

Article

From Price Shocks to Stability: The Role of Energy Communities in Electricity Market Volatility and Uncertainty

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Abstract

Renewable energy communities (RECs) are increasingly recognized as a strategic instrument for enhancing the sustainability and resilience of energy systems, promoting local renewable integration, and reducing consumer exposure to electricity market volatility. This study analyzes the Italian electricity market and assesses the economic performance of RECs relative to individual consumers using high-frequency hourly data from 2021 to 2023, covering both the 2022 European energy crisis and the subsequent Italian regulatory reform of incentive mechanisms. The optimization problem is formulated in physical terms, aiming to maximize locally utilized energy, defined as the sum of self-consumed and shared photovoltaic generation. This choice reflects the structure of the Italian regulatory framework, where incentives are directly linked to the amount of energy shared within the community. In this context, energy-based optimization is preferred to avoid embedding assumptions on discount rates, investment horizons, and financing conditions, which may vary significantly across users and introduce additional uncertainty. From a sustainability perspective, maximizing local energy utilization contributes to improving energy efficiency, reducing reliance on external energy sources, and enhancing the capacity of decentralized systems to absorb market shocks. For this reason, economic indicators such as Net Present Value (NPV) or payback period are not explicitly included in the optimization objective. This is justified by the focus of the analysis on short-term operational performance and exposure to electricity price volatility, rather than long-term investment evaluation. Moreover, given that the economic value of the REC is largely determined by shared energy volumes under the current Italian incentive scheme, maximizing local energy utilization provides a consistent proxy for economic performance. Nevertheless, the integration of financial metrics such as NPV or payback period represents a relevant extension for future research, particularly in the context of investment decision-making. Through panel econometric analysis, we estimate the sensitivity of economic value to electricity price fluctuations. Results show that RECs reduce price sensitivity by approximately 8–15% compared to individual users, as estimated by panel regression coefficients. Furthermore, the volatility of economic value decreases by around 1.95% under the community configuration, particularly during the 2022 price shock demonstrating that RECs exhibit significantly lower price dependence than standalone consumers. To assess the robustness of these findings, a machine learning framework is employed to relax linearity assumptions and capture potential non-linear effects. Results consistently show that while market prices remain an important determinant, RECs substantially attenuate their impact, particularly during periods of extreme price stress. A policy counterfactual comparison between pre- and post-reform incentive structures further indicates that the coefficient of variation decreases by approximately 4.4% under the post-reform incentive scheme, highlighting the role of policy design in



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supporting economically and operationally sustainable energy communities. Overall, this study develops a data-driven analysis based on a high-frequency synthetic dataset designed to reproduce realistic consumption and generation dynamics, providing robust evidence that RECs contribute not only to renewable energy deployment but also to the economic and systemic sustainability of electricity markets under conditions of high volatility.

Keywords: energy communities; price volatility; energy resilience; sustainable energy system

1. Introduction

Recent geopolitical tensions and structural transformations in global energy systems have significantly increased electricity price volatility, raising concerns about the economic vulnerability of end-users and long-term sustainability of local energy systems. The energy crisis observed in 2022 was characterized by unprecedented price spikes across European electricity markets. This situation highlighted the strong exposure of consumers to market dynamics and revealed the limitations of traditional centralized energy systems in ensuring a resilient and sustainable energy supply. In this context, understanding how energy systems respond to price shocks has become a central issue. Empirical evidence shows that energy consumption reacts significantly to price variations, particularly in the short run [1].

Within this evolving landscape, RECs have emerged as a key instrument for promoting decentralized and sustainable energy systems, enhancing local energy autonomy. RECs enable collective generation, consumption, and sharing of renewable energy, fostering new forms of local electricity markets and peer-to-peer interactions. Existing studies demonstrate that, compared to individual prosumers, energy communities can improve economic efficiency and increase the utilization of locally generated energy through collective self-consumption mechanisms [2]. In this perspective, the economic viability and sustainability of energy communities depend not only on technological factors but also on the internal allocation of energy and the interaction among participants.

At the same time, the growing diffusion of local energy markets has led to increasing attention to pricing mechanisms and internal energy transactions within energy communities. Recent contributions show that the design of pricing rules and peer-to-peer exchanges plays a crucial role in determining both individual incentives and collective outcomes [3] with important implications for the economic and social sustainability of decentralized systems. In particular, simulation-based approaches highlight that internal pricing mechanisms can significantly influence the distribution of economic benefits and the efficiency of energy sharing within communities.

Despite these advances, the economic and sustainable performance of energy communities cannot be fully understood without considering the role of market volatility. Electricity prices are increasingly characterized by high-frequency fluctuations driven by fuel price uncertainty, renewable intermittency, and geopolitical factors [4].

Furthermore, recent studies emphasize that the integration of demand-side flexibility within energy communities can enhance their performance and contribute to system stability [5]. By improving the alignment between local generation and consumption, flexibility mechanisms may reduce dependence on external markets and mitigate the impact of price fluctuations. Despite the extensive literature on Renewable Energy Communities, their role in mitigating exposure to electricity price volatility has not yet been clearly quantified using high-frequency data and combined econometric and data-driven approaches. In particular, the relationship between energy communities and price sensitivity remains underexplored, especially in the presence of extreme market conditions.

In addition, recent forecasting studies highlight the increasing complexity of electricity price dynamics, showing that both statistical and machine learning approaches are required to capture non-linearities and temporal dependencies in energy markets [6]. While hybrid econometric and machine learning approaches have been widely applied in energy-related studies, their application to Renewable Energy Communities—particularly in the analysis of price sensitivity and volatility—remains relatively limited. The contribution of this study lies in applying this framework to the context of Renewable Energy Communities, where such integrated analyses remain relatively unexplored. These findings suggest that traditional linear approaches may not be sufficient to fully capture the behavior of decentralized and sustainable energy systems under volatile market conditions [7,8].

This study aims to investigate whether energy communities can act as a stabilizing mechanism in electricity markets. In particular, it examines their ability to reduce the sensitivity of economic value to price volatility. The analysis focuses on three key aspects. First, it compares price responsiveness between individual and community configurations. Second, it explores the role of non-linear dynamics during high-price periods. Third, it evaluates the impact of incentive schemes on value stability.

To address these issues, the study employs a high-frequency dataset with hourly observations covering the period 2021–2023, explicitly capturing both the 2022 price shock and subsequent regulatory changes. Methodologically, the analysis combines panel econometric models with machine learning techniques. While econometric models provide a benchmark for estimating average price sensitivity, machine learning approaches—interpreted through SHAP (Shapley Additive Explanations)—allow for the identification of heterogeneous and state-dependent effects.

