailing consumption in response to real-time price signals or grid conditions.

According to the International Energy Agency (IEA), many industrial enterprises remain insufficiently aware of the flexibility potential offered by distributed generation (DG) systems and the economic benefits that can be achieved through their effective utilization within demand response programs [5]. Consequently, the continuous identification and quantitative assessment of energy flexibility opportunities in industrial facilities has become a critical priority. Furthermore, the country's current alignment with global development trends alongside the evolving geopolitical landscape, supply chain disruptions, reduction in fossil fuel dependence, and the need to minimize environmental impacts has led to new strategic decisions. Notably, the government has issued a resolution aimed at increasing the share of renewable energy utilization within enterprises to 30%.

In line with Uzbekistan's energy supply concept, which targets increasing the share of renewable energy to 20% by 2025 and 30% by 2030, the National Integrated Development Model 2030 (NIDM 2030) has also been tasked with advancing industrial decarbonization and the promotion of green manufacturing practices [1].

This study aims to develop and validate an AI-based control strategy for industrial peak-shaving with a hybrid solar PV and battery energy storage system (BESS) under Uzbekistan's time-of-use tariff.

The work reviews existing PV–BESS peak-shaving methods, designs an AI-driven scheduling algorithm using day-ahead PV forecasts and industrial load data, and tests the strategy on real operating data to quantify reductions in peak demand and electricity cost.

II. IMPROVING RENEWABLE ENERGY SOURCE

Among the five key strategic directions for improving the national electricity supply system, the fifth direction emphasizes the expansion, development, and integration of renewable energy sources (RES) into the unified power grid. As a result, the share of RES implemented through public-private partnership (PPP) mechanisms has been rapidly increasing [1]. Figure 1 illustrates the growth dynamics of PPP-based renewable energy projects during the first six months of 2024.

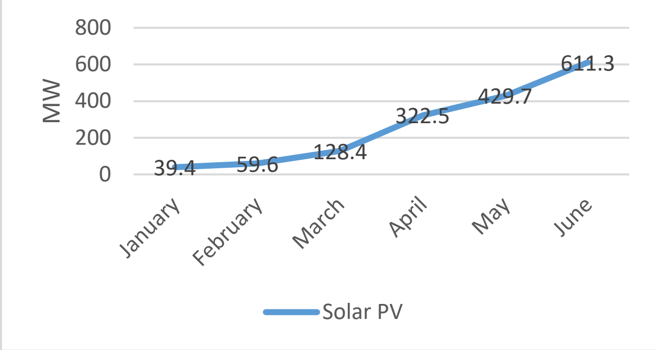

Figure 1. Growth of Installed Solar PV Capacity Growth in the First Six Months of 2024.

This graph illustrates the growth trajectory of renewable energy sources, specifically the commissioning of solar power plants under public-private partnership (PPP) frameworks during the first half of 2024. The rapid increase after 2020 is primarily driven by government incentives for solar deployment, falling PV module costs, and large-scale renewable energy programs in Uzbekistan. In January 2024, the newly commissioned solar power capacity amounted to 39.4 MW. By February, this figure increased to 59.6 MW. A notable surge occurred in March, reaching 128.4 MW. The growth trend continued in April, with the capacity rising to 322.5 MW. In May, this figure further increased to 429.7 MW, and in June, the installed capacity peaked at 611.3 MW—representing almost a 16-fold increase compared to January.

These strategic developments are part of broader national energy initiatives, which include the deployment of photovoltaic (PV) systems, battery energy storage systems (BESS), and demand response (DR) programs. DR strategies involve adjusting electricity consumption during peak demand periods to provide flexibility services and reduce the reliance on conventional generation sources [6].

Uzbekistan's peak shaving strategies are increasingly being reinforced through the use of differentiated electricity tariffs. These tariff structures are designed to incentivize reduced consumption during peak periods, thereby minimizing the need for additional energy generation and promoting sustainable energy use [7]. However, from the demand-side perspective, identifying and addressing barriers remains equally important to maximize the potential of these strategies [8].

Consequently, numerous researchers have investigated diverse approaches to peak shaving, including hybrid energy storage systems, intelligent energy management systems [9], improvements in pumped hydroelectric storage, and the integration of renewable energy sources into the power grid.

