

## Graphical Abstract

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## Highlights

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- Research highlight 1
- Research highlight 2

# Assessing the Energetic, Economic and Environmental Viability of Battery Storage in a Energy Community: A Case Study from Denmark

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## Abstract

This paper presents a modular and generalizable framework for assessing the integrated energy, economic, and environmental performance of renewable-based Energy Communities combining photovoltaic generation and battery energy storage systems (BESS). The framework includes four analytical modules — energy, economic, environmental, and break-even analysis — each designed to quantify specific Key Performance Indicators related to efficiency, profitability, and sustainability.

The proposed approach enables the evaluation of how battery integration impacts local self-consumption, energy autonomy, and CO<sub>2</sub> emissions, while identifying the maximum sustainable battery cost that ensures economic feasibility for end users. The methodology is applied to different scenarios, showing that the inclusion of BESS enhances energy self-sufficiency by up to 56% and reduces annual CO<sub>2</sub> emissions by more than 50 tons for a

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1 MW capacity system. Although the payback period and ROI remain constant across scenarios — by design, as the maximum sustainable battery cost is determined for a fixed payback target — annual savings increase significantly, demonstrating that storage becomes economically viable as market costs decline.

The framework provides policymakers and stakeholders with a transparent decision-support tool to evaluate investment feasibility and to design incentive mechanisms for a just and economically sustainable energy transition.

*Keywords:* Energy Communities, Battery Energy Storage Systems, Break-even Analysis, Economic Feasibility, Sustainable Energy Transition

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Symbol	Unit	Description
$E_{Sol}(t)$	[kWh]	Photovoltaic energy produced at instant $t$
$E_{load}(t)$	[kWh]	Electricity demand of the users at instant $t$
$p(t)$	[€/kWh]	Electricity wholesale price at instant $t$
$SOC(t)$	[kWh]	Battery state of charge at instant $t$
$E_{ch}^{PV}(t)$	[kWh]	Solar energy used for self-consumption at instant $t$
$E_{solar\ charge}(t)$	[kWh]	Solar energy charged into the battery during instant $t$
$E_{ch}^{grid}(t)$	[kWh]	Energy imported from the electricity grid during instant $t$ to charge the battery
$E_{dis}(t)$	[kWh]	Energy discharged from the battery during instant $t$
$E_{grid}^{imp}(t)$	[kWh]	Energy imported from the electricity grid during instant $t$ to feed the unmet demand
$E_{grid}^{exp}(t)$	[kWh]	Energy exported to the electricity grid during instant $t$
$P_{batt}$	[kW]	Maximum charge/discharge power of the battery
$E_{batt}$	[kWh]	Nominal energy capacity of the battery
$SOC_{min}$	[kWh]	Minimum allowable battery state of charge
$SOC_{max}$	[kWh]	Maximum allowable battery state of charge
$\eta_{ch}$	[-]	Battery charging efficiency
$\eta_{dis}$	[-]	Battery discharging efficiency
$I_{grid}$	[kgCO <sub>2</sub> /kWh]	Carbon intensity of electricity from the grid
$I_{PV}$	[€]	Initial investment for the photovoltaic system

## 1. Introduction

Energy communities represent a novel and participatory approach to energy management, where citizens, local authorities, and small businesses actively collaborate in the production, consumption, and sharing of electricity. Within the European regulatory framework, two main types of energy communities are recognized: Citizen Energy Communities (CECs) and Renewable Energy Communities (RECs). Both entities are legal bodies characterized by open and voluntary participation, autonomy, and the goal of providing environmental, social, and economic benefits rather than financial

profits. While RECs are geographically constrained to the vicinity of renewable energy projects and exclusively focus on renewable technologies, CECs operate across broader energy sectors, including non-renewable sources, without geographical limitations.

Over the past decade, energy communities have rapidly expanded in Europe, supported by legislative measures and financial incentives. As of 2023, nearly 4,000 energy communities with around 900,000 members were active in the EU, particularly in Germany, Denmark, and the Netherlands [1].

