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Techno-economic Assessment of Battery Energy Storage Systems in Renewable Energy Communities

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ABSTRACT

Renewable Energy Communities (RECs) are an important driver in the energy transition to foster renewables deployment in a cost-effective way, to engage citizens in the energy sector with an active participation, to share local energy, and to improve local balancing. A key element to maximize the utilization of renewable resources is the ability to store energy in renewable energy communities. By storing excess energy, communities can avoid curtailment, which occurs when renewable energy generation exceeds the immediate demand. This curtailed energy can be stored for later use which optimizes the functioning of an integrated system. This study highlights the cost-effectiveness of implementing Battery Energy Storage Systems (BESS) in the framework of REC. Findings support the potential benefits even when employing lower-efficiency storage systems, provided their costs are sufficiently low. Results show that, at the current level of technological development, BESS are not economically viable without additional revenue streams. It is also shown that BESS could be economically feasible in the future with anticipated technological development that would drive Capital Expenditure (CAPEX) down. Under these circumstances, cost savings are enhanced in the REC context, as members' energy storage capacities are shared within the community along with the renewable energy generation.

Keywords

Techno-economic Assessment;
Renewable Energy Communities;
Battery Energy Storage Systems;
Wind power;
Solar PV

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1. Introduction

The European Union (EU) introduced the concept of energy communities in the legislative framework of 2019, specifically the citizen energy communities and Renewable Energy Communities (RECs) under the Clean Energy for All Europeans initiative [1]. Directives EU 2018/2001 [2] and EU 2019/944 [3] further enhance the relevance of self-consumption (SC) and REC, strengthening their role in the energy market. EU member states have adjusted their national laws to endorse and foster these emerging entities. The Portuguese Decree-Law 15/2022 [4] outlines the concept, operational, and technical details of SC that RECs must comply with, including proximity criteria, energy sharing mechanisms, grid tariffs, and licensing protocols.

Within a REC environment [5], heterogeneous members aggregate themselves as one legal entity, each possessing different demand profiles, enabling energy production, consumption, sharing, and storage, whereas a designated managing entity oversees all energy and economic transactions. In [6], the authors outline the dynamics of REC in Europe, emphasizing their role in

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List of acronyms

BESS:	Battery Energy Storage Systems
CAPEX:	Capital Expenditure
CES:	Community Energy Storage
CSC:	Collective Self-Consumption
DAM:	Day-ahead-market
EC:	Energy Community
EGAC:	Collective Self-consumption Managing Entity
EGACF:	Collective Self-consumption Managing Entity Fixed Fees
EGACV:	Collective Self-consumption Managing Entity Variable Fees
EMS:	Energy Management System
EU:	European Union
GA:	Genetic Algorithm
HRES:	Hybrid Renewable Energy Sources
IRES:	Integrated Renewable Energy Systems
ISC:	Individual Self-Consumption
LCOE:	Levelized Cost Of Energy
LP:	Linear Programming
MILP:	Mixed Integer Linear Programming
P2P:	Peer-to-Peer
PV:	Solar Photovoltaics
REC:	Renewable Energy Communities
SmBMS:	Smart Battery Management System
TSC:	Regulator Self-Consumption Tariff
WACC:	Weighted Average Cost of Capital

promoting renewable energy sources and highlighting the multifaceted benefits they provide. These benefits include not only environmental advantages but also social and economic improvements for local communities. The study stresses the urgent need to modernize energy systems to support optimal self-consumption, energy sharing, and demand response mechanisms. Such advancements would enhance energy efficiency and grid stability.

Additionally, the involvement of policymakers is crucial in steering these sustainable energy transitions, ensuring that supportive frameworks and incentives are in place for the widespread adoption of renewable technologies.

1.1 Literature Review

1.1.1 *Energy Communities, markets and decarbonization strategies*

Energy communities (ECs) play a crucial role in the transition to sustainable energy by integrating renewable energy sources (RES) and optimizing storage solutions. A study in Lisbon [7] demonstrated that solar panels and battery storage systems enhance financial savings and self-sufficiency, significantly reducing reliance on external energy. Similarly, university campuses have been a focus for decarbonization strategies. Research [8] showed that integrating photovoltaic (PV) and storage systems led to substantial CO2 emission reductions, while another study [9] found that an integrated solar-storage system reduced community energy bills by 11.7%, encouraging greater participation and individual savings. Further extending the approach to decarbonization, a multi-objective optimization framework [10] emphasized the importance of sector coupling technologies and hydrogen integration to minimize carbon emissions and costs within ECs.

