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Assessment of Seasonal Renewable Energy Integration Using Real-World Consumption Data

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ABSTRACT

The integration of renewable energy into modern power systems is essential for achieving sustainability goals; however, seasonal variability in renewable generation and electricity demand continues to present operational and economic challenges. This study assesses seasonal renewable energy integration using real-world photovoltaic (PV) generation, electricity consumption, battery storage, and dynamic electricity pricing data. A quantitative data-driven approach was employed to evaluate seasonal variations in renewable generation, electricity demand, storage performance, and economic outcomes. Renewable penetration, energy balance, battery utilization, and cost-saving indicators were calculated, while the Kruskal–Wallis test and Spearman correlation analysis were applied to examine seasonal differences and inter-variable relationships. The results revealed significant seasonal variations in renewable generation, electricity consumption, and electricity prices ($p < 0.001$). Summer achieved the highest renewable penetration rate (51.53%) and the greatest economic benefit, with renewable energy offsetting 43.26% of seasonal electricity costs. In contrast, winter and autumn exhibited lower renewable penetration rates and greater dependence on grid electricity. Battery storage analysis demonstrated substantial contributions to system flexibility, with storage utilization ranging from 40% to 75% across representative operating profiles. Furthermore, renewable generation was consistently negatively correlated with electricity prices, particularly during spring and summer, indicating its potential to reduce market price pressure. The findings highlight the critical role of battery storage and adaptive energy management strategies in enhancing renewable energy integration under seasonal variability. This study provides valuable insights for policymakers, utilities, and energy planners seeking to improve renewable energy utilization and support the development of resilient and sustainable energy systems.

1. Introduction

The energy industry is undergoing a major shift as the world seeks sustainable solutions and a need to cut down on GHG emissions. Renewable energy technologies are key players in this transformation, in particular solar PV systems, which offer environmental advantages, decreasing installation costs and increasing technological maturity (Gielen et al., 2019; Bogdanov et al., 2021). In recent years, renewable energy has been recognized as a key enabler for worldwide sustainability and long-term energy security, resulting in significant investments in renewable energy infrastructure all over the world (Bulkot et al., 2023; Hassan et al., 2024). Despite the swift installation of renewable energy systems, however, their integration into the existing power network is still a great challenge in a large scale.

Intermittent and seasonal nature of renewable resources is one of the major difficulties faced in integrating renewable energy. Weather, daylight hours and seasonal variations have a significant impact on the generation of solar power, leading to energy fluctuations between different seasons of the year (Sousa et al., 2022). These shifts can cause electricity generation and demand to diverge, causing problems to the system to operate including energy curtailment, system instability and inefficient use of renewable energy resources. Another challenge is the seasonal variability in the system; energy load demands often are different from one season to the next, with certain seasons experiencing energy overproduction and others experiencing energy shortages. This makes the understanding of the performance of seasonal renewable energy sources more and more relevant in order to enhance the reliability and efficiency of modern energy systems.

Battery energy storage systems have long been considered as a viable option to reduce variability from renewable energy sources and system flexibility. The use of battery storage can enhance the self-consumption of power, decrease reliance on conventional power sources, and increase renewable energy use, as the battery stores excess electricity when there is abundant power generation from renewable sources and releases it during periods of low renewable power generation and high demand (Wu et al. 2022). PV systems coupled with energy storage technologies have been proven to have significant potential to optimize energy management and energy operational costs, especially in combination with dynamic electricity pricing mechanisms (Nguyen et al., 2018; Schwarz et al., 2020). Moreover, thanks to recent developments in smart energy systems and digital monitoring technologies, operational data of an unprecedented level of detail can be gathered in the real world, which opens new possibilities in assessing the performance of renewable energy systems in real operating conditions (Abuimara et al., 2022).

While some previous studies have explored integration of renewable energy and optimization of battery storage, most of the literature uses annual or aggregated datasets that may hide critical seasonal features. Furthermore, most studies have concentrated on a single component of the energy system, including renewable energy generation, energy storage, and electricity pricing, without considering the entire system, relying on abstract, idealized operating conditions and data (Wu et al., 2022; Zandi et al., 2023). Furthermore, while scenario-based approaches for renewable energy integration have proven to be effective in helping with decision-making under variable conditions, their use for assessing seasonal renewable energy integration is still limited (Steinke et al., 2023).