The results show that, although both individual users and energy communities benefit from increases in electricity prices, the latter exhibit a significantly lower sensitivity to price fluctuations. This difference becomes particularly pronounced during high-price periods, indicating that energy communities act as a conditional resilience mechanism. Moreover, the analysis highlights that policy design can introduce counter-cyclical effects, further reducing the dependence of economic value on market dynamics and supporting the long-term sustainability of energy communities.

Overall, this study contributes to the literature by providing:

- The data-driven quantification of price sensitivity in Renewable Energy Communities based on high-frequency consumption and price profiles;
- The comparison between individual and community configurations under different operational settings;
- The analysis of the stabilizing effect of RECs under extreme price conditions (2022 energy crisis);
- The integration of econometric and machine learning approaches to capture both linear and non-linear dynamics in sustainable energy system.

Building on these contributions, the remainder of the paper is structured as follows. Section 2 presents the legislative and regulatory framework of RECs in Italy. Section 3 reviews the relevant literature, with a focus on techno-economic modeling, market design, and data-driven approaches. Section 4 describes the data and methodology, including the construction of consumption profiles, the simulation framework, and the econometric and machine learning models. Section 5 reports the main results, highlighting the effects of price variability and policy design on the economic performance and sustainability of the REC. Section 6 discusses the implications of the findings in light of existing literature and regulatory perspectives. Finally, Section 7 concludes and outlines directions for future research.

2. Legislative Framework

The development of RECs in Europe is strongly rooted in the regulatory framework established by the Clean Energy for All Europeans Package, which promotes decentralized energy systems and active consumer participation in electricity markets [9]. In particular, Directive (EU) 2018/2001 (RED II) [10], transposed into Italian legislation through Legislative Decree 199/2021 [11], introduced the concept of RECs, defining them as legal entities that enable collective generation, consumption, and sharing of renewable energy at the local level.

In Italy, the transposition of the European directives has led to the progressive implementation of a regulatory framework aimed at fostering the diffusion of energy communities. The initial experimental phase of energy communities in Italy was regulated through ARERA provisions [12], allowing small-scale collective self-consumption schemes and establishing the first incentive mechanisms for shared energy. These schemes were later consolidated and expanded through subsequent regulatory updates, culminating in a more structured framework that defines the operational and economic conditions of energy communities.

A central element of the Italian framework is the incentive mechanism applied to shared energy. This mechanism remunerates the portion of electricity that is simultaneously generated and consumed within the community, thereby encouraging local balancing between supply and demand. During the initial phase (2021–2023), incentives were based on a fixed tariff for shared energy, as defined by ARERA and implemented by GSE [13]. The incentive provided a stable remuneration per unit of shared energy and this structure ensured predictability but did not explicitly account for market conditions.

The revised regulatory framework introduced by the Ministerial Decree of 7 December 2023 (DM CACER) [14] includes a variable incentive component linked to electricity market prices. In this configuration, the total incentive decreases as market prices increase, introducing a counter-cyclical mechanism. This design aims to balance efficiency and stability by reducing excessive remuneration during high-price periods while maintaining support under normal conditions [15].

These regulatory changes have direct implications for the economic value and volatility of revenues associated with Renewable Energy Communities [16]. Under a fixed tariff, the value of shared energy is largely independent of market dynamics, whereas under a variable scheme, the incentive becomes partially dependent on electricity prices. This change modifies the relationship between market signals and economic value, potentially affecting both the level and the volatility of revenues.

Within this regulatory context, the present study incorporates both incentive structures in order to assess their impact on the economic value and stability of energy communities. By comparing the pre-reform and post-reform schemes, the analysis provides insights into how policy design influences the resilience of community-based energy systems in the presence of price volatility.

3. Literature Review

The increasing diffusion of RECs has generated a growing body of literature investigating their economic, technical, and regulatory implications. However, existing studies have often developed along partially disconnected strands, focusing separately on economic performance, market design, or price dynamics, with limited integration between these dimensions [17,18].

A first stream of literature focuses on the economic performance of energy communities compared to individual prosumers. Several studies show that collective self-consumption mechanisms can improve the efficiency of distributed energy systems by

increasing the utilization of locally generated renewable energy and reducing reliance on external markets. In particular, comparative analyses highlight that energy communities can achieve higher economic value than stand-alone configurations due to demand aggregation and internal energy sharing [2]. Additional contributions emphasize the importance of optimizing energy allocation and sharing mechanisms to improve both technical and economic performance [19].

Closely related to this, a second line of research investigates the role of heterogeneity in consumption and production profiles. The literature highlights that differences in user behavior are a key driver of system efficiency, as they enable a better temporal alignment between electricity generation and demand. Recent studies propose classification approaches to identify consumption–production profiles within energy communities, showing that grouping users with complementary patterns significantly increases shared energy and reduces system imbalances [9]. This structural complementarity represents a fundamental advantage of community-based configurations over individual ones.

A third strand of literature examines the design of local electricity markets and pricing mechanisms within energy communities. With the emergence of peer-to-peer trading and decentralized market structures, increasing attention has been devoted to the rules governing internal energy exchanges. Simulation-based studies demonstrate that pricing mechanisms play a central role in determining both the distribution of economic benefits and the incentives for participation [3]. More recent research highlights that integrating price prediction and optimization models into energy sharing frameworks can improve decision-making and system efficiency.

Despite these advances, the interaction between energy communities and electricity price dynamics remains relatively underexplored. Electricity markets are increasingly characterized by high volatility, driven by fuel price fluctuations, renewable intermittency, and geopolitical shocks [4]. Empirical studies show that energy consumption responds to price variations, particularly in the short run [1]. At the same time, machine learning approaches highlight the increasing complexity of electricity price formation, emphasizing the need for high-resolution models capable of capturing multiple market drivers [20]. However, most existing contributions focus on forecasting or macro-level dynamics and do not explicitly analyze how different energy configurations respond to price variability.

In parallel, a growing body of research has investigated the broader economic effects of energy price shocks. These studies show that price volatility can have significant impacts not only at the micro level but also on macroeconomic stability [21]. However, the extent to which decentralized systems such as energy communities can mitigate these effects remains largely unexplored.

The financial sustainability of energy communities has also received increasing attention. Existing studies highlight both opportunities and challenges related to revenue streams, cost allocation, and investment structures. While energy communities can benefit from multiple sources of value, including self-consumption and incentive schemes, their performance is strongly influenced by regulatory frameworks and market conditions [22,23]. This highlights the central role of policy design in shaping both profitability and risk exposure.