Governance and stakeholder engagement play a critical role in the success of ECs. A project in Nigeria [11] highlighted gaps in community involvement and stressed the need for inclusive governance mechanisms to ensure project effectiveness. Multifamily residential blocks have leveraged serious gaming applications [12] to model energy efficiency scenarios, providing insightful feedback for optimizing energy use. A smart energy system in Riga [13] was developed for university districts, achieving 80% self-consumption of renewable energy. Meanwhile, the use of game theory [14] enabled fair distribution of shared energy resources, optimizing self-consumption and reducing battery payback periods.

A study conducted on Samsø Island [15] compared residential and communal PV battery setups, revealing that communal systems optimize grid efficiency, whereas residential setups promote energy independence. Expanding on community-level energy storage strategies, UK-based research [16] optimized PV time-shifting and demand management, demonstrating a reduction in costs and emissions. Similarly, in Japan [17], researchers tackled economic challenges of battery energy storage systems (BESS) through genetic algorithms and demand response simulations, achieving a 38.8% reduction in battery capacity needs and a 46.4% decrease in payback periods for energy storage investments.

The development of energy markets and policies for ECs is crucial to ensuring economic viability and long-term sustainability. Aggregator business models [18] have been shown to optimize market efficiency, reducing energy costs while increasing renewable adoption rates by up to 51%. Storage incentives [19] significantly improved self-consumption rates, lowering operational expenses and maximizing EC profitability. Research on governance approaches [11] highlighted the need for policy frameworks that promote active stakeholder engagement in energy-sharing models.

Demand-side management (DSM) strategies are also gaining prominence. A study in Switzerland [20] explored CES ownership models and demonstrated the financial benefits of lithium-ion batteries in peak shaving and energy arbitrage. Another study [21] analyzed shared storage frameworks for prosumers, showing that fair pricing and load-based participant matching could result in annual savings of €615 per community.

A macro-level review of integrated renewable energy systems (IRES) [22] indicated that combining RES with optimized storage strategies could reduce emissions by 10–50% and operational costs by 42%. The role of artificial intelligence (AI) in energy management is also expanding, with studies [23] highlighting its potential in stabilizing decentralized networks and ensuring optimal renewable energy integration.

1.1.2 Optimization models, hybrid and storage systems

Battery Energy Storage Systems (BESS) are critical to EC stability and efficiency. A study in Bangladesh [24] demonstrated that integrating BESS helps maintain voltage stability in ECs. In Italy [25], advanced scheduling techniques improved battery lifespan by 30%, while enhancing scheduling strategies to increase prosumer revenues by 10%. Research in Florence [26] showed that a smart Battery Management System (SmBMS) improved collective self-consumption and enhanced EC autonomy. A Swiss study [20] analyzed CES ownership models, revealing the efficiency of lithium-ion batteries in peak shaving and energy arbitrage. Further advancements in shared storage frameworks in Bangladesh [27] optimized energy use within ECs, yielding a 6.09% reduction in costs, and a hybrid system integrating solar, batteries, and hydrogen storage achieved a 100% renewable transition for rural areas.

Hybrid renewable energy sources (HRES) offer decentralized and flexible energy generation solutions. Research in India [28] demonstrated that GA-based HRES systems are more cost-effective than HOMER Pro, delivering energy at \$0.163/kWh with no unmet load. Another study in Romania [29] showed that wind-PV hybrid systems could supply up to 53% of household energy needs when supplemented by battery storage. A broader review [30] identified economic advantages of HRES over diesel generators, highlighting solar electricity costs as low as \$0.40/kWh. Further studies [31] examined surplus PV electricity utilization in high-solar penetration districts, demonstrating the feasibility of localized self-consumption.

A centralized optimization framework [19] was introduced for managing energy storage in ECs, improving local self-consumption by 44% and reducing energy community costs. A comprehensive review of hybrid energy storage systems [32] further consolidated insights into the integration of renewables, offering decision-makers a database of over 350 studies to support optimal storage solution selection. Peer-to-peer (P2P) hybrid solar-wind energy-sharing models [33] increased self-consumption from 59.1% to 79.5% and reduced energy costs by 34.5%, although challenges in battery cycling remain an issue for further investigation. Additionally, research has emphasized the adaptability of HRES within buildings and urban EC frameworks [34,35], demonstrating their potential for achieving greater energy autonomy and sustainability.