III. ENERGY DEMAND SCENARIO IN UZBEKISTAN

Uzbekistan's industrial sector encompasses a wide range of activities, including manufacturing, mining, metallurgy, and construction materials production. In 2022, more than 28.5% of the country's gross domestic product (GDP) was generated by the industrial sector, which also significantly contributes to the nation's overall industrial output and exports [10]. This sector is currently the largest electricity consumer in the country. Electricity pricing for industrial consumers typically includes a combination of fixed and variable charges. Until 2024, industrial enterprises operated under time-differentiated tariff systems and paid for electricity consumption according to hourly demand profiles [11]. These tiered tariffs aimed to optimize electricity usage by encouraging reductions during peak demand periods, particularly in large-scale industrial facilities [12]. However, based on the Resolution No. 204 issued by the Cabinet of Ministers of the Republic of Uzbekistan on April 16, 2024, titled "On Additional Measures for the Introduction of Market Mechanisms in the Fuel and Energy Sector," the pricing structure for electricity consumption was revised by the Regional Electric Networks JSC, effective from May 1, 2024. The updated tariff structure is presented in Table 1 [13].

TABLE I. CHANGES IN ELECTRICITY TARIFF RATES IN THE REPUBLIC OF UZBEKISTAN

№	Consumer Group and Category	Tariff (UZS/kWh)
1.1.	Group I & II consumers: a) Almalyk Mining and Metallurgical Complex JSC, Navoi Mining and Metallurgical Complex JSC, Uzbekistan Metallurgical Plant JSC and its subsidiaries, budget-funded organizations, and the portion of electricity consumed by pumping stations financed by the state budget б) All other consumers	1000 900
1.2.	Group III consumers, including households:	600
1.2.1.	Households equipped with centralized electric stoves in multi-apartment residential buildings and dormitories: - Up to 200 kWh per month - 201 to 1,000 kWh per month - 501 to 1000 kWh per month - 1,001 to 5,000 kWh per month - 5,001 to 10,000 kWh per month - Above 10,000 kWh per month	 300 400 500 750 875 1000
1.2.2.	All other residential consumers, based on monthly consumption: - Up to 200 kWh per month - 201 to 500 kWh per month - 501 to 1000 kWh per month - 1,001 to 5,000 kWh per month - 5,001 to 10,000 kWh per month - Above 10,000 kWh per month	 600 800 1000 1500 1750 2000
1.3.	fourth group consumers:	900

However, in accordance with the Presidential Decree of the Republic of Uzbekistan on "Measures to Ensure the Rational Use of Energy Resources," consumers connected to capacities of 750 kVA and above (excluding budgetary organizations, pumping stations of farmers' associations and water consumers' unions, as well as pumping stations financed by the State Budget) are subject to a differentiated tariff schedule based on the time of day. These consumers are charged according to the second-group tariffs applicable to legal entities [14].

Under this scheme, electricity consumed during peak hours of the day designated as the morning and evening maximum load periods, defined according to established regulations is subject to a 1.5x increasing coefficient applied to the standard tariff. In contrast, electricity consumed during off-peak hours (typically nighttime or dark hours) is billed with a 1.5x decreasing coefficient. During mid-load hours (daylight hours), the standard tariff is applied without modification [14].

In industrial enterprises, electricity costs incurred during peak periods have historically accounted for 30% to 70% of the total electricity payment. This significantly increases energy-related expenditures [15]. Therefore, an increase in the scale of production may lead to a corresponding rise in maximum demand charges. The growing electricity consumption during peak hours emphasizes the need for innovative approaches to ensure energy balance and maintain system stability.

IV. DEFINITION AND CONCEPT OF PEAK SHAVING

Peak shaving refers to the reduction of electricity consumption during periods of maximum demand. It is one of the key strategies for achieving stability in the power supply system. With the sharp increase in the integration of renewable energy sources, particularly solar photovoltaic (PV) systems in industrial enterprises, a combined approach involving battery energy storage systems (BESS) and demand response (DR) mechanisms is regarded as an ideal solution for industrial peak shaving.

During daylight hours, solar PV panels generate electricity, which is either directly consumed by the enterprise or stored in batteries. In peak demand periods or during sudden spikes in electricity consumption the stored energy is utilized to meet the enterprise's internal energy needs, thus reducing its load on the national power grid.