Photovoltaic systems have emerged as the cornerstone technology in energy communities due to their affordability, compatibility with self-consumption, and support under European and national policies. However, the intermittent nature of solar generation necessitates the integration of energy storage systems to maximize local self-consumption and ensure economic viability. Lithium ion batteries are the most widely used energy storage technology for photovoltaic applications, because of their high energy density, long life, and high cycle efficiency. As reported in the study by [2], battery storage (lithium batteries) allows prosumers to maximize their self-consumption of solar photovoltaic energy and further reduce their total annual energy costs. Despite the technological advantages, the cost of lithium-ion batteries represents a significant barrier to large-scale deployment. The initial investment costs are high and directly affect the profitability of the project. In recent years, however, there has been a continuous reduction in the specific price of batteries, thanks to technological advances and increased industrial production on a global scale. Lithiumion batteries have seen a price decrease of 82% between 2013 and 2023 [3]. Despite technological advances in PV systems and battery storage, a research gap remains regarding the economic feasibility of battery integration in energy communities, with limited focus on quantifying the threshold battery cost that ensures economic sustainability within participatory EC frameworks. This lack of economic analysis hinders clear guidance for stakeholders on the viability and deployment potential of storage systems in ECs. The OPTIX project provides insights directly relevant to this gap, demonstrating across seven European pilot sites how flexibility and digitalization solutions—such as advanced control, smart storage, and blockchain-based peer-to-peer trading—can optimize local energy management, enhance self-consumption, and facilitate community participation [4]. These pilot implementations, distributed across Ireland, Sweden, Denmark, Turkey, Germany, Austria, and Romania, illustrate how interoperable digital platforms can support Positive Energy Districts (PEDs) in improving self-

sufficiency and grid stability through coordinated renewable generation and storage management.

## 2. Methodology

### 2.1. Research Design and Conceptual Framework

The methodological framework developed in this study aims to evaluate the integrated energy, economic, and environmental performance of a renewable-based EC that combines PV generation and BESS. The overarching goal is to determine the economic feasibility of integrating BESSs into the EC configuration and to identify the maximum sustainable battery cost that ensures the investment remains financially attractive for users. The framework is designed to be generalizable and modular, allowing its application to different community scales, configurations, and policy contexts. Four interconnected analytical modules compose the overall structure of the proposed framework, each of them is dedicated to a specific dimension of the system performance, as illustrated in Figure 1:

1. Energy Module, which simulates interactions between PV generation, local load, and battery operation, computing key energy performance indicators.
2. Economic Module, that estimates investment costs, energy savings, and revenues from self-consumption and grid interactions.
3. Environmental Module, which quantifies avoided CO<sub>2</sub> emissions due to local renewable generation and storage.
4. Break-even Analysis Module, that integrates outputs from the previous modules to identify the threshold conditions (e.g., maximum battery cost) under which the system remains economically feasible.

Each module contributes to the computation of KPIs representing specific dimensions of performance: energy efficiency, financial profitability, and environmental impact. Together, these KPIs form a coherent decision-support tool to assess whether the integration of storage technologies in Energy Communities is technically beneficial, environmentally sound, and economically viable.

To ensure comparability and multidimensional evaluation, three categories of KPIs were adopted, as shown in Table 1.

Table 1: Key Performance Indicators for ECs

Category	KPI	Acronym	Unit	Description
Energy	Self-Sufficiency ratio	SSR	%	Share of total demand covered by local generation and storage.
	Self-Consumption ratio	SCR	%	Share of PV production used locally.
Economic	Payback period	PBP	years	Time required to recover the total investment.
	Return on Investment	ROI	%	Profit-to-investment ratio.
	Annual cost savings	CS	€/year	Energy cost savings from self-consumption and storage.
Environmental	CO <sub>2</sub> emission reduction	CER	kg CO <sub>2</sub> /year	Avoided emissions through renewable self-consumption.