Energy management strategies also play a key role in optimizing ECs. A study on hybrid power plants [36] introduced an energy management system (EMS) that increased battery storage efficiency by 1.41%, prolonging battery life and optimizing power dispatch. A similar EMS tailored for solar-plus-battery prosumers [37] demonstrated technical feasibility by lowering the levelized cost of energy (LCOE) and improving self-sufficiency, although cost-effectiveness varied depending on market conditions. Further innovations in battery management were demonstrated in Florence [26], where a smart Battery Management System (SmBMS) significantly improved collective self-consumption (CSC) and REC independence. In addition to these technological advancements, one paper [38] highlights the integral role of BESS in bolstering energy self-consumption and demand-side management while pinpointing a research gap in the integration of demand response.

1.2 Aim and contributions

Within this context, the efficient sizing and operation of a REC supported optimized investment and operational decisions is proposed, allowing members to invest not only in PV and wind generation technologies but also in battery energy storage systems. The study explores a mixed integer linear programming (MILP) that computes the optimal capacity for each technology, as well as the energy shared in each period, while considering local constraints such as the available on-site conditions for renewable projects.

Previous research about the integration of hybrid RES, conducted by [39], showed the benefits of CSC within a REC. Based on the literature analysis conducted in this manuscript, the novelty of the present study is twofold. First, the adoption of BESS within a REC is segregated among members using a methodology that determines the individual threshold CAPEX at which BESS becomes economically viable. Second, the study identifies a complementary relationship between BESS adoption and the installation of renewable energy capacity. In short, the significance and contributions of this work considering past literature are:

a) With the granular member-specific and temporal analysis made in this study it surpasses aggregate approaches, [40], by providing a detailed evaluation of ISC and CSC at both individual and collective levels. It analyzes each member's energy behavior, storage usage, and cost savings, allowing tailored decision-making and participation optimization. Additionally, it employs one year of high-resolution hourly data to capture short-term demand, production, and storage fluctuations, projecting long-term economic impacts. This contrasts with similar studies (e.g., [40] and [8] which often rely on static or averaged data, missing the nuanced effects of real-time variability over extended periods; b) The research delivers individual investment thresholds and dynamic optimization to REC members. By segmenting BESS investments within the REC, the study identifies member-specific CAPEX thresholds, accounting for financial constraints and consumption profiles, ensuring personalized investment strategies. The optimization framework integrates short-term operational strategies with long-term investment planning, balancing immediate energy-sharing strategies with future economic viability. This dual-layered model enhances BESS optimization beyond conventional approaches that aggregated investment models and isolate operational and investment decisions [41]; c) Interrelation of ISC, CSC, and long-term economic viability. Segregated BESS capacities enhance both ISC and CSC, optimizing energy sharing without compromising autonomy. This contrasts with aggregate-focused studies [8,41,42], which do not address individual and collective performance interplay. Additionally, the study quantifies trade-offs between short-term savings and long-term revenue potential from enhanced self-consumption and arbitrage, offering a structured approach for sustainable REC growth.

The structure of this paper is as follows. Section 2 illustrates the developed model, Section 3 presents the case study framework, and Section 4 provides a comprehensive discussion of the obtained results. Finally, Section 5 draws the conclusions.

2. Methods

The model developed and presented in this study evolves from the one presented in [39], where a planning model for REC with four members is proposed allowing for all to be consumers and simultaneously renewable energy producers using PV and wind power generation. In this derived model, the REC members can also integrate BESS and withdraw additional benefits of the REC framework.

The model is formulated as a minimization problem of the overall annualized costs of electric energy supply, considering revenues from selling the electricity surplus to the grid at the day ahead market (DAM) prices. The objective function includes: (i) the annualized investment costs of the installed renewable capacity (and BESS) of each REC member; (ii) the cost of the electric energy supplied by the retailers from the main grid; (iii) the variable costs of sharing electricity among the REC members that includes the managing costs of the community manager (EGAC, in the Portuguese acronym) and the internal REC energy exchange tariff; (iv) the fixed cost of the EGAC; and (v) the revenues coming from the surplus of electricity generation that is sold to the grid.