Demand response programs help manage electricity consumption by encouraging users to reduce or shift their energy usage during critical periods. However, it is important to note that the output of solar PV systems is directly dependent on solar irradiance levels [16].

In Uzbekistan, the average daily solar irradiance ranges between 4400–4700 W/m², with an annual solar energy potential of 1643 kWh/m². As such, PV systems are expected to play a vital role in the country's energy transition by 2050, potentially providing up to 10 GW of capacity and covering approximately 30% of total electricity demand by 2030 [1].

According to Uzbekistan's Energy Supply Concept, solar PV systems are expected to meet only about 10% of peak electricity demand by 2025. Therefore, the implementation of Battery Energy Storage Systems (BESS) is considered essential to support the development of grid infrastructure and improve system resilience.

Currently, BESS has become a highly discussed topic in Uzbekistan's energy sector. Moreover, BESS solutions are considered economically feasible for buildings of various sizes, regardless of the uncertainty in electricity demand patterns. The growing interest in sustainable and renewable energy solutions has led to increased attention toward analyzing the performance, feasibility, and integration potential of such technologies [17].

Due to the need for stable and continuous energy supply in industrial facilities, implementing real-time demand-side management interventions can be complex. To our knowledge, no comprehensive review exists that integrates practical findings and systematic analysis on the implementation of industrial peak shaving in a real industrial setting in Uzbekistan. This study aims to fill that gap by providing both a systematic review and a case-based demonstration of effective peak shaving for industrial consumers with capacities exceeding 750 kVA.

V. Contribution of This Work

Systematic review of industrial peak-shaving methods – We provide the first structured analysis of demand-response strategies and hybrid PV–BESS control frameworks applicable to emerging economies, with a focus on Uzbekistan's rapidly evolving electricity market and tariff reforms.

Minute-level case study of a real industrial facility – Using high-resolution load data recorded every minute, we quantify the variability of an actual Uzbek industrial plant and demonstrate how hybrid PV–BESS systems can effectively reduce peak demand under the country's new dynamic tariff structure.

AI-based control strategy for hybrid PV–BESS operation – We propose a novel artificial-intelligence controller that jointly considers solar irradiance forecasts, industrial load characteristics, and time-of-use pricing to optimize battery charging and discharging, achieving significant reductions in peak load and electricity cost.

These contributions together establish a replicable methodology for industrial enterprises in developing countries to integrate renewable energy and battery storage while improving grid stability and economic performance.

Furthermore, this research contributes uniquely by establishing a framework for Industrial Peak Shaving, highlighting the key parameters and strategic considerations necessary for successful implementation in emerging economies.

Energy Storage Systems (ESS) play a vital role in enhancing load management efficiency and maintaining power system stability. These systems provide a wide range of benefits, including frequency regulation, grid balancing, and the facilitation of renewable energy integration.

By smoothing the load curve and mitigating fluctuations in electricity demand and supply, ESS contribute significantly to stabilizing the power grid. Moreover, they support economic optimization through energy arbitrage, enabling energy to be stored when prices are low and discharged when prices are high. This capability ensures a better balance between supply and demand, particularly in systems with high penetration of intermittent renewable sources.

In addition, ongoing advancements in ESS technologies continue to improve performance metrics such as efficiency, response time, lifecycle, and cost-effectiveness, thereby offering enhanced opportunities for achieving both technical and economic goals.

Numerous studies have revealed that integrating Battery Energy Storage Systems (BESS) into industrial operations enhances the controllability and planning of renewable energy generation. BESS also significantly reduces electricity costs particularly during peak demand periods by mitigating peak power charges for industrial users.

However, the selection of the appropriate battery type and capacity is a critical factor in effectively achieving peak load reduction. For instance, Stuck and his team demonstrated that lithium-ion batteries are the most widely adopted and economically efficient option when compared to redox flow batteries and lead-acid storage systems.

Conversely, research conducted by Chen et al. concluded that Valve-Regulated Lead-Acid (VRLA) batteries can be highly cost-effective and offer maximum benefit for demand management applications. Nevertheless, they noted that VRLA systems may fall short in recovering the full capital investment, and thus should not be solely chosen for the purpose of achieving peak shaving goals.