These KPIs reflect the triple-bottom-line approach (energy, economy, environment) recommended by the EU for assessing sustainable urban energy systems. Together, they form a comprehensive assessment tool capable of supporting decision-making processes related to the integration of battery storage systems in community energy schemes. The research design and conceptual framework is illustrated in Figure 1. The following sections detail the analytical structure of each module, starting from the energy balance model that forms the basis for the computation of all performance indicators.

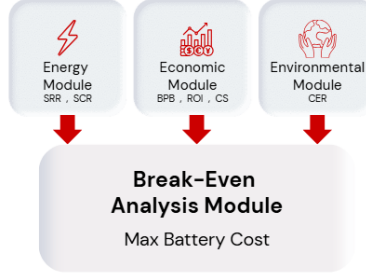


Figure 1: Research Design and Conceptual Framework

## 2.2. Energy Module

The Energy Module provides the quantitative basis for all subsequent analyses, thus representing the core of the framework. It models the interaction among PV generation, community electricity demand, the external grid, and the operation of BESS. Through this module, the main energy flows within the EC are reconstructed, allowing the calculation of energy performance indicators, such as SCR and SSR, that reflect how efficiently local renewable resources are utilized. Therefore, the module considers four primary energy exchanges at each instant  $t$ :

- electricity generated by the PV system,  $E_{Sol}(t)$ ;
- energy consumed by the community load,  $E_{load}(t)$ ;
- energy charged into or discharged from the battery,  $E_{ch}(t)$  and  $E_{dis}(t)$ ;
- electricity exchanged with the external grid,  $E_{grid}^{imp}(t)$  and  $E_{grid}^{exp}(t)$ .

The instantaneous energy balance of the system can therefore be expressed as in Eq. 1.

$$E_{PV}(t) + E_{dis}(t) + E_{grid}^{imp}(t) = E_{load}(t) + E_{ch}(t) + E_{grid}^{exp}(t) \quad (1)$$

### 2.2.1. PV Energy Generation

At each time instant  $t$ , the portion of PV energy directly used to satisfy the electric load,  $E_{PV}(t)$ , is computed as the minimum value between the PV energy produced  $E_{Sol}(t)$  and the electric load  $E_{load}(t)$ , as in Equation 2.

$$E_{PV}(t) = \min \left( E_{Sol}(t), E_{load}(t) \right) \quad (2)$$

The residual energy demand not covered by PV generation is computed as shown in Equation 3.

$$E_{res}(t) = E_{load}(t) - E_{PV}(t) \quad (3)$$

### 2.2.2. Battery Charging and Discharging Management

The charging and discharging of the battery are governed by the state of charge (SOC) and by the efficiencies of the charging and discharging processes,  $\eta_{ch}$  and  $\eta_{dis}$ .

Battery charging from PV occurs when a PV surplus is available after satisfying the immediate electricity demand and the battery is not yet fully charged [5]. This strategy ensures that locally generated solar energy is efficiently stored for later use before any export to the grid occurs and its amount is calculated as shown in Equation 4.

$$\begin{aligned} E_{surplus}(t) &= E_{PV}(t) - E_{load}(t) \\ SOC(t) &< SOC_{max} \\ E_{ch}^{PV}(t) &= \min \left( P_{batt} \cdot \Delta t, \frac{SOC_{max} - SOC(t)}{\eta_{ch}}, E_{surplus}(t) \right) \end{aligned} \quad (4)$$

Under certain conditions, the battery can also be charged from the grid, and the charged energy  $E_{ch}^{grid}(t)$  is computed as shown in Equation 5. The conditions that have to be met are: the economic convenience (e.g., low electricity prices), the PV surplus is not sufficient to meet the residual load, and the SOC is below its maximum value ( $SOC_{max}$ ).

$$E_{ch}^{grid}(t) = \min \left( P_{batt} \cdot \Delta t, \frac{SOC_{max} - SOC(t)}{\eta_{ch}} \right) \quad (5)$$

This strategy allows the community to take advantage of low electricity prices while ensuring that the battery is sufficiently charged for later use.

