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Impact of Seasonal Variability on Photovoltaic-Based Energy Management Systems

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ABSTRACT

The study investigates the impact of seasonal variability on photovoltaic-based energy management systems by analyzing hourly photovoltaic generation, electricity consumption, demand, and electricity price data across winter, spring, summer, and autumn. A quantitative secondary-data approach was employed using descriptive statistics, one-way ANOVA, effect size analysis, Pearson correlation, and seasonal energy performance assessment. The results revealed significant seasonal differences in all investigated variables. Photovoltaic generation was highest in summer and spring, with average values of 1075.05 kW and 1046.98 kW, respectively, while winter recorded the highest electricity consumption at 2839.99 kW. ANOVA confirmed statistically significant seasonal effects on photovoltaic generation, consumption, demand, and electricity prices ($p < 0.001$). The highest generation-to-demand ratio was observed in summer (0.515), followed by spring (0.431), indicating greater renewable energy utilization during high solar-resource periods. Economic analysis showed that spring achieved the lowest total electricity cost (€423,822.27), whereas winter recorded the highest cost (€558,311.18). Correlation analysis further indicated significant relationships among photovoltaic generation, consumption, and electricity prices. Overall, the findings demonstrate that seasonal variability strongly affects the technical and economic performance of photovoltaic-based energy management systems. The study highlights the need for season-aware energy management strategies to improve renewable energy utilization, reduce grid dependency, and enhance operational cost efficiency.

1. Introduction

There are several reasons for the world to make the transition to sustainable energy systems: climate change, energy security, and carbon emission reduction. Solar PV systems are one of the most widely adopted and economically viable renewable energy technologies in the world and are an important enabler in the transition towards decarbonisation (Gielen et al., 2019; Hassan et al., 2024). PV technologies have played a major part in decreasing the reliance on fossil fuels and aiding the shift to low carbon electricity generation (Lew et al., 2021; Peters, 2025). But the volatility of the sun's energy continues to be a hurdle to guaranteeing reliable and efficient energy provision.

Seasonal changes in solar irradiance, weather conditions and daylight hours cause significant fluctuations in electricity generation from PV systems throughout the year (Kumar et al., 2020). Concurrently, electricity usage fluctuates in response to seasonal shifts in temperature and occupancy behavior, as well as heating and cooling needs, which leads to dynamic interactions between electricity generation and use (Ralston Fonseca et al., 2019). To overcome these problems, the use of Energy Management Systems (EMS) in the modern renewable energy infrastructures has emerged as an indispensable tool to coordinate the optimal generation, storage, and consumption of energy resources to increase the efficiency and economic performance of the energy systems (Rafique & Jianhua, 2018; Vishwakarma & Kumar, 2023).

Renewable energy systems such as PV generation forecasting, battery storage optimization and demand response strategies. Although the existing research has helped build knowledge on the operational challenges, there has been little research that studies seasonality's impact on PV generation, electricity demand, energy pricing, and battery storage behavior within an integrated energy management framework. Hence, the aim of this study is to study the effect that the seasonal variation has on PV based energy management systems, focusing on the behaviour of the renewable energy production, consumption, electricity price and battery performance. The results will inform the development of adaptive and season-aware energy management strategies for better use of renewable energy and increase operational efficiency.

Research Objectives

RO1: To analyze the impact of seasonal variability on photovoltaic energy generation, electricity demand patterns, and battery state-of-charge dynamics within a photovoltaic-based energy management system

RO2: To evaluate the relationships among photovoltaic generation, electricity consumption, battery storage utilization, and dynamic electricity prices across different seasonal conditions

RO3: To assess the effects of seasonal variability on the operational and economic performance of photovoltaic-based energy management systems in terms of renewable energy utilization, grid dependency, and energy cost efficiency

2. Literature Review

PV energy systems are increasingly central to global efforts to transition to low-carbon electricity systems and have been gaining momentum for their scalability, decreasing costs, and ability to generate low carbon electricity. PV system technologies have also developed considerably with the enhancement of cell efficiencies, module design and system integration and manufacturing. As PV systems are increasingly used in the residential, commercial and utility sectors, Sinke (2019) highlighted the need for ongoing innovation in photovoltaic technologies to really make a difference on a global scale. Performance of PV systems is normally evaluated with the capacity factor, yield factor and the performance ratio. The energy produced divided by the energy that could be produced over the same period of time if the plant were running at full load capacity is called capacity factor, and the energy produced by the plant divided by its installed capacity is called yield factor. Performance ratio is a normalized measure of overall system efficiency that takes into consideration the loss due to temperature, inverter performance, shading and other operating conditions. These are some of the indicators that are vitally important to understand the impact of seasonal and environmental conditions on PV system productivity and reliability.