For these reasons, this study evaluates the integration of seasonal renewable energy using real-world consumption, photovoltaic generation, battery storage and electricity pricing. The study combines a variety of system components into one analytical framework and uses representative seasonal scenarios to comprehensively assess renewable energy performance by season. Based on the findings, there are valuable insights for energy planners, energy operators, and policymakers, in order to promote more efficient use of renewable energy, more energy self-sufficiency, and the development of energy systems that are resilient and sustainable with smart energy systems (Aunedi & Green, 2020).

Research Objectives

1. To assess seasonal variations in renewable energy generation and electricity consumption
2. To evaluate the contribution of battery storage to renewable energy integration across seasons

3. To analyze the economic performance of seasonal renewable energy integration under dynamic electricity pricing

2. Methodology

2.1 Research Design

In this study a quantitative research methodology was used to evaluate seasonal renewable energy integration with the actual operational data. These included a comparison of renewable energy generation, power consumption, battery performance and economic impacts for various seasons. The approach used was a data-driven one, which involved analyzing the data to look for seasonal trends and evaluate the performance of integrating renewable energy. The methodology was developed to give practical information to operate smart energy systems in different season conditions.

2.2 Dataset Description and Preprocessing

This study used a publicly available dataset that included hourly PV generation, electricity demand, battery SOC, and electricity pricing data. The data set was for all the year and classified as four seasons, winter, spring, summer and autumn. Data pre-processing included checking for missing data, eliminating inconsistencies, and grouping data into seasons. This process provided data quality and reliability prior to the next analysis (Tayenne,2025).

2.3 Seasonal Renewable Energy Assessment

The seasonal renewable energy integration was estimated by analyzing energy generation from PV and consumption of electricity over four seasons. Seasonal patterns were characterized using descriptive statistical measures such as mean, standard deviation, minimum and maximum. Renewable Energy Penetration (REP) was computed to see the contribution of renewable energy in total electricity demand. The seasonal energy balance was also analysed to detect any energy surpluses or deficits.

2.4 Battery Storage Performance Analysis

To evaluate the contribution of battery storage to the integration of renewable energy, the battery state of charge (SOC) data was used. The charging and discharging patterns of seasons were examined to understand the performance of the battery system in balancing the energy. The ratio of local renewable generation and storage capacity to electricity demand, known as the Self-Sufficiency Ratio (SSR), was also computed to assess the proportion of electricity demand supplied from local renewables and storage. These indicators gave insights into the value of battery storage for improving the flexibility of the system and decreasing the dependence of the grid.

2.5 Economic and Scenario-Based Analysis

Dynamic electricity pricing data was used to evaluate economic performance of renewable energy integration. The costs of electricity during the seasons and potential cost savings from utilizing renewables were estimated and compared. Moreover, representative seasonal scenarios in the dataset were utilized to check the performance of the system under different operating conditions. Comparative analyses were performed to determine the most favorable aspects of renewable energy integration and battery utilisation, and economic efficiency. All statistical and data analysis and visualization were done with python-based statistical and data analytics tools.

3. Results

3.1 Seasonal Variations in Renewable Energy Generation and Electricity Consumption

A summary of the seasonal renewable energy generation, electricity consumption, energy balance and penetration rates for renewables are shown in Table 1. There were significant differences in all the indicators across seasons.

Table 1. Seasonal Energy Performance Indicators

Season	Total Generation (kWh)	Total Consumption (kWh)	Energy Balance (kWh)	Renewable Penetration (%)
Winter	852,230	6,066,208	-5,213,978	14.05
Spring	2,336,867	5,427,449	-3,090,582	43.06
Summer	2,399,521	4,656,139	-2,256,618	51.53
Autumn	674,692	5,875,145	-5,200,453	11.48