The total energy charged into the battery is then:

$$E_{ch}(t) = E_{ch}^{PV}(t) + E_{ch}^{grid}(t) \quad (6)$$

On the other hand, battery discharging occurs when residual demand is positive and SOC exceeds its minimum threshold, thus the stored energy is used to satisfy this residual load. Therefore, the energy discharged  $E_{dis}(t)$

is calculated as shown in Equation 10. This strategy ensures efficient use of stored energy to minimize grid imports.

$$E_{res}(t) = E_{load}(t) - E_{PV}(t) > 0 \quad (7)$$

$$SOC(t) > SOC_{min} \quad (8)$$

$$E_{dis}^{max}(t) = \min \left( P_{batt} \cdot \Delta t / \eta_{dis}, SOC(t) - SOC_{min} \right) \quad (9)$$

$$E_{dis}(t) = \min \left( E_{dis}^{max}(t), E_{res}(t) / \eta_{dis} \right) \quad (10)$$

Therefore, the amount of energy discharged that is delivered to load from battery depends on the discharge efficiency of the BESS, as shown in Equation 11.

$$E_{dis \rightarrow Load}(t) = \eta_{dis} \cdot E_{dis}(t) \quad (11)$$

Additionally, the SOC evolution due to PV and grid charging and to meet the load demand is updated as in 12.

$$SOC(t+1) = SOC(t) + \eta_{ch} \cdot E_{ch}(t) - E_{dis}(t) \quad (12)$$

### 2.2.3. Grid Import and Export

Any excess solar energy that cannot be stored in the battery could be exported to the grid: if the solar generation  $E_{PV}(t)$  exceeds both the immediate load demand  $E_{load}(t)$  and the available storage capacity of the battery (SOC within the allowable range), the remaining energy is fed into the grid ( $E_{grid}^{exp}(t)$ ), ensuring that no locally generated solar energy is wasted (Equation 13).

$$E_{grid}^{exp}(t) = E_{PV}(t) - E_{load}(t) - E_{ch}^{PV}(t) \quad (13)$$

On the other hand, any remaining load that cannot be satisfied by either the solar generation or the battery is imported from the grid: if there is a positive residual demand after accounting for available local resources, the grid supplies the required energy to ensure that all demand is met.

$$E_{grid}^{imp}(t) = E_{load}(t) - E_{PV}(t) - E_{dis \rightarrow Load}(t) \quad (14)$$

### 2.2.4. Energy Management Logic

Depending on PV production and load profiles, the model determines the energy management strategy according to the following priorities:

1. PV energy is first used to cover local demand (*self-consumption*);

2. any PV surplus is used to charge the battery (*self-storage*);
3. if the battery is full, additional surplus is exported to the grid;
4. when local generation and stored energy are insufficient, the deficit is supplied by the grid.

This management logic ensures that locally produced renewable energy is prioritized, reducing both grid dependency and curtailment of PV production.

### 2.2.5. Calculation of Energy Performance Indicators (KPIs)

All instantaneous quantities are aggregated over the considered time horizon  $T$  to compute cumulative energy flows:

$$E_{x,tot} = \sum_{t=0}^T E_x(t) \quad (15)$$

From these cumulative quantities, two key performance indicators are derived:

- Self-consumption ratio:

$$SCR = \frac{E_{SC}(t)}{\sum_{t=1}^T E_{Sol}(t)} \cdot 100\% \quad (16)$$

- Self-sufficiency ratio:

$$SSR = \frac{E_{SC}}{\sum_{t=1}^T E_{load}(t)} \cdot 100\% \quad (17)$$

where the total self-consumed energy from PV and battery is:

$$E_{SC} = \sum_{t=1}^T \left[ E_{PV}(t) + (E_{dis}(t) - E_{ch}^{grid}(t)) \cdot \eta_{dis} \right] \quad (18)$$

Higher SCR values indicate better utilization of local renewable resources, while higher SSR values denote increased autonomy from the external grid. These indicators link the physical operation of the EC to its economic and environmental implications, providing the foundation for the subsequent Economic and Environmental Modules.