More recent contributions emphasize the role of demand-side flexibility as a key factor in improving the performance of decentralized energy systems. Flexibility mechanisms allow users to adjust their consumption in response to generation patterns or price signals, thereby increasing self-consumption and reducing reliance on external markets. Literature reviews show that the integration of flexibility within energy communities can enhance system efficiency and contribute to stability [5], while social and behavioral dimensions are increasingly recognized as relevant factors influencing participation and performance [17].

Finally, the increasing complexity of electricity markets has led to the adoption of advanced modeling approaches combining econometric and machine learning techniques. Traditional linear models are often insufficient to capture non-linear relationships and extreme events, while machine learning models have proven effective in identifying complex patterns in electricity prices and demand [6]. However, their application to the analysis of energy communities remains limited, particularly in terms of interpretability and integration with economic analysis.

Taken together, the existing literature provides important insights into the functioning and performance of energy communities but leaves several gaps. In particular, there is a lack of studies that jointly consider high-frequency price dynamics, explicitly compare individual and community configurations, and integrate econometric and machine learning approaches within a unified framework. Moreover, the role of energy communities as a mechanism for reducing exposure to price volatility and enhancing economic resilience has not been fully explored.

This study addresses these gaps by providing an integrated analysis of energy communities under conditions of price volatility. By combining high-frequency data, econometric modeling, and machine learning techniques, the paper contributes to the literature by explicitly linking price dynamics, energy sharing mechanisms, and policy design, thereby advancing the understanding of energy communities as tools for enhancing resilience in modern energy systems.

4. Methodology

The data-driven analysis is based on a high-frequency dataset covering the period from January 2021 to December 2023, constructed by integrating multiple data sources in order to capture consumption, generation, market conditions, and regulatory parameters. Electricity consumption profiles are derived from data provided by the Italian Regulatory Authority for Energy, Networks and Environment (ARERA) [24], which defines standardized consumption patterns for residential users within the national tariff structure. These profiles serve as a baseline representation of typical household demand and are subsequently adapted to reflect heterogeneous behavioral characteristics.

Hourly data on solar irradiation and expected energy production are gathered from the PVGIS (Photovoltaic Geographical Information System), developed by the European Commission, which is widely used for the estimation of solar energy production [25]. A photovoltaic system with a nominal capacity of 10 kW is considered, and the corresponding generation profile $G(t)$ is reconstructed for the geographical area of Foggia, ensuring consistency between climatic conditions and consumption patterns. In addition, the dataset includes the hourly zonal electricity price P_t representing wholesale market dynamics, as well as the incentive component TIP_t associated with shared energy within energy communities.

The modeling framework is designed as a controlled environment, where the impact of energy sharing can be analyzed independently from confounding factors. By construction, all configurations are evaluated under the same underlying price and demand conditions, allowing a consistent comparison of their response to price dynamics. To account for heterogeneity in consumption behavior, four representative residential profiles are constructed for the area of Foggia (Italy). These profiles correspond to working households, retired households, families with children, and young households, each characterized by distinct temporal consumption patterns. Starting from the standardized ARERA load curves, the profiles are further refined using information derived from the Time-of-Use Survey (TUS) [26], which provides empirical evidence on how electricity consumption is distributed throughout the day across different types of households.

The integration of ARERA profiles with TUS data is implemented through a calibration procedure that reshapes hourly consumption patterns while preserving total annual demand. Specifically, the intra-day distribution of consumption is adjusted to reflect observed behavioral differences, such as higher daytime consumption for retired households or more pronounced evening peaks for working families. This process, implemented through Python-based version 3.12.13 data processing routines, allows for the generation of synthetic yet realistic consumption profiles that are both consistent with regulatory benchmarks and representative of actual usage patterns.

The analysis considers both individual stand-alone configurations and a Renewable Energy Community composed of the four users. Within the community, a single photovoltaic system is assumed, and the allocation of generated energy is determined in order to maximize collective efficiency. At each time step, the available generation $G(t)$ is first used to satisfy the demand of the prosumer, whose auto-consumption is defined as:

$$SC_{pros}(t) = \min(G(t), C_{pros}(t)) \quad (1)$$

The remaining generation is then allocated to other members of the community as shared energy. The amount of shared energy is given by:

$$Shared(t) = \min(G(t) - SC_{pros}(t), \sum_{j \neq pros} C_j(t)) \quad (2)$$

Any residual generation that cannot be locally consumed is injected into the grid:

$$E_{grid}^{out}(t) = G(t) - SC_{pros}(t) - Shared(t) \quad (3)$$

while any unmet demand is satisfied through imports from the grid:

$$E_{grid}^{in}(t) = C_{tot}(t) - SC_{pros}(t) - Shared(t) \quad (4)$$

The optimal configuration of the energy community is determined by selecting the prosumer in such a way as to maximize the total amount of locally utilized energy. Formally, the optimal prosumer i^* is identified as:

$$i^* = \arg \max_i \sum_t [SC_i(t) + Shared_i(t)] \quad (5)$$

which is equivalent to minimizing the total energy exchanged with the grid:

$$\min \sum_t [E_{grid}^{out}(t) + E_{grid}^{in}(t)] \quad (6)$$

Although simplified, this formulation captures the core mechanism of energy sharing in renewable energy communities, which is commonly modeled in the literature through the interaction between local generation, demand, and grid exchanges [27].

The economic value is computed on an hourly basis for both individual and community configurations. For individual users, the value is defined as:

$$V_{ind}(t) = SC_i(t) \cdot (P_t \cdot 1.3) + E_{grid}^{out}(t) \cdot P_t \quad (7)$$

where self-consumed energy is valued at a retail-equivalent price which includes not only the wholesale electricity price but also additional components such as network charges, taxes, and system costs. In line with existing literature, a markup factor is applied to approximate the retail price, assuming that the final price is approximately 30% higher

than the wholesale zonal price. For the energy community, the value additionally includes the incentive associated with shared energy:

$$V_{CER}(t) = SC_{pros}(t) \cdot (P_t \cdot 1.3) + E_{grid}^{out}(t) \cdot P_t + Shared(t) \cdot TIP_t \quad (8)$$

To evaluate the sensitivity of economic value to electricity prices, a panel econometric model is employed:

$$V_{it} = \alpha + \beta P_t + \theta(P_t \cdot CER_i) + \mu_i + \epsilon_{it} \quad (9)$$

where CER_i identifies the community configuration and μ_i captures entity-specific effects. This framework allows for the comparison of price responsiveness between individual users and the energy community.