In a study conducted in China, Feng and his colleagues identified that the electricity tariff for grid consumption and the capital cost of storage infrastructure are the two most influential factors affecting the profitability of peak shaving. Furthermore, combining BESS with ancillary services such as energy arbitrage, frequency regulation, and peak shaving can maximize the utilization of battery storage benefits.

In the context of industrial demand management, two distinct Energy Management System (EMS) models are commonly employed to control battery-based energy storage systems [18].

In off-grid bidirectional models, the system operates similarly to an islanded mode in which the solar PV and battery system draw power from the grid but do not supply any power back to it. These configurations are designed for isolated or semi-isolated energy management and typically aim to maximize internal consumption.

In contrast, on-grid bidirectional models allow industrial consumers not only to draw power from the grid but also to feed stored or surplus energy back into the grid. This capability enables participation in frequency regulation mechanisms and opens opportunities for economic optimization by selling electricity back to the grid during peak demand periods.

The operational performance of a BESS depends on several factors, including the load profile, energy storage capacity, and cost components related to both power (kW) and energy (kWh).

Analytical findings indicate an inverse relationship between the storage capacity (kWh) and the power rating (kW) of a BESS in achieving peak shaving objectives. In particular, high-power systems are capable of covering large loads over short durations, thus requiring smaller storage volumes [19].

Figure 2 outlines the key factors to be considered when determining the appropriate size of a Battery Energy Storage System (BESS) for industrial peak shaving applications.

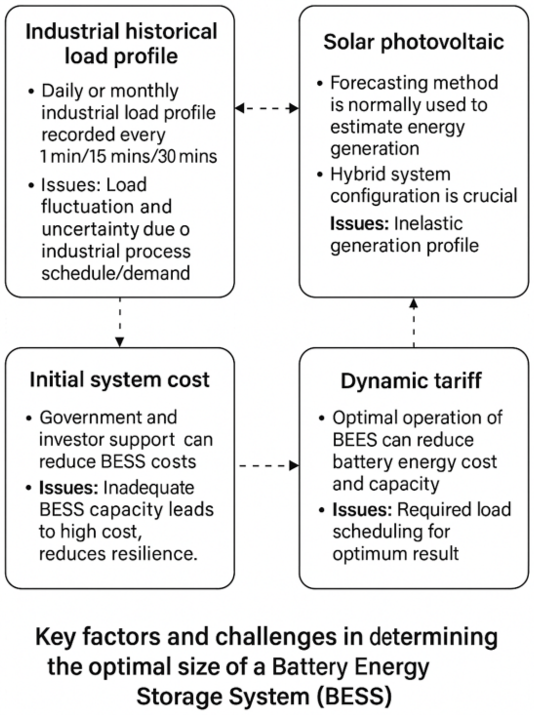

Figure 2. Key Factors and Challenges in Determining the Optimal Size of a Battery Energy Storage System (BESS).

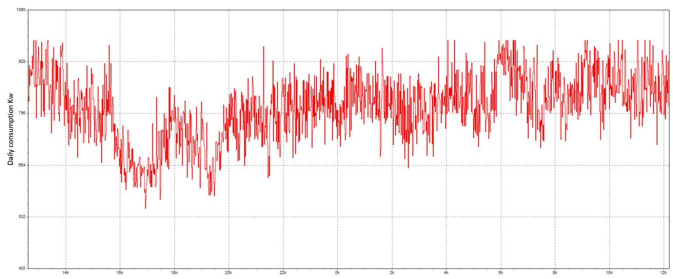

Figure 3. Daily Load Profile of the Industrial Facility.

Determining the optimal size of a Battery Energy Storage System (BESS) requires consideration of several critical factors. First and foremost, the historical electrical load data of the facility such as daily or monthly consumption profiles must be analyzed. These profiles reflect the variability of load patterns and the inherent uncertainties in the production processes. The proper sizing of BESS depends on the ability to capture periods of peak demand, optimize self-consumption, and support demand-side management strategies. A well-characterized load profile enables the identification of energy consumption peaks and helps determine the required storage duration and power rating. Figure 3 presents a representative daily load profile of an industrial facility, which serves as the baseline for evaluating the required storage capacity and performance characteristics of the BESS.

