



ADVANCES IN APPLIED SCIENCE AND ENGINEERING TECHNOLOGIES FOR SUSTAINABLE INNOVATION AND INDUSTRIAL DEVELOPMENT

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ABSTRACT

Renewable energy management has become an important applied engineering pathway for advancing sustainable innovation and industrial development. This study analyzed a secondary Excel-based dataset on daily energy management, including photovoltaic generation, electricity consumption, energy price profiles, seasonal energy behavior, and battery state-of-charge records. A quantitative, data-driven research design was used to evaluate renewable contribution, demand-generation balance, price-sensitive sustainability opportunities, and storage utilization. After preprocessing, 8,760 hourly observations from 2023 were retained, with no missing values in the analytical fields. The results showed that annual photovoltaic generation reached 6,263,310 kWh, while annual electricity consumption reached 22,024,941 kWh, producing a renewable contribution index of 28.44%. Seasonal analysis showed the highest renewable contribution in summer at 51.53%, followed by spring at 43.06%, while winter and autumn showed lower contributions of 14.05% and 11.48%, respectively. Renewable surplus occurred during 770 hours, indicating opportunities for storage charging, load shifting, or grid export. Correlation analysis showed a weak positive relationship between photovoltaic generation and consumption and a negative relationship between energy price and photovoltaic generation. Battery state-of-charge profiles confirmed active storage behavior. Overall, integrated photovoltaic generation, demand monitoring, pricing analysis, and battery storage supported sustainable industrial energy planning and data-driven engineering innovation.

1. Introduction

The development of sustainable innovation has become a central theme of applied science and engineering, since the necessity of developing technologies that enhance the productivity of industrial systems, while simultaneously decreasing the energy intensity, environmental impact, and reliance on traditional energy sources, has become more and more important. Research in engineering now goes beyond the particular technical performance of a system, but focuses more and more on the combined utilization of systems, including renewable energy generation, storage, digital monitoring, and data-driven decision-making. This transformation is especially significant in the industrial sector, where energy security, cost efficiency, and sustainability are directly related to business competitiveness. Energy integration with renewables has therefore become a feasible path to bring technological development and sustainable economic growth together, particularly in sectors with high energy consumption and ever-growing carbon reduction pressure (Chou et al., 2023).

Renewable energy technologies have come a long way from being used as power sources for the “supplementary” energy supply to playing a major role in modern energy systems. The use of photovoltaic generation, battery storage, and intelligent energy-management solutions is now being explored as engineering solutions for enhancing energy efficiency and system resilience. Beyond their primary role in electricity production, they are also seen as providing the potential for flexible energy use, lessening reliance on the electricity grid, and boosting sustainability results. Energy storage systems have been especially highlighted due to the temporal mismatch between the electricity production and consumption, so that the surplus energy can be stored and consumed when the electricity production is low, or consumption is high (Sayed et al., 2023).

A multi-disciplinary engineering solution needs to be used to integrate renewables into built and industrial environments. Combined solutions, which combine electrical engineering, power electronics, control systems, computational modelling, and sustainability assessment for building systems and industrial facilities, campuses, and microgrids, have become more and more key. This can be achieved by PV systems lowering external electricity demand, and energy monitoring and storage technologies can help to better manage the operation of the PV systems. These systems highlight the wider scope of applied engineering in solving scientific principles and applying them to practical solutions to sustain energy environments in the real world (Reddy et al., 2024).

Large-scale renewable integration is still technically difficult due to the variable nature of renewable energy generation, location, and temporal fluctuations. The PV's output fluctuates from one season to another, one day to the next, and throughout the day, depending on the weather, and the electricity demand fluctuates depending on the operational schedules, environmental conditions, and behavior of the users. Such variations cause imbalances in demand generation, which forces the grid to be flexible, to provide storage solutions, and to implement predictive energy-management strategies. Although solar energy is regarded as a promising renewable power source, several technical challenges must be addressed before it can be widely adopted. Some of these challenges include issues with grid stability, storage capacity, and the ability to control the flow of energy into the grid (Ergun et al., 2025).

Energy storage technologies are crucial technologies if the reliability of renewable energy systems is to be improved. Battery storage can change the time of renewable energy, aid peak-demand reduction, and enhance energy availability during the low-energy generation period. The integration of storage in sustainable power grids can make renewables more reliable power sources and less dependent on fossil fuels. This is a key engineering technology in sustainable energy planning and optimization of the energy used in industry (Malik et al., 2025).