Given the non-linear nature of electricity markets, the econometric analysis is complemented by a machine learning model based on gradient boosting, which estimates the relationship:

$$V_t = f(P_t, G(t), C_{tot}(t)) \quad (10)$$

without imposing linearity. SHAP (Shapley Additive Explanations) values are used to decompose predictions:

$$f(x) = \phi_0 + \sum_k \phi_k \quad (11)$$

thereby allowing the identification of the marginal contribution of electricity prices under different conditions.

Finally, the role of policy is assessed through a counterfactual analysis of alternative incentive schemes, while system stability is evaluated using a risk-return indicator defined as:

$$Sharpe = \frac{\mathbb{E}[V]}{\sigma(V)} \quad (12)$$

which captures the trade-off between economic performance and volatility. The risk-return trade-off is evaluated using a Sharpe-like indicator, defined as the ratio between expected economic value and its volatility. While this metric originates from portfolio theory [28] it has been widely adopted in energy economics to assess the performance of renewable energy investments under uncertainty [29,30]. In this study, it is adapted to evaluate the stability of economic outcomes within renewable energy communities. Although the Sharpe ratio provides an intuitive measure of the trade-off between expected value and volatility, it does not explicitly account for asymmetric or tail risk associated with extreme market events. Therefore, in the present study, it is interpreted as a comparative indicator of relative stability across energy configurations rather than as a comprehensive financial risk metric. The adoption of downside-risk measures, such as the Sortino ratio or Conditional Value-at-Risk (CVaR), represents an interesting direction for future research.

5. Results and Machine Learning Analysis

The results provide a comprehensive assessment of the economic performance of energy communities compared to individual configurations, combining econometric evidence with machine learning-based insights. The analysis is structured to highlight both average effects and non-linear dynamics, with particular attention to periods of high price volatility.

5.1. Econometric Results: Price Sensitivity

The panel regression results show a statistically significant relationship between electricity prices and economic value across both configurations, indicating that the coefficient associated with the zonal electricity price is positive and statistically significant. This suggests that increases in electricity prices lead to higher economic value for both individual

users and Renewable Energy Communities (RECs). Figure 1 presents the temporal evolution of economic value for both individual users and Renewable Energy Communities. The figure highlights the impact of the 2022 price shock, characterized by a significant increase in volatility. Notably, the individual configuration exhibits stronger fluctuations, while the community configuration appears more stable over time.

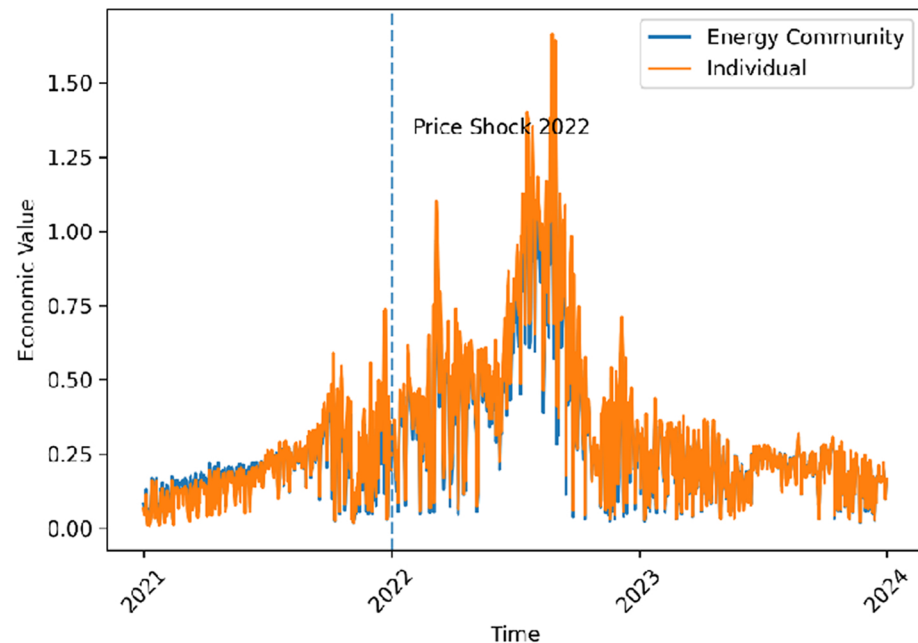


Figure 1. Relationship between zonal electricity price and economic value.

Table 1 presents the results of the panel regression model used to estimate the relationship between electricity prices and economic value across configurations.

Table 1. Panel regression results.

Variable	Coefficient	Std. Error	t-Stat	p-Value	CI Lower	CI Upper
const	0.013489212	0.002663	5.065261	4.08391×10^{-7}	0.00827	0.018709
Zonal Price	1.631413168	0.01332	122.4742	<0.001	1.605305	1.657521
interaction	−0.292002355	0.029785	−9.80352	<0.001	−0.35038	−0.23362

For individual users, the estimated coefficient associated with the zonal price is positive and highly significant, indicating that increases in electricity prices lead to higher economic value.

The interaction term is negative and statistically significant ($p < 0.001$), indicating that the sensitivity of economic value to electricity prices is lower in the energy community configuration. This suggests that energy communities mitigate exposure to price fluctuations. In quantitative terms, while the price elasticity for individual users is estimated at approximately 1.63, it decreases to about 1.34 in the community configuration. The confidence intervals are relatively narrow and do not include zero, confirming both the statistical significance and the robustness of the estimated effects. In particular, the negative interval associated with the interaction term provides strong evidence that the energy community configuration reduces price sensitivity. This result provides evidence that energy communities act as a mitigating mechanism, reducing exposure to electricity price fluctuations.

These results suggest that energy communities do not eliminate the impact of price dynamics, but rather attenuate their transmission, leading to a lower marginal effect of price variations on economic value.

Table 2 reports the main goodness-of-fit statistics of the panel regression model. The model is estimated on a high-frequency dataset comprising 131,400 observations, ensuring a high level of statistical precision.

Table 2. Goodness-of-fit results.

Metric	Value
Observations	131,400
R-squared (Within)	0.11769789
R-squared (Overall)	0.11769789
F-statistic	8763.822881
Prob > F	1.11022×10^{-16}

The within R^2 is approximately 0.118, indicating that the model explains around 11.8% of the variation in economic value over time. While this may appear moderate, it is consistent with expectations for high-frequency data and complex economic systems, where a significant share of variability is driven by unobserved factors. The overall R^2 confirms the consistency of the model, while the F-statistic is large and highly significant ($p < 0.001$), indicating that the explanatory variables are jointly relevant. Overall, these results support the validity of the econometric specification and provide a reliable basis for the interpretation of the estimated coefficients.