The optimal investment and operational decisions are computed by minimizing the REC total costs, i.e. the sum of the individual costs of each REC member i as presented in the objective function (1), constrained by (2) to (13).

$$
\begin{aligned}
minCost = \sum_i & \begin{pmatrix} CRF_{BESS} \cdot BESSCAPEX \cdot BESSCAPACITY_i + \\ CRF_r \cdot \sum_r CAPEX_r . P_{i,r} \end{pmatrix} \\
& + \sum_t \sum_i \left(T_{i,t} \cdot buyGrid_{i,t} \right) \\
+ \sum_t \sum_i & \left[\left(T_{sc} + EGAC^V \right) \cdot buyREC_{i,t} \right] + EGAC^F \\
- \sum_t & \left(S_t^{DAM} \cdot \sum_t sellGrid_{i,t} \right)
\end{aligned}
\tag{1}
$$

where C is the objective function expressing the total annualized costs of the REC members' electricity supply, CRF is the capital recovery factor of technology used to determine the annuity generated by the CAPEX invested by each member in BESS and in each renewable technology, r is the renewable technology (PV and Wind), i is the REC member index, $BESSCAPEX$ and $CAPEX_r$ represent the capital expenditure of BESS and renewables, $BESSCAPACITY_i$ is the BESS storage capacity of i, $P_{i,r}$ is the installed capacity by member i in renewable technology r, t is the hourly period index, $T_{i,t}$ is the electricity tariff of member i in period t, which includes both the electricity and grid components, $buyGrid_{i,t}$ is the energy supplied by the grid to member i in period t, T_{SC} is the self-consumption tariff, $EGAC_V$ is the $EGAC$ management fee, $buyREC_{i,t}$ is the electricity bought by REC member i in period t from other REC members, $EGAC_F$ is the fixed cost of the $EGAC$ management entity, is the DAM price for selling energy to the grid, $sellGrid_{i,t}$ is the energy sold to the grid by REC member i in period t. The optimization problem is subject to the following constraints:

$$\sum_r \left(R_{r,t} \cdot P_{i,r}\right) - D_{i,t} - sellREC_{i,t} + buyREC_{i,t} - sellDAM_{i,t} + buyGrid_{i,t} - BESSin_{i,t} + BESSout_{i,t} = 0, \forall i,t \quad (2)$$

$$BESSin_{i,t} \cdot \sqrt{EFF} - SoC_{i,t} - \frac{BESSout_{i,t}}{\sqrt{EFF}} + SoC_{i,t-1} = 0,\ \forall i,t \quad (3)$$

$$\sum_i (sellREC_{i,t} - buyREC_{i,t}) = 0,\ \forall t \quad (4)$$

$$buyGrid_{i,t}, buyREC_{i,t}, sellGrid_{i,t}, sellREC_{i,t}, BESSinput_{i,t}, BESSoutput_{i,t}, SoC_{i,t} \geq 0,\ \forall i,t \quad (5)$$

$$P_{min\, i,r} \leq P_{i,r} \leq P_{max\, i,r} \quad ,\forall i,r \quad (6)$$

$$\sum_r P_{i,r} \leq PTOTAL_{max\, i} \quad ,\forall i \quad (7)$$

$$BESSP_{min\, i,r} \leq BESSP_{i,r} \leq BESSP_{max\, i,r} \quad ,\forall i,r \quad (8)$$

$$BESSCAPACITY_{\min i} \leq SoC_{i,t} \leq BESSCAPACITY_i \leq BESSCAPACITY_{\max i} \quad ,\forall i,t \quad (9)$$

where $R_{r,t}$ is the normalized generation profile of renewable technology r in period t, $D_{i,t}$ is the electricity consumption of REC member i in period t, $sellREC_{i,t}$ is the electricity shared by REC member i with other REC members, $P_{min\ i,r}$ and $P_{max\ i,r}$ are the installed capacity limits REC member i in renewable technology r, $BESSCAPACITY_{\min\ i}$ and $BESSCAPACITY_{\max\ i}$ are the BESS installed capacity limits by REC member i, $BESSin_{i,t}$ and $BESSout_{i,t}$ are the BESS charging and discharging energy flows (respectively) for REC member i, EFF is the BESS roundtrip efficiency, $SoC_{i,t}$ is the state of charge of REC member i in period t, and $SoC_{i,t-1}$ is the state of charge of REC member i in the previous period $t-1$.