Energy Management Systems (EMS) play a pivotal role in optimizing the performance of renewable energy systems, achieving efficient energy generation, storage, use, and grid integration. In a smart grid context, the architecture of EMS typically includes data acquisition modules, forecasting models, optimization algorithms, control modules and communication network. Rathor and Saxena (2020) state that EMS plays a key role as an enabling technology for smart grids by allowing real-time monitoring, load scheduling, energy optimization, and improving the reliability of the grid. Similarly, Mahapatra and Nayyar (2022) pointed out that HENMS integrate sensors, smart meters, controllable load, renewable energy generation resources and storage facilities to optimise the use of energy and reduce electricity costs. Demand side management is one of the pivotal roles of EMS which enables consumers or automatic controllers to adjust electricity demand, cut, or optimise their usage, based on the availability of electricity generation, and price signals. Smart grid integration to EMS is also valuable including bidirectional communication, dynamic pricing response, coordination of distributed energy resources and flexibility in power system operations.

Intermittency is a challenge for renewable energy, and Battery Energy Storage Systems (BESS) are an emerging technology that can help solve it, when used in conjunction with solar power.Battery Energy Storage Systems (BESS) are increasingly becoming used in conjunction with photovoltaic systems, in order to overcome the problem of intermittency in renewable energy. Battery storage allows excess PV generation to be stored during times of peak PV generation then released during times of low PV generation and high demand. The significance of the right battery size in renewable energy systems was discussed by Yang et al. (2018), who pointed out that the storage capacity plays an important role in the reliability, cost, and operational aspects of the system. The state of charge (SOC) dynamics, charging and discharging efficiency, depth of discharge, cycle life and degradation behavior are commonly used as criteria for battery operation. Advanced Battery Management Systems (ABMS) play a crucial role in ensuring battery safety, enhancing battery longevity, and optimizing battery performance across a wide range of operating conditions, according to Nyamathulla and Dhanamjayulu (2024). Seasonal variations also pose further challenges for battery storage, as fluctuations in PV production and load demand affect the possibility for charging, as well as the frequency of discharging and the storage capacity. In summer, for instance, there may be more charging available, while in winter there is less irradiance, and more reliance on the grid, with decreased storage flexibility.

Seasonal variation is one of the key factors that impacts renewable energy generation, electricity demand and energy management performance. Temporal changes in solar irradiance, weather, temperature and climatic conditions have a significant impact on the use of renewable energy resources. Jiang et al. (2023) showed that the generation of renewable energy shows distinct seasonal variations and could not be ignored in the planning and operational modeling of renewable energy. Solar irradiance variability is critical in PV based systems, directly influencing the electricity production, so a seasonal estimate is a key point for the system evaluation. Coddington et al. (2019) demonstrated the changes in solar irradiance for various temporal scales and the need for model–measurement comparisons at all scales in order to understand the uncertainty of solar resource. Seasonal load characteristics also affect system performance, in addition to generating variability. PV generation and demand can be mismatched as electricity usage could increase for particular seasons or times because of heating, cooling, lighting or occupancy. Magaña-González et al. (2023) also noted the significance of the seasonal complementarity and variability of renewable resources in enhancing the planning and integration of renewable energy resources.

The literature has been expanded by earlier research that has provided useful insights into PV technology development, EMS design, battery storage optimization, and seasonal renewable energy modelling, but there is a lack of coherence. Presently, the majority of studies focus on the single aspects (PV performance, smart grid EMS architecture, battery sizing or solar irradiance variability), but do not consider the role of these elements when working in an integrated PV-based energy management system. There has been limited research that has also investigated the variation of PV generation, electricity consumption, energy pricing, and battery SOC behaviour by season. This margin is important because the ability of the EMS to perform relies on the interaction between the availability of generation, the demand characteristics, the storage response, and economic signals. Thus, an in-depth seasonal assessment is needed to aid the development of adaptive EMS strategies that would boost the use of renewable energy, minimize dependence on power grid, and maximize PV energy system economic efficiency.

3. Methodology

3.1 Research Design

A quantitative research design, in the form of secondary data analysis, was used in this study to examine how PV-based energy management systems are affected by the seasonal variations. A data-driven method was used to analyse the electricity demand seasonal shift, the PV generation seasonal shift, the battery storage behavioural changes and the electricity prices. The study mainly aimed to identify operational and economic differences among various seasonal conditions.