PV-battery systems are a viable approach to studying the management of renewable energies in applied engineering research. PV-BAT systems use batteries as a form of energy storage and integrate this with both generation and exchange with the external power supply so that energy systems can dynamically adjust to meet the changing demands and price of energy. The relevance of these systems for residential and/or industrial applications is because they enable self-consumption, cost reduction, and/or better grid interaction (Zhang et al., 2022).

Energy management has been extended, with the help of data, to include data-driven energy management, which further increases the use of renewable energy systems. Energy demand forecasting, PV generation/consumption coordination, and advanced coordination of battery operations via deep learning techniques can be achieved using the advanced computational methods. This is crucial, as today's energy systems produce vast amounts of operational information which can help in making sound and adaptive decisions (Alam et al., 2022).

For Grid Connected Photovoltaic-Battery Systems, effective control strategies for achieving both technical and economic goals are also needed. Energy-management models are able to decide when energy should be used directly, stored, exported, or bought from the energy market. Such decisions are important in cases where the price of electricity varies, where such storage and generation can mitigate the impact of high-cost grid electricity (Ali et al., 2022).

Another key goal for sustainable management of industrial energy is peak-demand reduction. Appropriate sizing and utilization of PV-battery systems can help to lower the peak loads, enhance the efficiency of the system, and facilitate more stable energy operation. There are some valuable statistical tools available to help evaluate the nature of demand and determine the best way to store water for peak management (Nematirad et al., 2023).

The low-energy buildings and other efficient infrastructure are also in energy storage and management system design. PV-storage systems optimised can help to reach more sustainable design goals, increase self-sufficiency, and lower energy use. These applications demonstrate the capabilities of engineering technologies in terms of environmental performance and operational efficiency (Liu et al., 2020).

With its ability to predict, adapt, and make real-time decisions, AI has found more and more applications in optimizing renewable energy systems. AI technologies can enhance the scheduling, storage management, fault detection, and demand response planning of renewable energy resources. In this direction of technology, the connection between applied science, digital innovation, and sustainable engineering practice is reinforced (Ukoba et al., 2024).

In recent years, there have been some indications of the potential of grid-tied solar PV-battery microgrids with the use of reinforcement learning and other intelligent optimization methods. These approaches enable self-governing decision-making processes in the context of varying generation and demand levels and prices. They are being applied in energy management and prove the application of new engineering technologies that can enhance the utilization of renewable energy sources and aid sustainable industrial development (Muriithi & Chowdhury, 2021). This research analyzed renewable generation, electricity consumption, energy price, seasonal energy use, and battery state-of-charge data to assess the potential for integrated applied engineering technologies in order to spur sustainable innovations and industrial development.

Objectives of the study:

1. To analyze photovoltaic generation, electricity consumption, and energy price patterns in the selected energy dataset.
2. To assess seasonal renewable contribution and demand–generation balance for sustainable energy management.
3. To evaluate battery storage behavior as an applied engineering technology for supporting industrial sustainability.

2. Methodology

2.1 Research Design

The research design chosen for this study was quantitative and data-driven to investigate the applied engineering case of renewable energy management for sustainable innovation and industrial development. This dataset has been used for the analysis of technical patterns of photovoltaic generation, electricity demand, electricity prices, and battery storage operation.\

2.2 Dataset Description

A secondary dataset obtained from Excel was used for the study, called Dataset for Daily Energy Management: Renewable Generation, Consumption, and Storage. The data consisted of renewable generation, electricity demands, energy price profiles, seasonal scenarios, and battery state of charge. It was chosen due to its recentness, compactness, public availability, and sustainability energy systems, applied engineering analysis applicability (Tayenne et al., 2025).

2.3 Data Screening and Preprocessing

The data was checked for relevant worksheets, missing data, formatting, and anything that was not only about analyzing the data. Worksheets on generation, consumption, pricing, seasonality, and storage were kept. Unnecessary columns, metadata cells, and blank rows were eliminated. All column names and time variables were normalized if necessary; all numerical data from the original data were retained.

2.4 Analytical Variables and Indicators

PV generation, energy consumption, energy price, energy profiles of the season, and battery state of charge were the main variables. Four derived indicators were created to evaluate renewable contribution, demand–generation balance, price-sensitive sustainability opportunity, and storage utilisation. These indicators directly related the dataset to the sustainable engineering and industrial energy-management goals.