The constraints expressed in (2) to (9) represent: (2) is the Kirchoff-Law applied to the REC member i node energy flows including the BESS charging and discharging flows; (3) is the Kirchoff-Law applied to the BESS node energy flows affected by losses for REC member i; (4) sets that internal electricity exchanges between all REC members in each hourly period t must add to zero (Kirchoff-Law to the REC energy exchanges); (5) forces all modelled energy flows to be non-negative for consistency; (6) sets the installed capacity limits by REC member i in renewable technology r; (7) limits the cumulative installed capacity in each REC member i; (8) limits to the installed capacity of the BESS for each REC member i; (9) sets the BESS storage capacity limits for each REC member i.

The following Eq. (10) presents the capital recovery factor, $CRF_{r,BESS}$ in (10), used to determine the CAPEX annuity for each technology r and $BESS$ at each REC member i, where $WACC$ is the Weighed Average Cost of Capital of the investment, $LT_{r,BESS}$ is the lifetime expectation for each renewable technology r and the $BESS$ technology.

$$CRF_{r,BESS} = \frac{WACC \cdot (1+WACC)^{LT_{r,BESS}}}{(1+WACC)^{LT_{r,BESS}} - 1} \quad ,\forall r, BESS \quad (10)$$

Finally, the model has a built-in mechanism to prevent the simultaneous BESS charging and discharging during the same period t that is implemented using two binary variables: $BESScharging_{i,t}$ and $BESSdischarging_{i,t}$ to set the corresponding mode using an arbitrary large integer constant, M, in two constraints (11) and (12). Finally, the two binary variables are not allowed to be "ON" simultaneously using (13).

$$BESSin_{i,t} \leq M \cdot BESScharging_{i,t} \quad ,\forall i,t \quad (11)$$

$$BESSouT_{i,t} \leq M \cdot BESSdischarging_{i,t} \quad ,\forall i,t \quad (12)$$

$$BESScharging_{i,t} + BESSdischarging_{i,t} \leq 1 \quad ,\forall i,t \quad (13)$$

The model described was implemented using two different tools: GAMS and PuLP (an open-source Python library), mostly for validation of results. GAMS denoted an advantage in the LP computation speed to determine the optimal solution.

3. Case study

The model described in the preceding section is applied to a real-world REC with four members: REC 1, REC 2, REC 3, and REC 4, which are connected to the medium voltage distribution grid. This model evolves from the one presented in [39] where a planning model for REC with four members is proposed allowing all members to be consumers and renewable energy producers using PV and wind technologies. In this upgraded model, REC members can also invest in BESS and achieve additional benefits in the REC framework, as presented in Figure 1.

We used one year data collected from real consumers with hourly granularity, however their names will be kept anonymous: REC 1 is a university campus made up of multiple buildings where classes take place, laboratories, admin and ancillary services buildings; REC 2 is a large media outlet building; REC 3 is commercial purpose building with regular opening hours; REC 4 is a large commercial outlet opened every day of the week and operating extended opening hours. Figure 2 shows the average demand curve for each member for weekdays and weekends

It must be noted in Figure 2, that REC members 2 and 3 already own PV production facilities and thus the demand data used in our model represents the outstanding or demand to be served. REC 4 has chosen not to install production facilities despite its availability to contemplate joining a REC. This decision has been reflected in our model using constraints.

3.1 Assumptions

Normalized profiles are used for the PV and Wind generation with 8760 data points representing a full year which are scaled-up according to the optimal capacity of PV and wind in the model. The main features, considering the Weighted Average Cost of Capital (WACC), of the renewable generation and BESS technologies are presented in Table 1.

BESS roundtrip efficiency is considered at 90% and energy and capacity limits of 5 MWh and 800 kW, respectively.

The Portuguese regulation on REC establishes the possibility for compensation fees to the Collective Self-consumption Managing Entity (EGAC) as means to sponsor the establishment and administration of the RECs. These can be fixed or variable, as a function of the exchanged energy between the members, EGACF and EGACV, respectively.