The daily load profile of the industrial facility was recorded using a Fluke-430II power quality analyzer, capturing real-time load data at 1-minute intervals. This high-resolution dataset provides critical insights into short-term fluctuations in electricity consumption and enables accurate modeling of energy storage requirements. In the proposed methodology, the optimal battery capacity is determined based on the deviation between the maximum allowable contracted power as defined in the consumption agreement with the utility company and the actual observed peak demand from the load curve. The selected battery capacity must be sufficient to supply the excess demand beyond the contract limit during peak periods, thereby ensuring compliance and avoiding overage charges.

Table II presents the statistical characteristics and coefficient of variation for the 1-minute interval power consumption time series of the analyzed industrial facility. These statistical indicators provide a foundation for understanding load volatility and designing a robust Battery Energy Storage System (BESS).

TABLE II. STATISTICAL PARAMETERS OF THE 1-MINUTE LOAD POWER TIME SERIES FOR THE ANALYZED INDUSTRIAL FACILITY

Load Metric	Unit	Value
Maximum Load	kW	983.01
Average Load	kW	811.9
Median Load	kW	814.66
Minimum Load	kW	553.17
Standard Deviation	kW	84.13
Coefficient of Variation	%	10.37

The statistical analysis of the facility's 1-minute load profile provides key insights into load fluctuation characteristics and energy demand dynamics. As shown in Table I1, the maximum observed power demand reaches 983.01 kW, while the average demand is 811.90 kW. The relatively high median value of 814.66 kW compared to the average indicates a skewed distribution, suggesting frequent high-load events.

To determine the optimal battery size for peak shaving, additional parameters such as standard deviation, variance, and coefficient of variation must be calculated. These metrics help assess the volatility of the load profile, which directly impacts the design and control strategy of the BESS.

The statistical parameters presented above offer valuable insights into the facility’s operational regime and reflect the nature of its electricity demand profile. Based on this data, the standard deviation of the daily load is used as a basis for selecting an optimal battery power rating for the BESS. This methodology assumes that the BESS should be sized to cover daily load fluctuations corresponding to one standard deviation, allowing for effective peak shaving and frequency regulation.

By implementing such demand response (DR) strategies, load variability can be significantly reduced, leading to improved power quality, enhanced voltage stability, and decreased overall energy costs. Currently, DR programs in Uzbekistan are aligned with dynamic tariff schemes, encouraging consumers to reduce peak load consumption in response to time-based electricity pricing. This approach allows industrial users to achieve substantial cost savings during critical peak demand hours.

Furthermore, the integration of BESS into DR programs has been increasing steadily among industrial consumers. Recent research also promotes the use of BESS to enhance industrial sector participation in DR schemes [20]. In particular, the combination of renewable energy sources (RES) and energy storage systems has been recognized as an optimal solution for reducing peak loads and minimizing operational costs in industrial settings.

When the system operates alongside a solar photovoltaic (PV) plant, the daily solar power forecast and generation profile must be taken into account. This increases the importance of hybrid system configurations and their operational planning.

In addition, variable electricity tariffs (e.g., time-of-use pricing) allow for optimal charging and discharging schedules of the battery, leading to reduced system costs and more accurate sizing of the storage system. If government subsidies, incentive programs, or investor support are available, the initial capital investment for the BESS can be significantly reduced. Otherwise, incorrectly sized storage systems may result in elevated operational costs and lower system efficiency.

In this study, a block diagram of an AI-based control system was developed to ensure optimal coordination of solar PV generation and BESS in an industrial facility for the purpose of peak load reduction. This control framework considers external and internal influencing factors, such as solar irradiance, load characteristics, and demand variability.

Figure 4 below illustrates the structure of the proposed intelligent control system.