3.2 Data Source and Description

Data for the study was extracted from the Daily Energy Management Dataset from the repository (Tayenne et al., 2025). The data set include hourly data for PV power generation, electricity consumption, battery state-of-charge (SOC), and price of electricity. These variables represent a complete picture of the dynamics of energy production, storage and consumption in an energy management system based on PV. The data was grouped according to seasons for easy comparison.

3.3 Data Preprocessing

The data were initially screened to ensure data quality and consistency before analysis. Common data cleaning methods were used to identify and address missing values and outliers. Observations were classified into four seasons: spring, summer, autumn and winter, based on the information on the timestamp. Data were normalized and validated to better ensure analytical accuracy and comparability of the data across seasons and scenarios.

3.4 Data Analysis Techniques

Descriptive statistical analysis was used to summarise seasonal variations of the PV generation, electricity demand, battery SOC and electricity price. To examine the relationship among the variables being studied the Pearson correlation technique was used. Moreover, whether there were significant differences between the seasonal groups was determined using one-way analysis of variance (ANOVA). Statistically significant results ($p<0.05$) were obtained for these.

3.5 Performance Assessment Framework

To assess the energy management system based on PV technical and economic indicators were used. Technical evaluation was determined based on parameters of PV generation, battery usage and seasonal energy demand profile. Cost assessment of electricity was performed to find if there is a difference in cost of electricity by seasons. The integrated framework enabled a comprehensive analysis of the effects of the seasonality on the efficiency of the system, storage usage and the performance of the energy management system.

4. Results

4.1 Seasonal Variations in Photovoltaic Generation, Electricity Demand, and Energy Prices

The seasonal descriptive statistics of photovoltaic generation, electricity consumption, demand and electricity prices are given in Table 1. The findings show that there are significant seasonal variations for all variables. The average photovoltaic generation was highest during summer (1075.05 kW), high during spring (1046.98 kW), and low in the autumn (312.36 kW) and winter (398.98 kW). However, the highest average electricity consumption (2839.99 kW) and demand (0.239 pu) was recorded during winter periods, whereas the lowest electricity consumption (2086.08 kW) and demand (0.176 pu) was recorded during summer periods. There was also a difference in prices by season, with prices of electricity being highest in summer (0.098 €/kWh) and lowest in winter (0.097 €/kWh).

Table 1. Seasonal Descriptive Statistics of Energy Management Variables

Season	Generation (kW) Mean	Consumption (kW) Mean	Demand (pu) Mean	Energy Price (€/kWh) Mean
Winter	398.984	2839.985	0.239	0.097
Spring	1046.983	2431.653	0.205	0.079
Summer	1075.054	2086.084	0.176	0.098
Autumn	312.357	2719.975	0.229	0.079

4.2 Seasonal Significance Analysis

One-Way ANOVA was used to compare system performance by season to determine if there was significant difference. From the Table 2, all the variables are statistically significant for seasonal difference ($p < 0.001$). The observed seasonal influence was the highest for PV generation with F-statistic (272.617). Effect size analysis also highlighted that there was an acceptable level of practical significance, and that the PV generation had the highest effect size ($\eta^2 = 0.0854$).

Table 2. ANOVA and Effect Size Results

Variable	F-statistic	p-value	Eta Squared (η^2)
Generation (kW)	272.617	<0.001	0.0854
Consumption (kW)	155.880	<0.001	0.0507
Demand (pu)	155.880	<0.001	0.0507
Energy Price (€/kWh)	158.004	<0.001	0.0514

4.3 Relationships Among Energy Management Variables

Results of Pearson's correlation are shown in Table 3 and graphically illustrated in Fig. 1. Electricity consumption and PV generation had a weak positive correlation ($r = 0.245$, $p<0.001$). There was a weak negative correlation between PVs generation and electricity prices ($r = -0.225$, $p < 0.001$), with renewable energy generation tending to occur during periods of lower electricity prices. The correlation between electricity consumption and electricity prices was very weak and negative ($r = -0.067$, $p < 0.001$).