We have set EGACF to zero to avoid its external influence on the results and picked 0,000815€/kWh iteratively for EGACV. The EGACV must be low enough to not

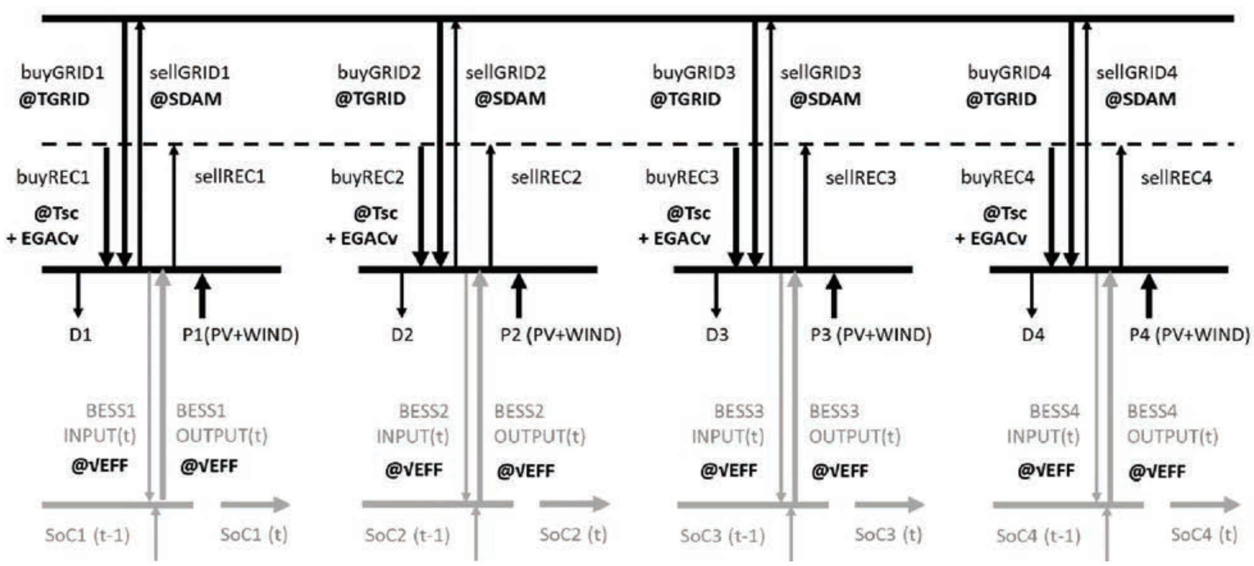

Figure 1: Outline of the REC with energy flows and operational data (costs, prices, fees, and losses).

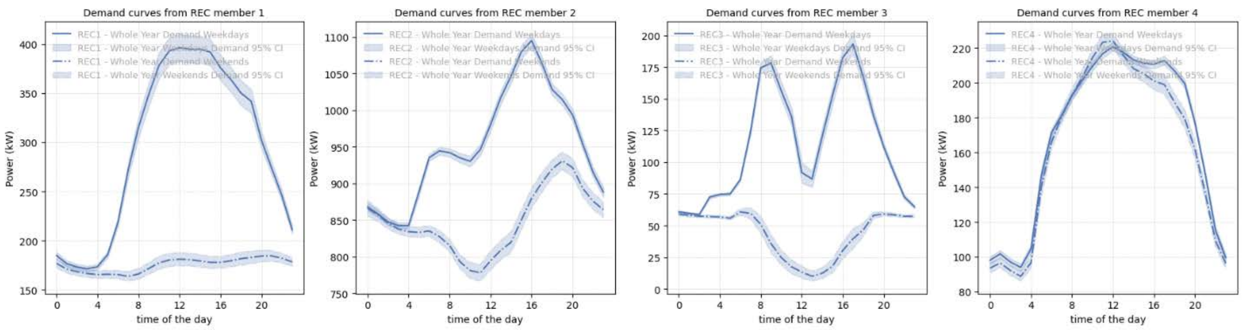

Figure 2: REC members' daily demand average values, and confidence intervals, for weekdays and weekends.

Table 1: Characteristics of the simulated technologies.

Tech	CAPEX	Lifetime	WACC	P_{min} / P_{max}	E_{min} / E_{max}
PV	1 100 €/kW	25 years	5%	0 / 4 000 kW	n.a.
WIND	1 700 €/kW	20 years	5%	0 / 4 000 kW	
BESS	100, 200, 500 € /kWh	15 years	5%	0 / 800 kW	0 / 5 MWh

discourage the exchange of energy between the members but not null. A null value would not make the model realistic as Self-Consumption behaviour must be prioritized over the CSC mode within the REC. Furthermore, to avoid the influence of other external variables to the results, the valuation of the surplus power was ignored in our economic analysis by setting to null. The sale of the surplus power represents the potential for free cash-flows for equity but at an unquantified degree of risk and variability across the project lifetime.