2.5 Statistical Analysis

Python was used to compute descriptive statistics (mean, median, minimum, maximum, range, and standard deviation) for the primary variables. Records were analyzed in a comparative manner between seasonal and scenario-based records. Additionally, Python was used for the correlation analysis to explore connections between PV generation, consumption, and price, as well as PV battery usage.

2.6 Methodological Alignment

The applied engineering case was chosen as renewable energy management. PV generation was used to model renewable technology, electricity consumption was used to model operational demand, electricity price was used as the techno-economic decision-making criterion, and battery state of charge was used as the criterion for the performance of the storage system. Within this structure, the study was able to correlate the data with applied science, engineering technologies, sustainable innovation, and industrial development.

3. Results

3.1 Dataset Characteristics

The dataset included 26 worksheets: these included full-year hourly energy data, seasonal profiles, scenario-based records, and battery state of charge data. Following the preprocessing, 8,760 hourly observations from 2023 were kept for the analysis. Retained analytical fields in the cleaned data set were PV generation, electricity consumption, energy price, seasonal energy profiles, and battery SOC variables. There was no missing data in the analytical fields. The numerical features of the cleaned dataset for analysis are presented in Table 1.

Table 1. Dataset characteristics after preprocessing

Dataset feature	Result
Worksheets	26
Full-year observations	8,760
Main year analyzed	2023
Battery profiles	3
Missing values in retained fields	0

3.2 Descriptive Energy-System Performance

The average PV production was 714.99 kW, whereas the average electricity demand was 2,514.26 kW for the whole year. The average electricity price was EUR 0.088 per kWh. The PV generation value was higher, meaning that PV generation decreased electricity demand, but it was not sufficient to meet the annual demand. The descriptive statistics of full-year PV generation, consumption, and energy price are presented in Table 2.

Table 2. Descriptive statistics of full-year variables

Variable	Mean	Median	Minimum	Maximum	SD
PV generation (kW)	714.99	31.00	0.00	5,429.00	1,211.85
Consumption (kW)	2,514.26	1,992.00	0.00	11,866.00	1,293.02
Energy price (EUR/kWh)	0.088	0.092	0.000	0.220	0.040

3.3 Seasonal Energy Performance

Good Seasonal variability in Renewable contribution. The highest renewable contribution was in the summer (51.53%), and the lowest was in the spring (43.06%). The contributions from renewables were lower during winter and autumn, suggesting reliance on grid supply or storage support. The seasonal variation in the renewable contribution is shown in Figure 1 for winter, spring, summer, and autumn. Table 3 presents the seasonal variation of PV generation, consumption, price, and renewable contribution.

Table 3. Seasonal energy performance

Season	Mean PV generation (kW)	Mean consumption (kW)	Mean price (EUR/kWh)	Renewable contribution
Winter	398.98	2,839.99	0.097	14.05%
Spring	1,046.98	2,431.65	0.079	43.06%
Summer	1,075.05	2,086.08	0.098	51.53%
Autumn	312.36	2,719.97	0.079	11.48%