Table 3. Pearson Correlation Matrix

Variable	Generation	Consumption	Demand	Energy Price
Generation	1.000	0.245	0.245	-0.225
Consumption	0.245	1.000	1.000	-0.067
Demand	0.245	1.000	1.000	-0.067
Energy Price	-0.225	-0.067	-0.067	1.000

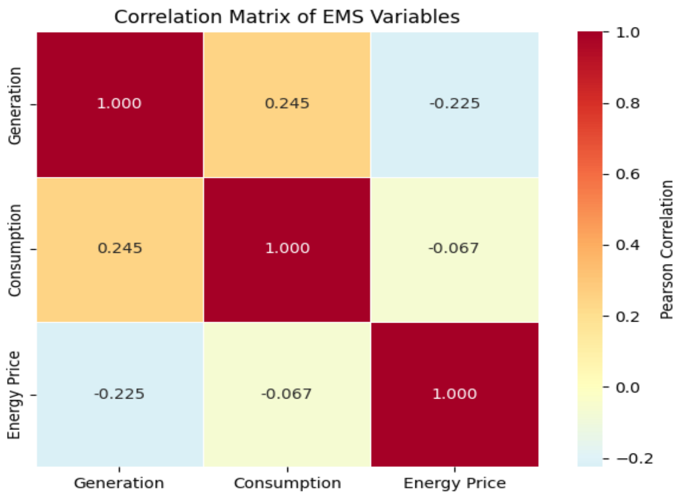

Figure 1. Correlation Heatmap of Energy Management Variables

4.4 Seasonal Energy Performance Assessment

Table 4 shows results of the energy performance during the seasons. As for the total photovoltaic generation and the ratio of generation to demand, the highest was in the summer (2,399,521 kWh) and the generation to demand ratio was 0.515, meaning that PV systems provided around 51.5% of the seasonal electricity demand. Spring also showed good results with a ratio of 0.431. In contrast, the renewable energy contribution was found to be much lower in the autumn and winter periods (0.115 and 0.140 for generation to demand, respectively).

Table 4. Seasonal Energy Performance Indicators

Season	Total Generation (kWh)	Total Consumption (kWh)	Mean Price (€/kWh)	Generation-to-Demand Ratio
Winter	852,230	6,066,208	0.097	0.140
Spring	2,336,867	5,427,449	0.079	0.431
Summer	2,399,521	4,656,139	0.098	0.515
Autumn	674,692	5,875,145	0.079	0.115

4.5 Economic Performance Assessment

The electricity cost analysis by season is given in Table 5. The total and hourly electricity cost (in €) are all the highest in winter due to high electricity demand and relatively low PV generation. The spring season was the most economically successful with the minimum electricity cost (€423,822.27) and minimum average hourly cost (€189.88). The highest electricity prices were found in summer but strong PV generation reduced electricity expenditure in this period relative to winter and autumn.

Table 5. Seasonal Electricity Cost Analysis

Season	Total Cost (€)	Average Cost (€)
Winter	558,311.18	261.38
Spring	423,822.27	189.88
Summer	453,660.36	203.25
Autumn	478,259.50	221.42

Overall, the findings show that variability has an important impact on PV generation, electricity demand, RE use, and electricity costs. The best operating conditions occurred in spring and summer, while the lowest operating conditions were in winter, the highest renewable penetration during winter, and the highest economic losses during winter.

5. Discussion

The results of this study show that the operational and economic efficiency of photovoltaic driven energy management systems can be strongly influenced by the seasonal variations. The descriptive and inferential analyses showed that there were significant seasonal variations in PV production, electricity consumption, demand, and electricity price. The ANOVA tests showed these differences to be statistically significant for all of the variables under investigation and thus provided an increased awareness of the need to consider seasonality in energy management systems.

The seasonal change of PV generation is in line with the basic seasonality of solar energy production due to the dependency of solar irradiance and climatic conditions. The summer season and the spring season had the greatest PV generation, while the winter season and the autumn season had significantly less PV generation. All of this is consistent with the results of Coddington et al. (2019) which showed that temporal variations in solar radiation had a pronounced impact on PV performance. Likewise, Magaña-González et al. (2023) found that one of the most important factors affecting renewable energy availability and system performance is the seasonal variability. The longer daylight hours, more solar radiation and more favorable weather conditions in the summer, may explain the higher PV generation. On the other hand, during winter, PV productivity is hampered by the decreased daylight and reduced irradiance. The same seasonal behavior has been observed in long-term PV field studies showing that the efficiency of energy production was significantly affected by environmental and climatic conditions (Javed et al., 2020).

The result also showed that the highest and the lowest use of electricity and demand occurred in winter and summer respectively. This trend indicates that the energy behaviour is greatly affected by seasonal climatic changes. Winter is typically a time when energy demand rises, and is linked to electricity use for heating, decreases in daylight hours, and increases in household energy use. The results confirm the results of Heydari et al. (2023) which highlighted the close relationship between the energy consumption pattern and the environmental and seasonal conditions. Therefore, energy management systems need to consider time-variant demand, in order to balance the energy supply and demand efficiently.