Recent studies have adopted integrated sensitivity analysis frameworks to assess the impact of price uncertainty on key economic indicators, highlighting the critical role of market conditions in determining project viability [31]. This perspective provides additional support for our findings, suggesting that the positive relationship between electricity prices and economic value observed in the panel regression reflects a broader and well-established economic mechanism.

However, the inclusion of the interaction term between price and the energy community configuration reveals a different dynamic. The estimated coefficient for the interaction term is negative and statistically significant, implying that the sensitivity of the community's value to price changes is lower compared to individual users. In other words, while both configurations benefit from higher prices, the marginal effect of price is attenuated in the case of the energy community.

This result provides the first evidence supporting the hypothesis that energy communities reduce exposure to price fluctuations. Importantly, the effect is identified as an average relationship, reflecting the overall behavior across the entire sample period.

5.2. Non-Linear Dynamics and Machine Learning

To complement the econometric analysis, a machine learning approach based on gradient boosting is employed in order to capture non-linear relationships between economic value and its main drivers. The model is trained using key variables, including electricity prices, photovoltaic generation, and total consumption, and is evaluated against alternative non-linear models such as Random Forest and LightGBM.

Table 3 shows that all non-linear models achieve a high level of predictive accuracy, with Random Forest providing the lowest prediction error in terms of RMSE, followed by LightGBM and XGBoost. However, the differences across models are relatively limited, suggesting that the underlying relationships are captured consistently.

The machine learning models are implemented using standard hyperparameter configurations. The XGBoost models include 100 estimators with a maximum depth of 4 and a learning rate of 0.1. The Random Forest model consists of 100 trees with a maximum depth of 10. The LightGBM model is configured with 100 estimators and 31 leaves. The LSTM model is implemented with 50 units, a dropout rate of 0.2, and is trained using the Adam

optimizer for 20 epochs with a batch size of 32. These configurations are selected based on standard practices in the literature, without extensive hyperparameter tuning, in order to ensure a consistent and interpretable modeling framework.

Table 3. Model comparison.

Model	RMSE	MAE	R ²
LSTM	0.01852198	0.009620897	0.998748772
XGBoost	0.030181868	0.018390318	0.996677585
Random Forest	0.017683999	0.006451956	0.998859428
LightGBM	0.075128199	0.029562597	0.979414207

However, despite its slightly lower predictive performance, XGBoost is selected for the interpretability analysis due to its greater stability and consistency of SHAP-based explanations in gradient boosting models. This choice reflects a trade-off between predictive performance and interpretability, with the latter being central to the objectives of the study.

The comparison across models also suggests that the underlying system, while non-linear, does not exhibit extreme complexity, as indicated by the relatively small differences in predictive performance. This finding reinforces the validity of the econometric results while justifying the use of machine learning techniques to uncover subtler dynamics.

5.3. SHAP Analysis: Interpreting Price Effects

The SHAP analysis provides a detailed decomposition of the contribution of each variable to the predicted economic value. In particular, the SHAP values associated with electricity prices allow for a direct assessment of their marginal impact under different conditions. To investigate the relationship between electricity prices and economic value, SHAP dependence plots are used to capture the marginal effect of zonal price. Figure 2 shows the relationship between zonal price and economic value for individual users. The results indicate a strong positive relationship, with higher prices leading to a significant increase in economic value.

Figure 3 reports the same relationship for the energy community configuration. While the positive relationship remains, the slope appears less steep, suggesting a reduced sensitivity to price variations.

To complement the visual interpretation, Table 4 shows quantitative measures of feature importance are derived from SHAP values. In particular, the mean absolute SHAP value is computed for each variable, providing a ranking of their relative contribution to the model prediction.

Table 4. SHAP feature importance.

Feature	Mean SHAP REC	Mean SHAP Individual
Production	0.364820339	0.384595315
Zonal Price	0.132557571	0.161350727
Total Consumption	0.004326693	0.002113639

The results confirm that the zonal electricity price is the most influential variable in both configurations, followed by photovoltaic production and total consumption. Moreover, the relative importance of price is slightly lower in the energy community configuration, supporting the evidence of reduced price sensitivity. For individual users, the impact of price is more dispersed and exhibits higher variability, reflecting a stronger dependence on market conditions. In contrast, the energy community shows a more concentrated distribution of SHAP values, indicating a more stable response to price changes.

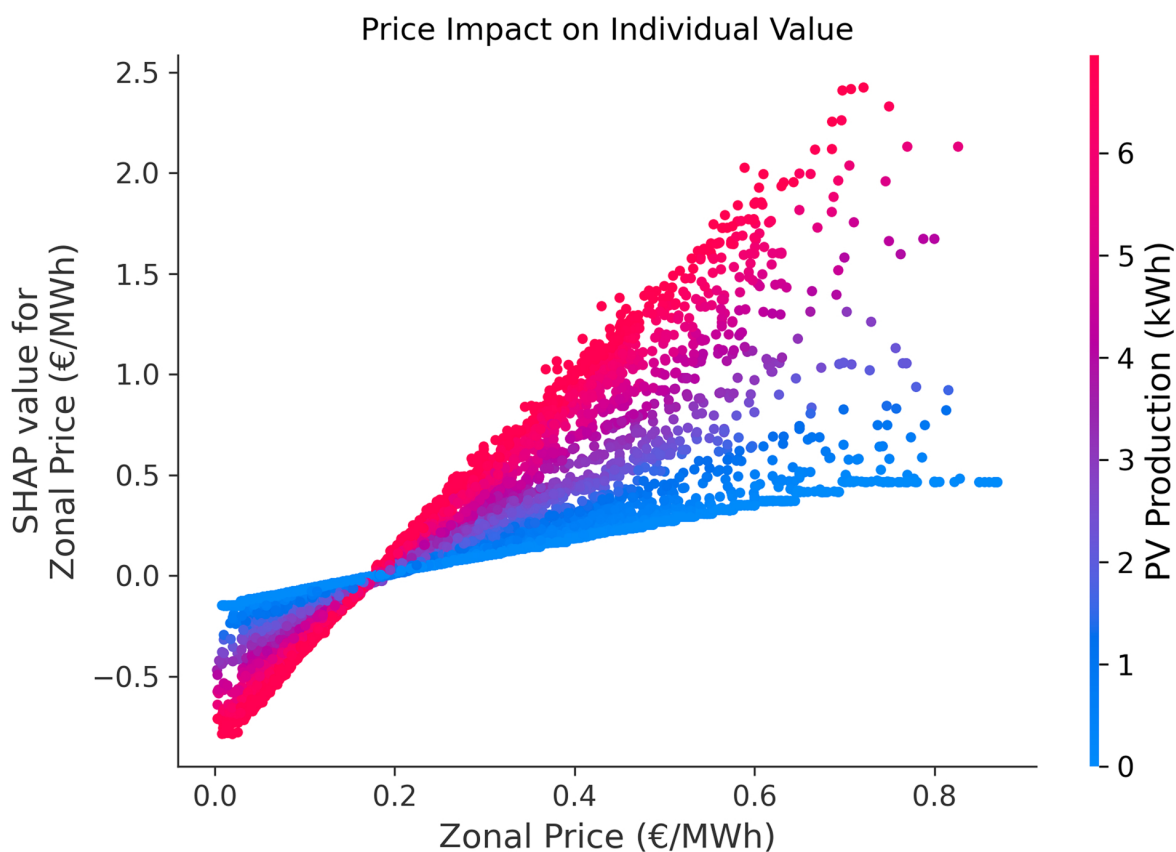


Figure 2. SHAP dependence plot for zonal price in the individual configuration.