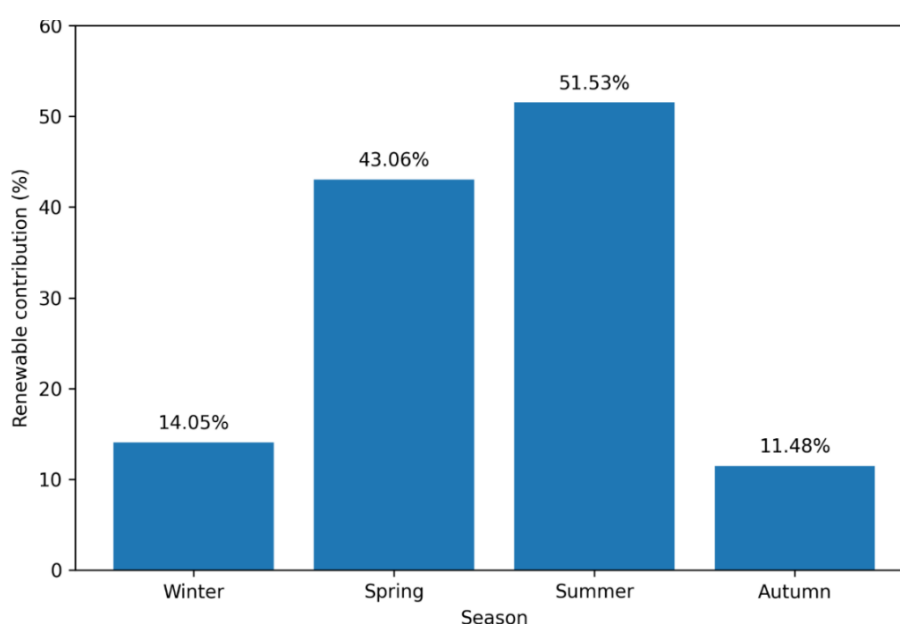


Figure 1. Seasonal Renewable Contribution Across Energy Profiles

3.5 Renewable Contribution and Demand–Generation Balance

PV annual production was 6263310 kWh, and the annual electricity consumption was 22024941 kWh. The renewable contribution index was 28.44%. Renewable surplus was generated for 770 hours, which could be used for storage charging, load shifting, or grid export. The annual comparison of the PV generation to the electricity consumption is shown in Figure 2. Annual renewable contribution and demand–generation balance indicators are presented in Table 4.

Table 4. Renewable contribution and demand–generation indicators

Indicator	Result
Annual PV generation	6,263,310 kWh
Annual electricity consumption	22,024,941 kWh
Renewable contribution index	28.44%
Mean net demand after PV	1,799.27 kW
Maximum net demand	10,232 kW
Maximum renewable surplus	3,660 kW
Hours with renewable surplus	770 hours

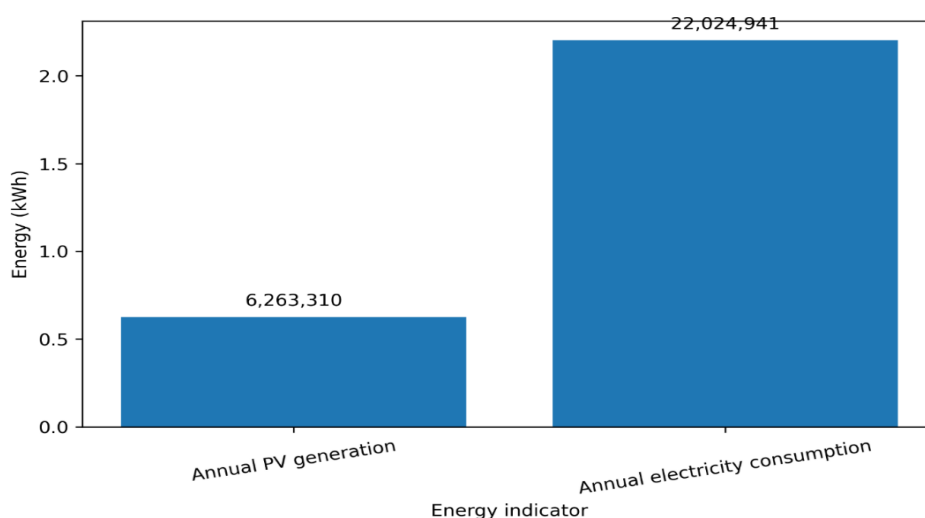


Figure 2. Annual Photovoltaic Generation and Electricity Consumption

3.6 Correlation and Price-Sensitive Sustainability Findings

There was a weak positive correlation between PV generation and consumption. There was a negative correlation between energy price and PV generation, suggesting that when the energy price was high, PV generation was low, and vice versa. Renewable contribution decreased to 10.82% during high price periods, highlighting the necessity of a price-responsive and storage-based energy management approach. Figure 3 shows that the energy price and PV generation were correlated, as well as energy consumption and PV generation. The results of the correlation and price-sensitive sustainability are presented in Table 5.