Correlation analysis gave further insights in the relations between the system variables. The weak positive correlation between pv generation and electricity consumption suggests that when pv production rose, there was a slight increase in electricity consumption. This correlation can be attributed to the fact that users or automated systems will use local renewable energy resources if they are available. In addition, the negative correlation between PV generation and electricity prices shows that more renewable (PV) energy could lead to lower market electricity prices. This result aligns with the study of Fuke and Ohashi (2025) who found that an increase in solar power penetration can lead to lower electricity price levels and price volatility, due to an increase in renewable energy supply.

One of the most important results obtained from this study is the seasonal energy performance evaluation. The highest generation to demand ratio (0.515) occurred in summer, meaning that more than half of the electricity demand was met by PV generation during this season. Spring also proved to be strong with a ratio of 0.431. In contrast, the renewable energy contribution for winter and autumn was much lower. The results above underscore the importance of the seasonal availability of solar resources for penetration of renewables and system self-sufficiency. In the context of renewable energy management, this relationship between resource availability and system efficiency, as well as dependence on the grid, has been observed in several relevant studies (Yakubiv et al., 2019).

The economic evaluation also proved that the seasonal fluctuations substantially influence the operational costs. Despite the highest average electricity price in summer, the electricity expenditure was still relatively low due to high electricity generation from PV. On the contrary, the total electricity cost was the highest in winter as the demand is high and renewable energy generation is low. Overall, the spring season was the most economically viable one, with the highest renewable energy usage and the lowest electricity cost. The results in this paper agree with the notion that the proper energy management strategies must take into account the availability of renewable generation, the nature of the demand, and the market prices of energy (Heydari et al., 2023; García Vera et al., 2019).

The results also have important implications for battery energy storage integration. Previous research has underscored the significance of battery systems in alleviating intermittency issues with renewables and enhancing flexibility of energy systems (Denholm et al., 2020; Sayed et al., 2023). Battery storage can store excess electricity produced by the PV systems and decrease reliance on the grid during peak periods. In contrast, during the winter months when renewable generation is reduced and demand is high, stored energy can help balance renewable generation and be used to increase system reliability. Hence, the use of season-aware batteries scheduling and storage management is seen as pivotal for optimising PV based energy management systems.

The results support the implementation of adaptive and intelligent control strategies from an energy management point of view. Various advanced energy management solutions, such as optimization-based and AI-based technologies, have shown great potential to enhance the use of renewable energy and operational efficiency (Hu et al., 2018). The large seasonal differences revealed in this study indicate that fixed energy-management policies may not be sufficient to cover the different operational conditions that occur across the year. Rather, adaptive EMS structures, which can change their behavior dynamically in response to seasonal variations in energy generation and demand and energy prices, are likely to perform better technically and economically.

The findings validate the fact that the seasonal variability is one of the major influencing factors for performance of PV systems, energy consumption pattern, use of renewable energy and operational cost. Incorporating seasonal factors in designing energy management systems can improve the penetration of renewables, boost the economic benefits, lower the grid dependency, and ensure long-term sustainability of PV-based energy systems.

6. Conclusion

This study focused on the effect of the seasonality on photovoltaic based energy management systems by analyzing the PV generation, electricity consumption, electricity prices and energy performance indicators for four different seasons. The findings showed that the use of an energy management system is sensitive to seasonal fluctuations in both operating and economic levels. The summer season and the spring season recorded the maximum PV production, which led to better renewable energy utilization with generation-to-demand ratio equal to 0.515 and 0.431, respectively. On the contrary, the PV output was low during winter and autumn and a higher fraction of external energy sources had to be used. The results of the statistical analysis revealed that there exist significant differences between the PV generation, electricity consumption, electricity demand, and electricity prices in different seasons ($p < 0.001$), which is vital to consider the seasonal dynamics in energy management strategies. Furthermore, correlation analysis identified statistically significant relationships between generation, consumption and electricity prices, highlighting how electricity prices could be impacted by renewable energy supply changes and how system operation could be affected. The economic assessment indicated that spring delivered the best performance, with the lowest electricity cost, while winter had the highest operational cost, as increased demand and decreased renewable energy production took a toll on the electricity cost. Overall, the findings highlight the potential of SEEM strategies to enhance renewable energy resources utilization, reduce electric energy costs, and improve efficiency. As a realization of the crucial role of seasonal elements in PV energy management systems, it is essential to increase the robustness of the system, enable energy sustainability transitions, and fully utilize the benefits of PV energy resources in modern power systems.

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