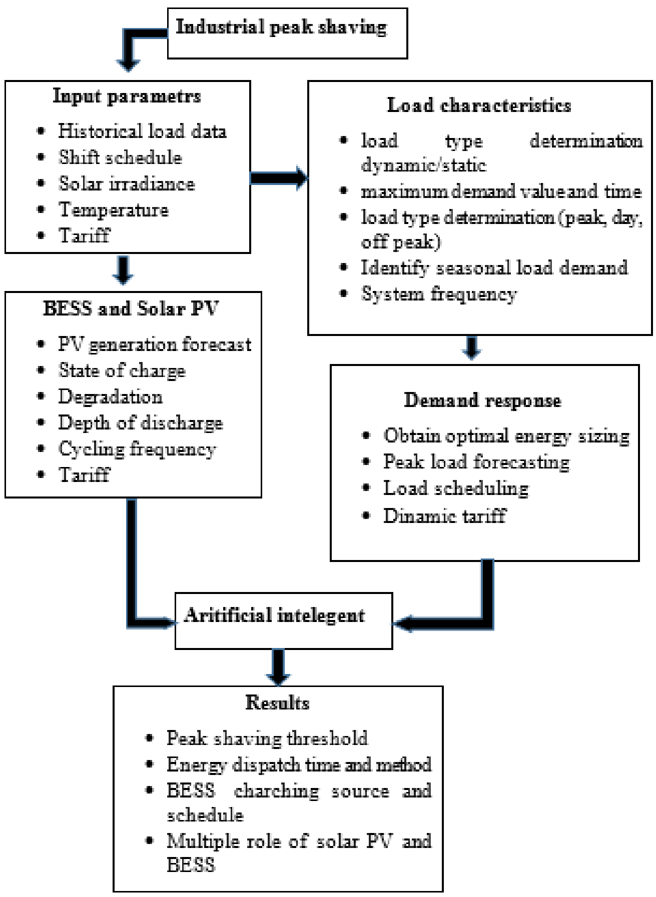

Figure 4. Block Diagram Representing the Key Parameters and Strategies for Industrial Peak Shaving.

As illustrated in the figure, the block diagram presents a comprehensive overview of critical parameters and strategic elements that are applicable to various types of industrial enterprises. This generalized framework supports decision-making processes aimed at reducing peak demand periods through the integration of energy storage, renewable generation, and smart load management.

The block diagram consists of seven key components, each contributing to the overall objective of load leveling and cost optimization. The system is designed to be adaptable across different industrial use-cases with variable load dynamics.

The process flow includes recommended steps for analyzing energy consumption, evaluating system constraints, and identifying control strategies. These steps are summarized in the table below.

TABLE III. DESCRIPTION OF THE PROPOSED FRAMEWORK FOR INDUSTRIAL PEAK SHAVING

№	Component / Stage	Description
1	Goals	Industrial peak shaving
2	Input parametrs	Historical load data, shift schedule, solar irradiance, temperature, tariff
3	Load characteristic	load type determination dynamic/static, maximum demand value and time, load type determination (peak, day, off peak), Identify seasonal load demand, system frequency
4	BESS and Solar PV	PV generation forecast, state of charge, degradation, depth of discharge, cycling frequency
5	Demand response	Obtain optimal energy sizing, peak load forecasting, load scheduling, dynamic tariff
6	Artificial intellligence	optimal control in real time
7	Results	Peak shaving threshold, energy dispatch time and method, BESS charcging source and schedule, multiple role of solar PV and BESS

VI. AI-BASED CONTROL STRATEGY FOR HYBRID PV-BESS SYSTEMS

In sizing and managing hybrid photovoltaic (PV) and Battery Energy Storage Systems (BESS), artificial intelligence (AI) plays a critical role by dynamically responding to time-varying load demand and generation uncertainties. Based on the enterprise's load dynamics and the structure of demand response programs, the AI system determines the optimal energy dispatch schedule, including the charging/discharging times and power levels for BESS, while ensuring maximum peak shaving performance.

The intelligent controller takes into account operational constraints and forecasted solar generation to coordinate energy flows between the PV array, storage units, and the industrial load. This framework supports not only optimal performance of the hybrid system but also offers a basis for cost reduction and improved grid interaction. The approach is designed to guide both researchers and stakeholders in optimizing hybrid energy systems for energy savings, load relief, and future research enhancement.

VII. RESULTS

To evaluate the effectiveness of the proposed AI-based control strategy, a one-day simulation was carried out using the measured industrial load profile from the case-study facility. A 60 kW photovoltaic (PV) plant was modelled with a typical daytime generation curve, while a 80 kW/200 kWh Battery Energy Storage System (BESS) operated under Uzbekistan's current time-of-use (TOU) tariff. An AI-based control strategy was developed to optimally manage the charging and discharging of the hybrid PV–BESS system under Uzbekistan's time-of-use tariff. The algorithm combines the day-ahead PV production forecast, the industrial load schedule, and tariff information to determine when the battery should charge from PV or from the grid and when it should discharge to support the facility during peak-price periods.