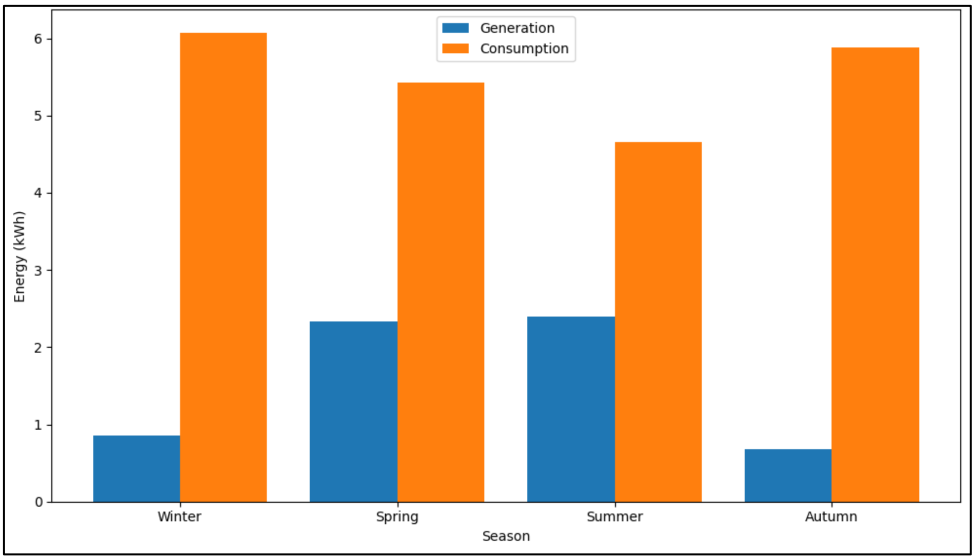

Figure 1. Seasonal Comparison of Renewable Energy Generation and Electricity Consumption

Figure 1 illustrates the seasonal variation in renewable energy generation and electricity consumption. Spring and summer recorded substantially higher renewable generation than winter and autumn, while electricity consumption remained consistently higher across all seasons, resulting in persistent energy deficits and varying renewable penetration levels.

The highest renewable energy generation (2,399,521 kWh) and highest renewable penetration rate (51.53%) were observed during the summer season as presented in Table 1 and Figure 1, respectively, meaning that more than half of the electricity demand in the season was met by renewable energy. There was also a significant contribution from renewables in Spring, accounting for 43.06% of the total contribution. Winter and autumn, on the other hand, had relatively low renewables penetration rates, which indicated less availability of solar energy and a higher reliance on grid electricity.

The energy balances were also negative for all seasons, showing a higher demand for electricity than renewable electricity generation during the study period. The biggest deficits were seen in winter and autumn, and the smallest deficit in summer, because of the increased PV generation.

The Kruskal–Wallis's test was applied to see if there was a significant difference between the seasons and the results are shown in Table 2.

Table 2. Kruskal–Wallis Test Results

Variable	H Statistic	p-value
Generation (kW)	463.399	<0.001
Consumption (kW)	868.998	<0.001
Energy Price (EUR/kWh)	461.456	<0.001

3.2 Battery Storage Performance

The ability of batteries to store energy was evaluated using three representative states of charge (SOC) curves included in the data set. The descriptive statistics of battery profiles are reported in Table 3.

Table 3. Battery SOC Performance Summary

Profile	**Mean SOC (%)**	**Min SOC (%)**	**Max SOC (%)**	**SOC Range (%)**	**Mean Temperature (°C)**
Profile 1	53.81	25	100	75	29.18
Profile 2	39.29	24	86	62	29.47
Profile 3	34.78	23	63	40	28.34

The charging and discharging curves for the three battery profiles are shown in figure 2. Profile 1 had the highest average SOC and the highest storage capacity utilization, suggesting that it can store more energy generated by the renewables. The least operational flexibility was observed in Profile 3 with the lowest storage utilization.