### 2.3. Economic Module

The Economic Module translates the energy flows computed by the Energy Model into monetary terms. It quantifies the revenues from energy exports, and the overall import costs in order to evaluate the economic performance, computed respectively as in Equations 19 and 20.

$$Revenue = \sum_{t=1}^T E_{grid}^{exp}(t) \cdot p(t) \quad (19)$$

$$Import\ Cost = \sum_{t=1}^T [E_{ch}^{grid}(t) + E_{grid}^{imp}(t)] \cdot p(t) \quad (20)$$

These variables serve for the calculation of Economic Performance Indicators, such as the annual savings from direct consumption and battery discharge, the payback period, and the ROI. Their computation is in Equations 21, 22, and 23.

$$Savings = \sum_{t=1}^T [E_{PV}(t) + \eta_{dis} \cdot E_{dis}(t)] \cdot p(t) \quad (21)$$

$$Payback = \frac{I_{PV} + E_{batt} \cdot C_{batt}}{Savings + Revenue} \quad (22)$$

$$ROI = \frac{Savings + Revenue}{I_{PV} + E_{batt} \cdot C_{batt}} \cdot 100\% \quad (23)$$

### 2.4. Environmental Module

The Environmental Module quantifies the environmental benefits generated by the system through the reduction of CO<sub>2</sub> emissions. These benefits derive from the replacement of electricity drawn from the national grid, which is often produced from fossil fuels, with self-consumed renewable energy from PV generation and battery storage. The model provides an essential sustainability metric to complement the economic and energetic analysis. The indicator used to assess environmental performance is the overall CO<sub>2</sub> emission reduction:

$$CO_2 = E_{SC}(t) \cdot I_{grid} \quad [\text{kg CO}_2] \quad (24)$$

where  $I_{grid}$  is the carbon intensity of electricity from the grid.

### 2.5. Break-even Analysis Module

This section aims to determine the maximum sustainable battery unit cost,  $C_b^{\max}$  (in €/kWh), for which the investment in a PV system coupled with storage remains economically viable, and specifically, competitive with a PV-only configuration in terms of payback period. The maximum battery cost is then defined as:

$$C_b^{\max} = \max\{C_b \mid \text{Payback}(C_b) \leq \text{Payback}_{\text{target}}\} \quad (25)$$

This approach quantifies the break-even cost threshold beyond which the battery investment would no longer meet the economic viability criterion defined by the target payback period. The resulting value of  $C_b^{\max}$  provides actionable insights for investors and policymakers by identifying under which cost or subsidy conditions battery storage becomes an economically attractive component within ECs.

## 3. Case Study: Application to Lyngby Idrætsby

### 3.1. Overview

The proposed methodology was applied to the Lyngby Idrætsby Sports Centre, located in the municipality of Lyngby-Taarbæk (Denmark), one of the pilot sites of the OPTIX Project [4]. Within the same European initiative, other pilot sites demonstrate how interoperable digital platforms can enhance local renewable integration and flexibility across diverse urban contexts. The Lyngby Idrætsby Sports Centre includes a range of infrastructure such as gyms, sports fields, parks, and a swimming pool, and was selected as a representative case study for testing the integration of PV systems and BESS in urban energy communities. Although the sport center currently operates behind a single metering point, the consumption data represent the sum of all buildings.

The model was implemented in Python using standard libraries (Pandas, NumPy, SciPy) and applied over a full calendar year, using hourly time-series data for electricity demand and PV generation. The simulation reflects typical climatic and energy usage patterns observed in Denmark, where electricity demand is generally higher during the winter months due to heating requirements (Figure 2). The PV system was designed specifically for the rooftop surfaces available on-site (Figure 3). 430 Wp DUPLEX bifacial modules were

use: each PV module has dimensions of 1,722 mm  $\times$  1,134 mm, corresponding to an area of 1.953 m<sup>2</sup> and a power density of approximately 220 Wp/m<sup>2</sup>. The final configuration includes 2,452 PV modules and 11 inverters, resulting in a total nominal installed power of 1,054 kWp.