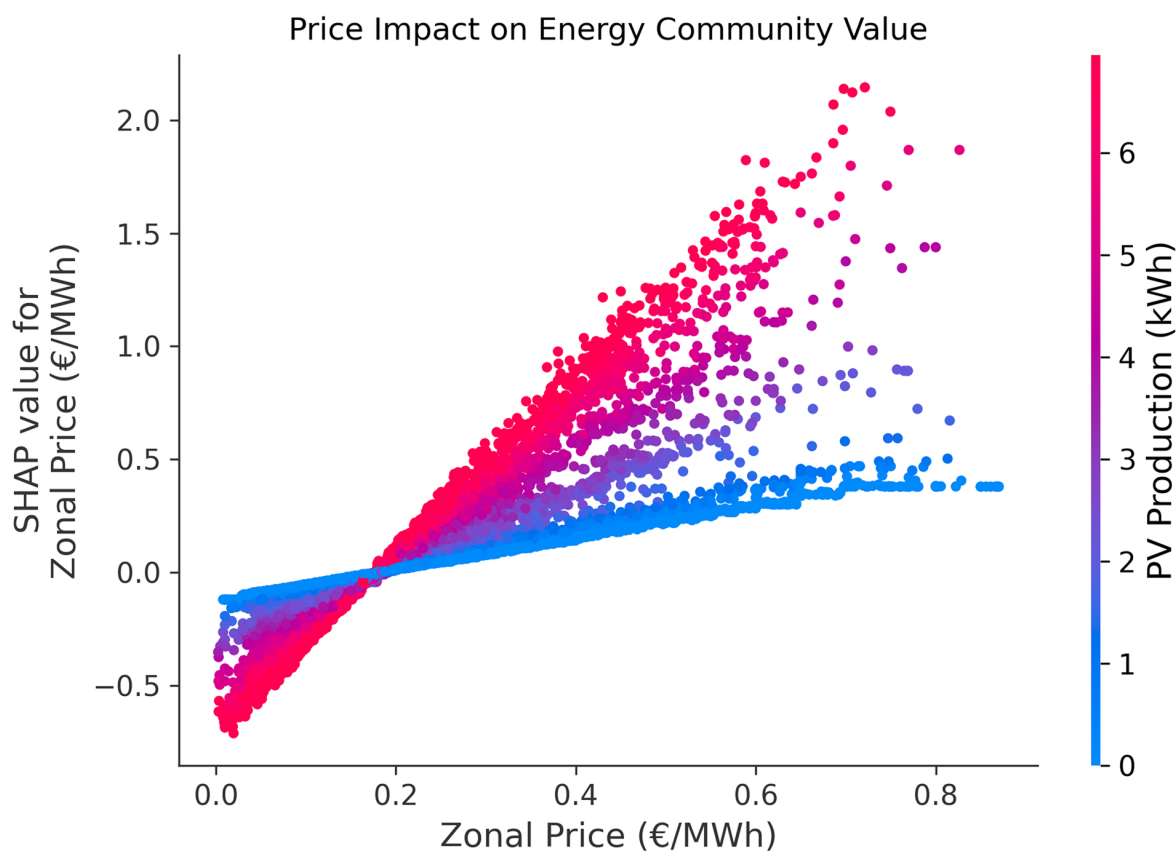


Figure 3. SHAP dependence plot for zonal price in the energy community configuration.

To further compare price sensitivity across configurations, Figure 4 reports the distribution of SHAP values associated with zonal price. The results show that the variability of price impact is lower in the energy community configuration compared to individual users. This indicates that RECs mitigate exposure to price fluctuations.

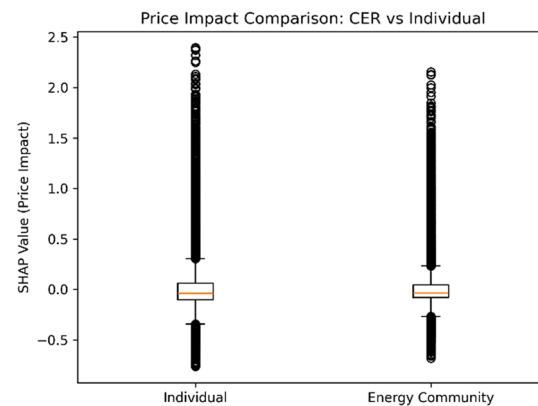


Figure 4. Boxplot comparison of SHAP values.

Furthermore, the results show that this difference is relatively small under normal price conditions but increases significantly during periods of high prices. In particular, during the 2022 price shock, the impact of price on individual configurations becomes substantially larger than that observed for the energy community.

This finding highlights a key insight: energy communities do not fundamentally alter the relationship between value and price under normal conditions, but they significantly reduce exposure during periods of market stress. In this sense, the stabilizing effect of energy communities can be interpreted as a conditional mechanism that becomes particularly relevant during extreme events.

To further investigate the drivers of economic value, SHAP summary plots are analyzed. Figure 5 presents the SHAP summary plot for the individual configuration. The results show that zonal price is the dominant driver of economic value, followed by photovoltaic production. The distribution of SHAP values is relatively dispersed, indicating a high sensitivity to variations in these variables.