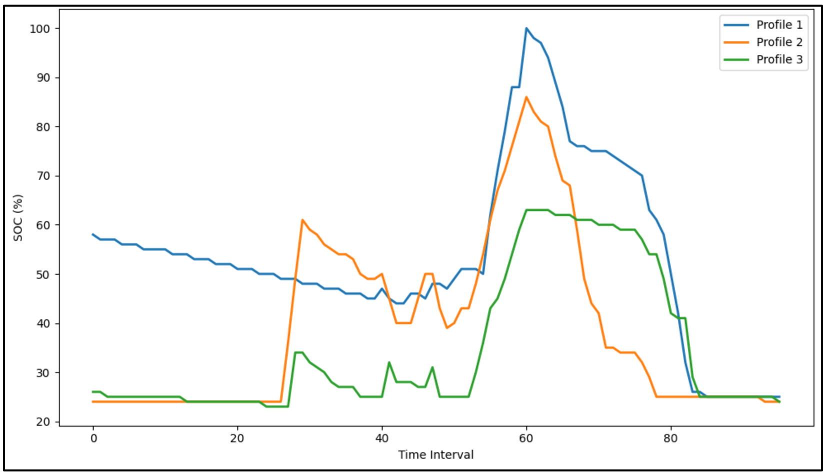

Figure 2. Comparative State-of-Charge (SOC) Profiles of Battery Storage Systems

Figure 2 presents the charging and discharging behavior of three battery storage profiles over the monitoring period. Profile 1 achieved the highest SOC levels and utilization range, while Profile 2 exhibited greater operational activity. Profile 3 maintained lower SOC levels, indicating comparatively limited storage flexibility.

Table 4. Advanced Battery Performance Metrics

Profile	**SOC Std Dev**	**Utilization Index (%)**	**Flexibility Score (%)**	**Charge–Discharge Activity**
Profile 1	17.93	75.00	33.31	155
Profile 2	17.80	62.00	45.31	190
Profile 3	14.41	40.00	41.42	122

Table 4 shows advanced battery performance metrics. The greatest storage utilization index was realized for Profile 1 (75%), indicating the widest range of operation. But, Profile 2 showed the maximum flexibility score and charge discharge activity, which means that the battery was more dynamic during its operation. The results indicate that energy balancing and flexibility in energy system operation are important possibilities for improving the integration of renewable energy with battery storage systems.

3.3 Economic Performance of Renewable Energy Integration

The seasonal economic performance of renewable energy integration is summarized in Table 5.

Table 5. Seasonal Economic Performance Indicators

Season	**Grid Cost (€)**	**Renewable Value (€)**	**Savings Ratio (%)**
Winter	558,311.18	77,507.32	13.88

Spring	423,822.27	137,872.67	32.53
Summer	453,660.36	196,264.83	43.26
Autumn	478,259.50	45,818.43	9.58

Table 5 and Figure 3 indicate that the energy value of renewable energy is the highest in Summer (€196,264.83) and the savings ratio is the highest (43.26%). There were also significant economic advantages during the spring season, as renewable energy accounted for 32.53% of the electricity costs. However, winter and autumn saw relatively modest savings because there was less renewable energy produced and more demand for electricity from the grid.

The findings show that there is a close connection between economic benefits and the penetration levels of renewables. The greater the renewable generation, the higher the cost savings and the better the economic performance, across all seasons.

3.4 Correlation Analysis

Spearman correlation analysis was carried out to explore the correlation between renewable generation, electricity consumption and electricity prices. Table 6 shows the correlation coefficient for each season.

This information is presented visually in seasonally correlated heat maps (Figure 4). The relationship between renewable generation and electricity consumption was found to be positive and consistent for all the seasons with correlation value from 0.386 to 0.512. This means that the periods of renewable generation were generally when there was higher demand for electricity.

In addition, the electricity prices were negatively correlated with renewable generation in all seasons, especially in spring and summer. The results indicate that higher access to renewables results in lower electricity prices and less reliance on the grid. The weak correlations between electricity prices and consumption were observed in the case of electricity, suggesting that electricity demand is not very responsive to short-term price changes.