Regarding cost assumptions, the total capital expenditure (CAPEX) for the PV system includes both equipment and installation costs. Following standard practice, installation costs were assumed to account for approximately 20% of the total PV investment.

Table 2 summarizes the key technical and economic input parameters used in the model simulations.

Table 2: Summary of input data and technical parameters

Parameter	Description / Value
$E_{load}(t)$	Hourly demand provided by Lyngby-Taarbæk Municipality (2024).
$E_{Sol}(t)$	Simulated using <b>PV*SOL Premium</b> , based on site-specific geographic coordinates and local meteorological data.
$p(t)$	Hourly wholesale market prices for DK2 region (Ember dataset, 2024).
$I_{grid}$	Hourly data from Energinet’s Energi Data Service (2024).
PV system	1.054 MWp total capacity; 2,452 bifacial panels (430 Wp each).
Battery storage	Two alternative configurations tested: 4-hour and 8-hour energy storage capacity.
$I_{PV}$	€588,000 ( $\approx$ 4.54 million DKK).
Simulation resolution	Hourly time step ( $\Delta t = 1$ h) over one full year (8,760 h).

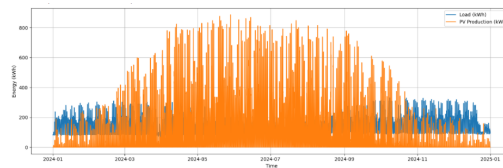


Figure 2: PV generation and energy demand over the analysis period.

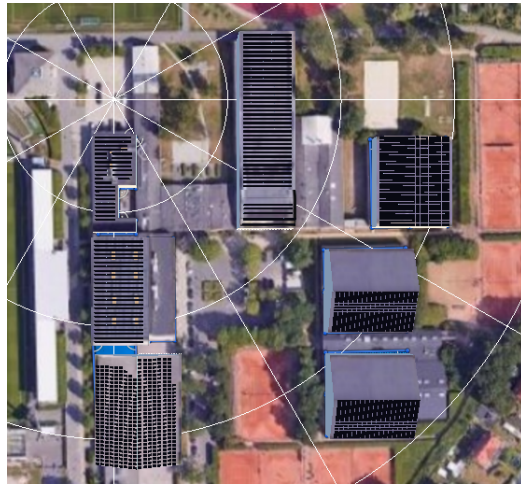


Figure 3: Top view of the PV system

### *3.2. Scenarios*

Four progressively complex scenarios were evaluated, and they are described in Table 3.

Table 3: Overview of simulated scenarios

Scenario	Description	Key Characteristics
Base Case	No PV, no storage	Entire electricity demand covered by grid imports. Benchmark for economic and energy performance comparison.
Scenario 1	PV only	Local PV generation used for direct self-consumption. No storage system. No export allowed.
Scenario 2a	PV + 4h battery	Battery charged exclusively from PV surplus. No grid charging. Focus on maximizing on-site renewable use.
Scenario 2b	PV + 4h battery	Battery charged from PV surplus and, when economically advantageous, from the grid at low price periods.
Scenario 3a	PV + 8h battery	Larger storage capacity. PV-only charging strategy. Surplus PV can be exported to the grid.
Scenario 3b	PV + 8h battery	Battery charged from both PV and the grid; surplus PV can be exported.

### 3.3. Results and Discussion

The KPIs were computed for each scenario, as summarized in Table 4. Battery integration leads to improvements in self-consumption, self-sufficiency, and CO<sub>2</sub> emissions reduction, as shown in Figure 4 and Figure 5.