Table 5. Correlation and price-sensitive findings

Measure	Result
PV generation vs. consumption correlation	0.245
Energy price vs. consumption correlation	-0.067
Energy price vs. PV generation correlation	-0.225
High-price threshold	0.116 EUR/kWh
Mean PV generation during high-price hours	258.42 kW
Mean consumption during high-price hours	2,388.21 kW
Renewable contribution during high-price hours	10.82%

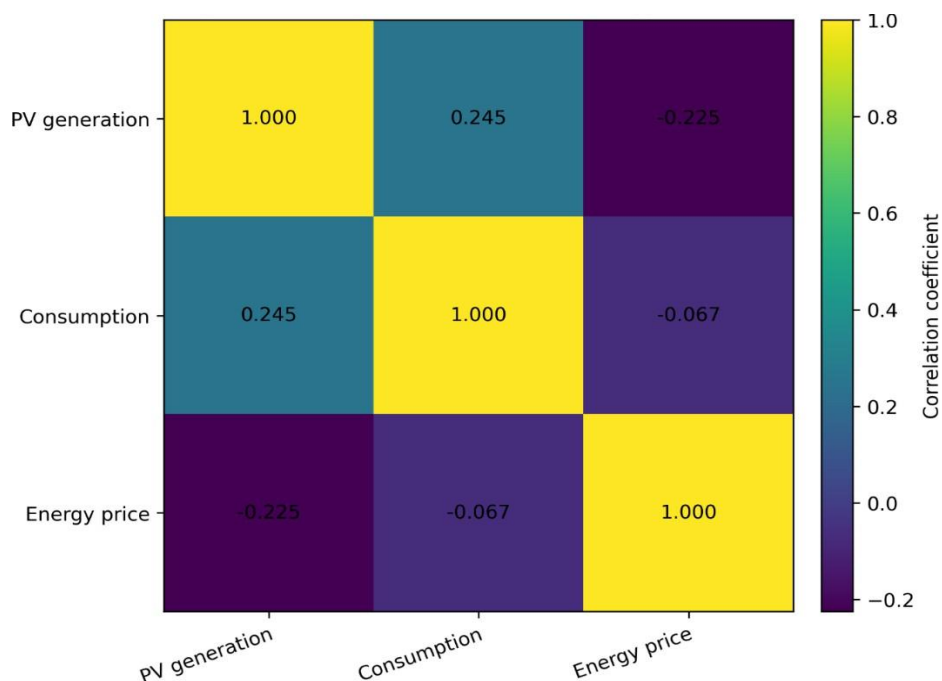


Figure 3. Correlation Heatmap of Energy-System Variables

3.7 Battery Storage and Integrated Engineering Interpretation

Battery SOC profiles revealed that there was active charging and discharging behavior. The SOC range in Profile 1 was the widest, from 25% – 100%. Profile 2 had the most movement in total SOC, and thus was the most cyclic profile. The activity of profile 3 was considered as moderate storage activity.

These results demonstrated the usefulness of battery storage for balancing the intermittent energy supply from renewables, matching demand with generation, and mitigating high prices. The overall results showed that renewable generation, electricity demand, pricing, and storage can be combined as applied engineering technologies in support of sustainable innovation and industrial development.

4. Discussion

The results indicated a multi-faceted and interconnected approach between renewable generation, electricity use, electricity pricing, and battery storage as a component of an applied engineering system. PV generation accounted for 28.44% of the annual electricity demand, which reflects the role of PV generation, but not quite a dominant one. This finding confirms that RENs can help to decrease dependence on the grid, but need to be linked with coordinated energy management and storage technologies to overcome intermittency. The need for significant energy storage was seen, and confirmed that the mismatch between generation and demand is not sustainable with renewable generation. However, to guarantee reliability and optimize self-consumption, use and support operational energy planning, battery energy storage, and intelligent control are still required (Nazaralizadeh et al., 2024).

Seasonal analysis revealed that the renewable contribution was at its maximum during summer and spring, and at its minimum during autumn and winter, on the one hand, where the PV contribution was less significant. This pattern highlighted the seasonal fluctuations in solar generation and how energy-management strategies should be tailored to the time of year. The renewables contribution in summer was 51.53% while the autumn contribution was just 11.48%, highlighting the sometimes stark differences in performance of the same energy system in different seasons. This variability is relevant to industrial facilities, campuses, and built spaces as it demands flexibility in energy planning, particularly in terms of energy generation, storage capacity, and load demands. Battery optimization for built environments as a key technology to facilitate the use of renewable energy in

the presence of variable generation and demand has been recognized (Coccato et al., 2025).