Table 6. Seasonal Spearman Correlation Coefficients

Season	Generation–Consumption	Generation–Price	Consumption–Price
Winter	0.386	-0.077	-0.077
Spring	0.512	-0.385	0.017
Summer	0.482	-0.420	-0.012
Autumn	0.499	-0.137	0.143

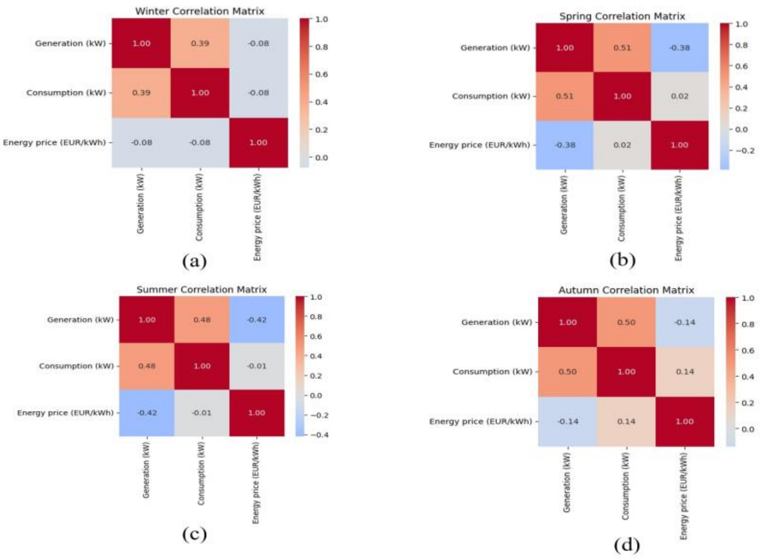

Figure 4. Seasonal Correlation Heatmaps of Renewable Generation, Electricity Consumption, and Electricity Prices

Figure 4 presents seasonal correlation matrices illustrating relationships among renewable generation, electricity consumption, and electricity prices. Panels (a)–(d) show that renewable generation was consistently positively associated with consumption and negatively associated with energy prices, with the strongest inverse relationships observed during spring and summer.

4. Discussion

The results of this study showed that seasonal variation is significant in the performance of renewable energy integration. There were significant differences among the four seasons in terms of renewable energy generation, consumption of electricity and prices of electricity, indicating the need to consider the seasonal dynamics in energy planning and management. The highest renewable penetration was realised during summer (51.53%), with significantly lower penetrations in winter and autumn. The results align with those of previous studies that highlight how resource availability and environmental conditions significantly influence renewable energy performance, especially during the seasons (Mararakanye & Bekker, 2019; Oyekale et al., 2020). The higher share of renewables during the summer is likely due to higher solar energy input and longer daylight hours, which boosts PV generation and lessens the need for electricity from the grid.

Although significant renewable generation occurred in spring and summer, in all seasons, the electricity demand remained greater than the electricity supplied from renewables. The discovery indicates that even if electricity demand increases, renewable power sources such as solar and wind are not enough to meet the demand and shows that grid support and energy storage are still vital. Comparable findings have been observed in other research on grid-integrated renewables, where fluctuations in renewable energy generation and demand can lead to mismatch in supply and demand, necessitating the need for more flexibility resources to address these mismatches (Tavakoli et al., 2020; Impram et al., 2020). The findings thus further support the view that growth of renewables should be supported by investments in storage solutions as well as flexible energy management solutions.

The battery storage analysis also highlighted the need for storage solutions to support the integration of renewables. Profile 1 had the highest storage utilization index (75%) whereas Profile 2 had the highest number of charge and discharge operations and operational flexibility. The results show that the operating strategy of batteries can have different effects on the system performance. High utilisation profiles achieve high energy storage capacity, while high activity profiles optimise responsiveness to fluctuations in generation and demand. This finding is consistent with that of Dratsas et al. (2021), which points out the role of battery energy storage systems in providing system adequacy and operational reliability. Likewise, Maka and Chaudhary (2024) found that the variability in renewable energy generation can significantly alter the stability of the system and the utilization of renewable energy, such as battery-integrated photovoltaic systems. These results thus validate the importance of battery storage as a key enabler for the integration of renewable energy, for providing flexibility and energy balancing functions.

The economic assessment showed that there is significant variation between the economic advantages of renewables integration by season. The highest savings ratio was recorded in summer (43.26%), followed by spring (32.53%), a value which is significantly lower for the other seasons of the year, namely autumn (17.57%) and winter (13.37%). The findings suggest that there is a close link between economic performance and the amount of renewable generation and renewable penetration rates. In times of high PV production (Photovoltaics), this can help meet a higher share of electricity demand and limit the impact of market electricity prices. This result aligns with the previous study that showed that a renewable energy system can save substantial amounts of electricity costs if combined with intelligent energy management and energy storage solutions (Schwarz et al., 2020; Rasheed et al., 2025). Furthermore, the study indicates that dynamic pricing approaches can boost the value of renewable energy by incentivizing increased usage when its production is high.