Table 4: KPIs for ECs

Category	KPI	Unit	Base	S1	S2a	S2b	S3a	S3b
Energy	SSR	%	0.00	36.69	48.31	48.15	55.13	56.19
	SCR	%	0.00	45.53	59.94	59.75	68.40	69.72
Economic	Payback Period	years	-	21	21	21	21	21
	ROI	%	-	4.62	4.76	4.76	4.76	4.76
	Annual Savings	€/year	0	27,159	39,920	46,136	47,038	55,404
Environmental	CO <sub>2</sub> Emission Reduction	kgCO <sub>2</sub> /year	0	34,651	45,621	45,475	52,059	53,065
Break-even Analysis	Max Battery Cost	€/kWh	-	-	347.70	529.00	424.83	544.22

The simulation highlights a clear evolution in system performance as successive configurations are introduced—from basic photovoltaic integration to

advanced storage and grid interaction strategies.

The Base Case, relying solely on grid electricity, reflects the highest level of energy dependency and the absence of any environmental or economic benefits. It serves as a reference point for evaluating the improvements achieved through system enhancement.

Scenario 1, which introduces photovoltaic generation, reduces reliance on the grid and lowers emissions. However, the system’s performance is constrained by the seasonal mismatch between solar production (which peaks in summer) and energy demand (which is higher in winter). Without the ability to store or export excess energy, a significant portion of production is wasted, limiting both financial returns and sustainability gains.

Scenario 2a addresses this by integrating a battery energy storage system, used exclusively to store photovoltaic surplus. This enhances self-consumption and self-sufficiency, and reduces both energy costs and emissions. However, since the battery is underutilized during winter months, its full economic potential is not realized. Scenario 2b introduces a smart operational strategy: the battery is allowed to charge from the grid when electricity prices fall below a predefined threshold—typically during off-peak or low-demand periods. This enables the battery to remain active throughout the year, especially in winter, when solar production is minimal. By leveraging price volatility, the system improves its cost-efficiency and increases the economic viability of storage, without compromising environmental performance.

Scenario 3a builds on this by enabling the export of surplus solar energy to the grid. This eliminates curtailment and ensures full utilization of locally generated energy—either for self-consumption, storage, or export. Export revenues improve economic performance, making the system more attractive from a return-on-investment perspective.

Scenario 3b combines the benefits of export with the smart import logic introduced in scenario 2b. The battery is charged during low-price hours and discharged when prices are high, while any surplus solar energy is exported to the grid. This configuration optimizes both environmental and financial outcomes, achieving the best balance across all performance dimensions: emissions, self-sufficiency, self-consumption, and profitability.

From the results summarized in Table 4, it is evident that the introduction of BESS leads to a substantial improvement in both energy and environmental performance. The SSR increases from 36.7% in the basic configuration (S1) to over 56% in the most advanced scenarios (S3b), while the SCR rises from

45.5% to nearly 70%. These results confirm that storage integration significantly enhances the capacity of the community to exploit locally generated renewable energy, reducing dependency on the external grid and associated CO<sub>2</sub> emissions. Indeed, the CO<sub>2</sub> emission reduction improves from 34.6 to over 53 tons of avoided emissions per year. As shown in figure 6, energy import/export gradually improves across the scenarios. From an economic perspective, the annual savings increase markedly with the scale of PV and storage deployment, from roughly 27 k€ in S1 to more than 55 k€ in S3b.

However, the Payback period and ROI remain constant across scenarios, around 21 years and 4.8% respectively. This behavior is not coincidental as the break-even analysis explicitly identifies, for each scenario, the maximum sustainable battery cost that maintains the same payback as the base case. In other words, each scenario represents a configuration where the battery cost has been adjusted until the payback equals the predefined target. The total investment cost of a lithium-ion battery system in 2025 is estimated at around €330/kWh, including cells, packs, and additional system components. The figure 7 compares this reference market cost with the modeled battery prices obtained in the different simulation scenarios, showing how each case performs relative to the benchmark. The maximum sustainable battery costs range from €348 to €544/kWh—well above current market prices—suggesting that battery adoption approaches full economic viability even without further cost reductions. These values indicate that, under current market trends, battery technologies are approaching a cost threshold that makes them economically viable for collective self-consumption applications. The results underscore that advanced storage strategies, particularly those combining smart import/export logic, not only enhance environmental performance but also provide a financially attractive path for system optimization.