The annual demand–generation balance showed that PV generation decreased the total electricity demand, but it was not enough to meet the total demand. The system operated in a renewable surplus mode during 770 hours, indicating the possibility of further reducing its inefficiency through storage charging, demand shifting, and/or using grid export. These unused or poorly managed renewable energy periods presented valuable engineering opportunities, as renewable energy that is not in use or not well managed can result in a decrease in the technical and economic value of PV systems. Smart-grid solutions are applicable in this context as the digital technologies could coordinate generation, storage, demand, and grid interaction more effectively. The digital energy systems enable better monitoring, control, flexibility, and decision making in the energy transition to support sustainability (Campana et al., 2025).

In the correlation analysis, the PV generation and electricity consumption were found to have a weak positive correlation. This discovery indicated that there was some synchronicity between the production of renewables and the consumption of energy, but also that production and consumption were not tightly coupled. A weak negative correlation was found between energy price and PV generation, meaning that high price periods were more likely to coincide with a low availability of PV generation. This is relevant for techno-economic energy management, where energy storage systems can be more valuable when they are charged during periods of surplus energy or low energy prices and discharged during high energy prices or periods of low energy generation. This process can be enhanced by the help of AI that is able to forecast energy generation and predict energy demands and optimise energy dispatching under varying operating conditions (Wen et al., 2024).

High price analysis reveals that contributions from renewables dropped to 10.82% at high price times. This finding indicated that the system was most vulnerable to grid-cost risk if the PV support was low. It would therefore be crucial that energy management is done in a price-sensitive manner, for the sake of cost-effectiveness and sustainability. Demand response (DR) measures could be implemented to move the flexible load off the high-cost hours, and distributed generation and storage (DG+S) planning could help to minimize reliance on high-priced grid power. Distributed Generation and Demand Response have been proven to enhance energy system investments and operational results in a more flexible and reliable system (Sharma et al., 2024).

Battery state-of-charge profiles showed active storage behavior of the analyzed profiles. Profile 1 exhibited the greatest range in SOC, and Profile 2 had the greatest SOC movement. The results showed that storage systems have the potential to enable renewable balancing, peak management, and flexible operation. This is particularly true in grid-connected systems, where the demand, generation, and price signals fluctuate from one time period to another. The use of renewable and battery systems integrated with the grid also plays an increasingly important role in other important industrial electrification fields, such as electric-vehicle charging, where storage can help lessen grid stress and improve the utilization of sustainable energy (Rehman et al., 2024).

The comprehensive interpretation of the results helps to tie up the whole article theme, and puts renewable energy management as a representative applied engineering technology for sustainable innovation and industrial development. The PV generation was the renewable technology, operational energy demand was the consumption, the price was the techno-economic decision making, and the battery SOC was the battery storage system control. The multi-objective optimization has become a common approach in microgrid-based energy systems, as the technical reliability, cost reduction, emissions reduction, and renewable energy utilization need to be taken into account (Rajagopalan et al., 2024).

The results also suggest that sustainable engineering systems of the future must be data-driven instead of just static ones. There are different types of seasonal variations, surplus generation, exposure to high prices, and battery cycling patterns that demand predictive and adaptive control. Under uncertainty, data-driven optimization methods can be used to optimize the energy dispatch, storage scheduling, and techno-economic performance. This can be especially important when developing the infrastructure and operations of factories, as these methods can help ensure the efficient use of

energy, operational resilience, and sustainable infrastructure (Yaghoubi et al., 2025). In general, the analysis revealed that a pathway for sustainable innovation and industrial energy transformation is feasible and possible through integrated renewable generation, prices, demand monitoring, and battery storage, from an engineering perspective.

5. Conclusion

The use of renewable energy was shown to be a useful engineering tool for sustainable innovation and industrial development. The analysis revealed that the PV generation accounted for 28.44% of the total annual electricity demand, highlighting the significant impact of PV on the grid and the need for complementary energy storage and management solutions. The seasonality revealed good performance of renewables in summer and spring, and more flexibility from the grid or storage in winter and autumn. The demand–generation balance also indicated that there are 770 hours of renewable surplus, which can be utilised for battery charging, load shifting, or exporting electricity to the grid. Results of correlation and price-sensitive performance showed that high electricity prices are often related to low PV contribution, which revealed the need for predictive and price-sensitive energy management. The battery SOHC profiles showed a successful operation of battery storage as an intermittency balancing resource and as an enabling resource for flexibility. As a whole, PV integration for production, consumption monitoring, pricing analysis, and battery storage enabled an energy planning approach in the industrial sector with a sustainability profile, enhanced operational efficiency, and boosted data-based engineering innovations.

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