The correlation analysis also gives more insights into the operational relationships between renewable generation, electricity demand and electricity prices. All of the renewable generation and electricity consumption was found to be positively correlated, but in a moderate manner, for all seasons, suggesting that the production of renewable energy was generally during periods of active demand. This is a good relationship, as it enables more energy to be used locally from renewable sources and less from the grid. Moreover, electricity prices were negatively associated with renewable energy throughout the year, particularly in the spring and summer. The research indicates that increased renewable energy use helps to lower electricity costs by decreasing reliance on conventional (nonrenewable) energy sources. Renewable energy market impacts on electricity markets and grid economics studies (Mararakanye & Bekker, 2019; Tavakoli et al., 2020) have reported similar market impacts.

The opposite trend of renewable electricity generation and electricity prices observed also has significant implications for the future energy system (Upadhyay et al., 2021). When there is higher generation, excess electricity supply can occur as renewable energy penetration grows, which can cause renewable energy curtailment. Although curtailment is a longstanding challenge for the grid, it is now being considered as a new opportunity for flexible demand response, energy storage, and new energy vectors like hydrogen production (Laimon, 2025). Therefore, renewable energy systems of the future need to take advantage of the excess renewable energy, not just through the traditional grid system, but with integrated flexibility solutions.

Real world, the findings could be useful for policy makers, utilities and energy planners. This considerable seasonal variation in renewable integration performance suggests that a single energy management approach could not work all year long. In this case, however, it is necessary to devise a different operational plan for each season to maximize the use of renewable energy and the deployment of storage. In addition, the scenario-based approach used in this research reinforces the need to apply adaptive planning frameworks that consider seasonality and variability or uncertainty, as suggested by the seasonal scenario planning literature (Steinke et al., 2023). Furthermore, the incorporation of batteries into smart local energy systems can enhance the flexibility in operation and help achieve a greater integration of renewables (Aunedi & Green, 2020).

The results show that the performance of renewable energy integration is still significantly influenced by seasonal variations. PV generation can deliver large economic and environmental returns in certain seasons, but integration needs to be complemented by other storage solutions, by flexible energy management solutions and by adaptive planning solutions. The joint consideration of renewable generation, electricity demand, battery storage and market pricing gives a complete picture of the dynamics of renewable energy and gives actionable advice for improving the resilience, efficiency and sustainability of the future energy system.

5. Conclusion

This study evaluated the integration of seasonal renewable energy with actual PV generation, electricity demand, battery storage and dynamic electricity pricing data. Renewable generation, electricity demand and energy prices were found to show significant seasonal variations, confirming that seasonality has a significant impact on the integration performance of renewable energy. The highest renewable penetration rate (51.53%) and economic benefit occurred in the summer with 43.26% of electricity costs being covered by renewable energy, while the lowest contribution in terms of renewables and highest dependency on grid electricity were found in the winter and autumn months. While renewable electricity was able to meet demand for electricity during some of the spring and summer months, all seasons had negative energy balances, meaning that electricity demand was not fully met by renewable electricity alone. The importance of battery storage system for providing flexibility and enabling the use of renewable energy was highlighted through battery storage analysis, with the battery storage profiles tested showing different levels of utilization, flexibility, and charge–discharge activities. Moreover, correlation analysis revealed that renewable generation was significantly correlated with electricity demand, and that it was negatively correlated with electricity prices, suggesting that it can help to alleviate market price pressures and enhance economic outcomes. The results highlight the need to incorporate seasonal variability in the use of battery storage and adaptive energy management techniques for optimal benefits from renewable energy. Overall, the study offers practical guidance for policy makers, utilities, and energy planners looking to optimize renewable energy use, boost energy self-sufficiency, and advance resilient and sustainable smart energy systems. Further studies on multi-year datasets, advanced optimization methods, and flexible solutions that combine flexibility should be explored to further enhance integration performance of renewable energy systems.

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