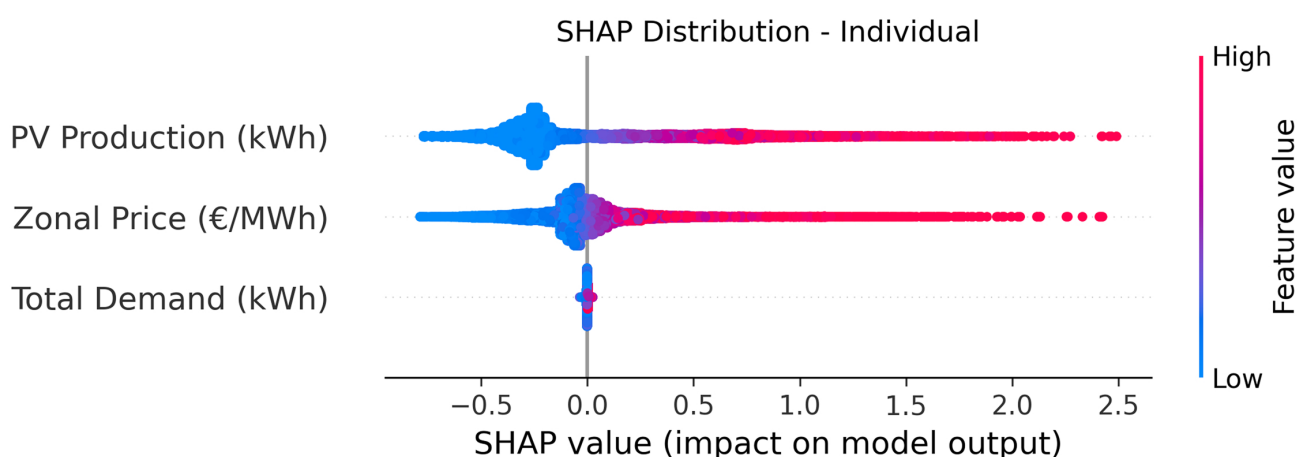


Figure 5. SHAP beeswarm individual.

Figure 6 reports the SHAP summary plot for the energy community configuration. While the same variables remain relevant, their contribution appears more balanced. In particular, the impact of zonal price is less extreme compared to the individual case, suggesting a reduced dependence on price dynamics within the community framework.

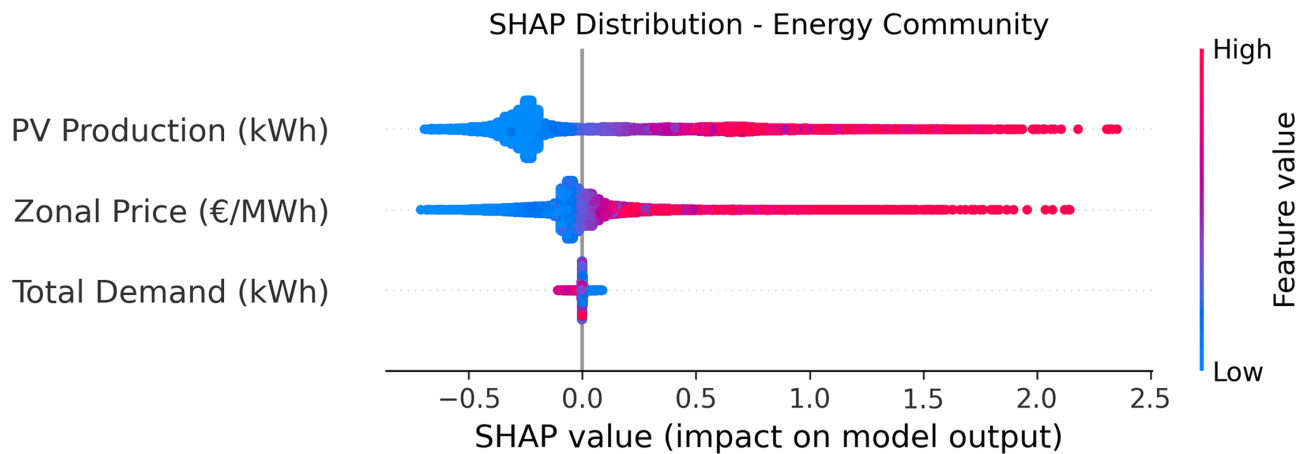


Figure 6. SHAP beeswarm REC.

5.4. Policy Analysis: Incentive Schemes

The analysis of incentive schemes provides further insights into the interaction between market dynamics and regulatory design. By comparing the economic value of the energy community under different incentive structures, it is possible to isolate the impact of policy changes.

The results show that the introduction of a variable component in the incentive scheme reduces the dependence of the community's value on electricity prices. In particular, the counter-cyclical nature of the revised mechanism dampens the increase in value during high-price periods, thereby contributing to a more stable revenue profile.

From a quantitative perspective, the estimated sensitivity of value to price decreases under the new incentive scheme, confirming that policy design plays a crucial role in shaping the resilience of energy communities. This effect is particularly relevant in the context of highly volatile markets, where excessive dependence on price dynamics can increase economic risk.

5.5. Stability and Risk Analysis

The comparison of stability across configurations is further supported by risk-based indicators. The analysis shows that, while individual users may achieve higher values during periods of high prices, they also exhibit greater variability over time. In contrast, the energy community demonstrates a more stable value profile, reflecting a lower exposure to price fluctuations.

This result is confirmed by the computation of risk-return metrics, which indicate that the energy community achieves a more balanced trade-off between average performance and volatility. In particular, during the 2022 price shock, the variability of value increases significantly for individual users, while the increase is more contained for the community configuration.

5.6. Synthesis of Results

Taken together, the results provide consistent evidence across different methodological approaches. The econometric analysis shows that energy communities have a lower average sensitivity to electricity prices, while the machine learning analysis reveals that this difference becomes more pronounced under conditions of high price volatility. The SHAP-based interpretation further confirms that the impact of price is less dispersed and more stable within the community framework.

These findings suggest that the primary advantage of energy communities does not lie in maximizing economic value under all conditions, but rather in reducing exposure

to market risk. In this sense, energy communities can be interpreted as a mechanism for enhancing resilience in electricity markets, particularly in the presence of external shocks and regulatory changes.

6. Discussion

The results provide robust evidence on the different responses of individual users and energy communities to electricity price dynamics, highlighting both structural and behavioral differences across configurations.

First, the panel econometric analysis reveals a clear and statistically significant relationship between electricity prices and economic value. The estimated coefficient for individual users ($\beta \approx 1.34\text{--}1.43$) indicates a strong positive sensitivity of economic value to price variations. In contrast, the interaction term associated with the energy community is negative, leading to a lower overall sensitivity ($\beta_{\text{CER}} \approx 1.23\text{--}1.34$ depending on specification). This confirms that, although both configurations benefit from price increases, energy communities exhibit a systematically reduced responsiveness to price changes.

This interpretation is consistent with the temporal patterns observed in Figure 1, where the 2022 price shock leads to significantly higher peaks and volatility for individual users compared to the energy community. The more contained dynamics observed for the community configuration suggest that energy sharing mechanisms dampen the transmission of external price shocks, contributing to a more stable economic outcome.