Based on these predictive inputs, the controller generated the operating schedule that is summarized in Table V.

TABLE III. AI-BASED CONTROL STRATEGY FOR INDUSTRIAL PEAK SHAVING OF THE HYBRID PV–BESS SYSTEM

Parameter	Value	Description
Total PV generation (kWh)	**311**	Day-ahead forecast of PV energy production
Night-time charging start time	**04:00**	Grid charging during low tariff hours
SOC 100 % reached (night)	**06:00**	End of night charging
Daytime PV charging start time	**10:30**	Beginning of PV-based charging
SOC 100 % reached (day)	**17:00**	End of daytime PV charging
Morning discharge window	**07:00 – 08:30**	First maximum load in peak period
Evening discharge window	**18:00 – 20:00**	Second maximum load in peak period
Energy stored in BESS (kWh)	**200**	Total energy accumulated
Charging tariffs (UZS/kWh)	**600 (night) / 900 (day)**	Rates applied during charging
Peak tariff (UZS/kWh)	**1 350**	Grid price during peak discharge
Economic effect	—	200 kWh consumed at 600–900 UZS instead of 1 350 UZS

During the next-day operation the PV plant was forecast to generate 311 kWh. According to the AI-based schedule, the BESS first charged overnight during the low-tariff period and reached full capacity by 06:00, then discharged in the early-morning peak to reduce grid demand. During the day the battery charged again from PV output starting at 10:30 and reached 100 % SOC by 17:00, after which it discharged while the PV system continued to feed the grid. Before 10:30 all PV energy was exported directly to the grid.

This two-stage strategy allowed about 200 kWh to be stored at 600–900 UZS/kWh and later discharged during the morning and evening peaks when the tariff rises to 1 350 UZS/kWh, thereby lowering grid demand and reducing daily electricity cost. As summarized in Table V, this control plan reduced the facility's daily peak-period consumption by approximately 400 kWh, which in turn lowered the electricity payment during peak hours by about 44 % compared with the base case.

These results confirm the effectiveness of the AI-based control strategy in shifting low-cost energy to high-tariff periods and significantly decreasing both peak grid demand and daily operating cost.

VIII. CONCLUSION

The key contribution of this research lies in combining a systematic review with a real-world AI-based control demonstration, providing a practical and replicable framework for optimizing hybrid PV–BESS systems in Uzbekistan's industrial sector. This study explored the capabilities of hybrid solar photovoltaic (PV) and Battery Energy Storage Systems (BESS) for effective energy management in industrial enterprises, particularly with the objective of reducing peak demand periods. Against the backdrop of increasing electricity demand due to rising living standards and industrial expansion, the need for stable, sustainable, and environmentally conscious energy strategies becomes more critical.

The analysis reveals that hybrid PV-BESS systems provide a viable alternative for mitigating peak load stress on the grid, particularly in industrial settings. Leveraging solar energy during the daytime and storing excess energy in batteries for use during high-demand periods allows for the coordinated PV–BESS operation reduced daily peak demand by about 400 kWh and lowered peak-hour payments by approximately 44 %, confirming the effectiveness of the AI-based control strategy..

Moreover, with the introduction of new electricity tariff schemes, there is an increasing need for advanced load management strategies. The coordinated operation of PV and BESS enables efficient load shifting, where excess daytime solar energy is stored and later discharged during peak hours, effectively flattening the demand curve. This study proposes an AI-based energy management framework that incorporates both external (e.g., irradiance, tariffs) and internal (e.g., load profiles, system configuration) factors. It optimizes parameters such as peak shaving thresholds, charging/discharging times, and power dispatch methods by leveraging the multi-role functionality of both PV and BESS units.

In conclusion, the results of this study provide a solid theoretical and practical foundation for the implementation of hybrid energy systems in the industrial sector. The framework contributes to cost optimization, grid stability, and can serve as a basis for developing national energy strategies, investment planning, and the design of advanced AI-driven control algorithms.

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