Figure 4: SSR and SCR for all scenarios [%].

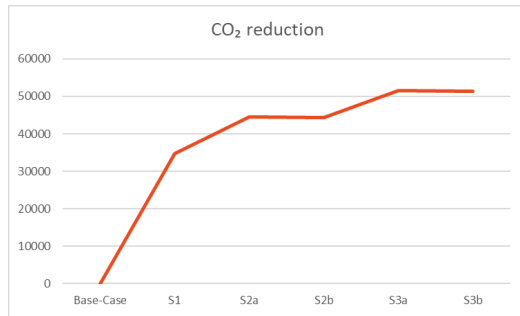


Figure 5: Annual CO<sub>2</sub> emission reduction across all scenarios [kgCO<sub>2</sub>/year].

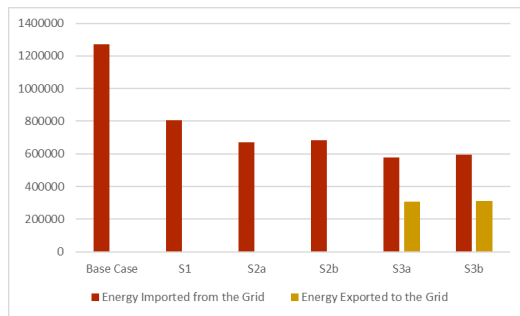


Figure 6: Annual energy import and export for all scenarios [kWh].

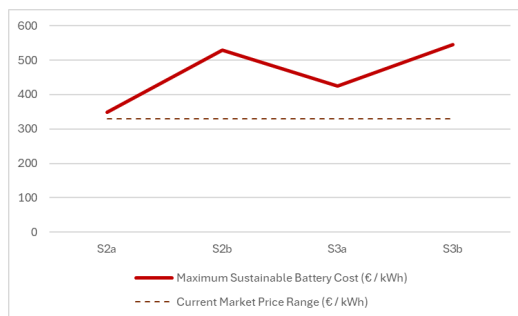


Figure 7: Comparison of battery costs across different scenarios and current market price [€/kWh].

#### 4. Conclusion and Policy Implications

This study proposed a modular and generalizable framework for the integrated assessment of the energy, economic, and environmental performance of ECs combining PV generation and BESS. By applying the framework to different operational and policy scenarios, the analysis quantified how battery integration affects local energy autonomy, cost savings, and environmental benefits. Modeled battery prices in all configurations remain below the estimated 2025 market benchmark of €330/kWh, indicating that storage deployment is economically advantageous and represents a cost-effective addition to the system. These findings collectively demonstrate that battery integration is not only technically feasible but also economically and environmentally advantageous.

From a policy standpoint, several implications emerge. First, BESS integration should be recognized as a strategic component for enabling flexibility, decarbonization, and local energy independence. Second, stable and transparent regulatory frameworks are essential to encourage investment in storage, ensuring that community-scale projects can benefit from both environmental and economic returns. Third, the adoption of collective ownership and energy-sharing mechanisms could further enhance cost-effectiveness, reducing the initial investment burden and fostering social participation in the energy transition.

Despite its robustness, the framework has some limitations. It is based on deterministic input data and does not account for the stochastic variability of solar generation, electricity prices, or demand behavior, which may influence the profitability of storage. Additionally, only electricity-based interactions

were modelled, while potential synergies with other energy carriers, such as heating, cooling, or e-mobility, were not considered.

Future research will therefore focus on extending the framework to multi-energy and multi-actor contexts, incorporating uncertainty analysis and dynamic optimization of BESS operation. These developments will support policymakers and stakeholders in designing economically efficient and socially inclusive strategies for accelerating the just and sustainable energy transition.

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