Second, the relationship between price and value, illustrated in Figures 2 and 3, reveals important structural differences. For individual users, the wider dispersion at higher price levels indicates a highly heterogeneous response, with the potential for extreme outcomes. In contrast, the more compact distribution observed for the energy community suggests the presence of a saturation effect, whereby the marginal contribution of price increases becomes progressively limited.

This behavior can be explained by the underlying economic mechanism of energy sharing. While individual users are directly exposed to market prices, energy communities partially internalize value through shared generation, reducing reliance on external price signals. As a result, the amplification of price shocks is mitigated. This interpretation is consistent with recent studies on renewable energy communities, which highlight the role of local energy sharing in reducing exposure to market volatility and improving system resilience [32].

Third, the SHAP-based analysis provides additional insights into the non-linear and state-dependent nature of price effects. The dependence plots indicate that, for individual users, the contribution of price increases sharply at higher price levels, confirming the presence of non-linear amplification effects. Conversely, the energy community exhibits a more gradual and bounded response, reinforcing the idea of reduced exposure to extreme price conditions.

This interpretation is further supported by the distributional evidence discussed in relation to Figure 4, where individual users exhibit a wider spread of SHAP values, particularly in the upper tail. This implies a higher exposure to extreme positive shocks, but also to increased variability. The energy community, instead, shows a more concentrated distribution, indicating greater stability in the contribution of price to economic value.

The SHAP summary analysis (Figures 5 and 6) further clarifies the role of different drivers. In both configurations, zonal price emerges as the dominant determinant of economic value. However, its contribution is more dispersed and extreme in the individual case, while it appears more moderated and balanced in the energy community. This suggests that, although price remains the primary driver, its influence is partially mitigated by the internal dynamics of energy sharing.

Taken together, these results provide consistent evidence across econometric, graphical, and machine learning approaches. The convergence of these methodologies strengthens the robustness of the findings and confirms that energy communities reduce the sensitivity of economic value to electricity price fluctuations.

Importantly, this stabilization effect should not be interpreted as a reduction in economic performance, but rather as a shift in the risk–return profile. While individual users may benefit more from extreme price increases, they are also more exposed to volatility. Energy communities, instead, trade off part of the upside potential in exchange for greater stability and predictability.

From a policy perspective, the results provide several important implications for the design of incentive schemes supporting Renewable Energy Communities (RECs), particularly in contexts characterized by high electricity price volatility. A contribution of this study is the comparison between alternative incentive structures, moving from a purely fixed tariff scheme to a hybrid mechanism combining a fixed and a variable component linked to market prices. The results show that this structural change has direct implications for both the level and the stability of economic value. Under a fixed incentive scheme, the economic performance of RECs remains strongly exposed to market price dynamics. While this allows participants to fully benefit from high-price periods, it also leads to increased volatility and amplifies the effects of market shocks, as observed during the 2022 energy crisis. In this configuration, the stabilizing effect of energy sharing is only partial, as external price signals still play a dominant role. In contrast, the introduction of a variable component linked to market prices modifies this dynamic. The results indicate that such a hybrid scheme reduces the sensitivity of economic value to price fluctuations, effectively introducing a counter-cyclical mechanism. During periods of high prices, the marginal contribution of the incentive is reduced, preventing excessive amplification of economic value. Conversely, in low-price conditions, the incentive provides additional support, contributing to a more stable revenue profile.

In this context, hybrid structures combining fixed and variable components emerge as the most effective solution, as they ensure baseline predictability while maintaining adaptive responsiveness to market conditions. The effectiveness of such schemes can be further enhanced through threshold-based mechanisms, which intensify support during periods of extreme price volatility. Overall, this implies a shift from efficiency-oriented to risk-oriented policy frameworks, where the evaluation of incentives should extend beyond average performance to include risk-adjusted metrics, such as variability and risk–return trade-offs. In this perspective, well-designed hybrid incentives can strengthen both the economic performance and the stabilizing role of Renewable Energy Communities in volatile electricity markets.

7. Conclusions

This study investigated the role of RECs in mitigating the effects of electricity price volatility, with a particular focus on the comparison between individual users and community-based configurations. Using high-frequency hourly data over the period 2021–2023, the analysis combined econometric models and machine learning techniques to provide a comprehensive assessment of how different energy configurations respond to market dynamics.

The results show that, while both individual users and energy communities benefit from increases in electricity prices, the latter exhibit a significantly lower sensitivity to price fluctuations. This finding highlights a key property of energy communities: their ability to reduce exposure to market volatility through internal energy sharing and aggregation mechanisms. In particular, the analysis demonstrates that this stabilizing effect becomes

more pronounced during periods of high price variability, such as the 2022 energy crisis, suggesting that energy communities act as a conditional resilience mechanism.

From an economic perspective, these results imply that the value of energy communities should not be assessed solely in terms of average profitability, but also in terms of their capacity to reduce variability and manage risk. While individual configurations may achieve comparable or higher short-term economic value under certain conditions, energy communities provide a more stable and predictable economic outcome, which is particularly relevant in increasingly volatile energy markets.

The analysis of incentive schemes further confirms the importance of policy design. The introduction of a dynamic component linked to electricity prices contributes to reducing the dependence of community value on market conditions, generating a counter-cyclical effect that enhances stability. This finding underscores the role of regulatory frameworks in shaping not only the profitability but also the resilience of decentralized energy systems.

Methodologically, the integration of econometric and machine learning approaches proved effective in capturing both average and non-linear dynamics. While panel models provided clear estimates of price sensitivity, machine learning techniques—interpreted through SHAP analysis—allowed for a deeper understanding of heterogeneous and state-dependent effects, particularly during extreme price events.

Overall, this study contributes to the literature by providing new evidence on the role of energy communities as instruments for managing price risk in decentralized energy systems. By explicitly linking price volatility, energy sharing mechanisms, and policy design within a controlled and data-driven framework, the paper offers insights into the potential role of energy communities in enhancing resilience in electricity systems.

Despite these contributions, some limitations remain. The analysis does not explicitly account for investment and operational costs, which may affect the overall economic attractiveness of energy communities. Furthermore, the results are based on a specific case study and may not fully capture the diversity of regulatory and market conditions across different contexts.

Future research should extend this framework by incorporating cost structures, exploring alternative community configurations, and analyzing the interaction between energy communities and additional flexibility resources such as storage and demand response. Further investigation is also needed to assess the scalability of these findings across different geographical areas and policy environments.

In conclusion, the findings of this study suggest that energy communities represent not only a tool for promoting renewable energy and local energy autonomy, but also a promising mechanism for enhancing resilience in electricity markets characterized by increasing uncertainty and volatility.

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