We conveniently used the Regulator Self-Consumption Tariff (TSC) as a mechanism to enable the CSC mode, by setting TSC to null, or to discourage the exchange of energy within the REC and limiting the model to the ISC mode by using an arbitrary high TSC value, e.g. 1 €/kWh. Finally, we choose to use 0,1€/kWh for grid costs as is a typical value used in business cases evaluation in Portugal that would stand the test of time.

4. Results

The renewable investment cases are shown in the Table 2 for three BESS CAPEX levels representing the present, the mid-term, and a long-term (future) projection. For each BESS CAPEX level, simulations were carried out for the REC setting, that is with CSC, and non-REC, that is the ISC.

Table 2 presents the simulation results for the installed capacity of renewable energy sources (PV and wind) and batteries for each REC member, along with the total costs, which include the capital costs of renewables and batteries, as well as electricity supply tariffs. These results are provided for both ISC and CSC across three battery CAPEX scenarios: Scenario 1 reflects the current CAPEX of 500 €/kWh, Scenario 2 represents the mid-term anticipated CAPEX of 200 €/kWh [42] , and Scenario 3 assumes an optimistic reduction in battery costs with a CAPEX of 100 €/kWh, and Scenario 3 for an optimistic view about batteries cost reduction with a CAPEX of 100 €/kWh.

In the base case scenario, which corresponds to the current state of BESS development in terms of specific costs (500 €/kWh) and efficiency (90%), there is no incentive for investing in BESS as can be seen in the BESS rows of Table 2 for Scenario 1.

Scenario 2 takes into consideration technological developments in the BESS so that the investment cost drops to 200 €/kWh. In this scenario, investment is considered economically feasible for a moderate level of BESS which induces cost savings of 0.2% in ISC and 4.9% in CSC. The integration of BESS allows more investment in the renewable generation technologies as the electricity surplus can now be used to replace supply from the grid.

Table 2: Optimal installed capacity of renewables (PV and Wind) and batteries, and total costs of electricity sourcing, in ISC and CSC, for Scenario 1 (BESS CAPEX of 500 €/kWh), Scenario 2 (BESS CAPEX of 200 €/kWh), and Scenario 3 (BESS CAPEX of 100 €/kWh).

	ISC mode				**CSC mode**			
	REC1	**REC2**	**REC3**	**REC4**	**REC1**	**REC2**	**REC3**	**REC4**
Scenario 1	COST = **1 028** k€ (reference case)				COST = **979** k€ (4.8% savings)			
BESS (kWh)	0	0	0	0	0	0	0	0
Renewables (kW)	678	2 234	220	-	744	2 560	328	-
PV (kW)	390	1 110	106	-	450	1246	179	-
Wind (kW)	288	1 124	114	-	294	1314	149	-
Scenario 2	COST = **1 026** k€ (0.2% savings)				COST = **978** k€ (4.9% savings)			
BESS (kWh)	60	344	112	0	0	457	139	0
Renewables (kW)	688	2 311	243	-	768	2 633	345	-
PV (kW)	400	1 181	132	-	468	1 326	203	-
Wind (kW)	288	1 130	111	-	300	1 307	142	-
Scenario 3	COST = **995** k€ (3% savings)				COST = **941** k€ (8% savings)			
BESS (kWh)	1 152	4 826	600	0	2 823	4 812	1 741	0
Renewables (kW)	858	2 973	304	-	1 110	3 271	543	-
PV (kW)	621	1 999	229	-	980	2 230	479	-
Wind (kW)	237	974	75	-	130	1 041	64	-

Scenario 3 goes deeper in the technological performance of BESS and considers a specific investment of 100 €/kWh. The total renewable capacity and BESS increases even more with cost saving accounting for 3% in ISC and 8% in CSC. However, it is observed that wind capacity is reduced, for all REC members, either in ISC or CSC, to a level below the base case, as PV plus BESS outperforms the wind contribution.

Table 3 presents the energy balance of the aggregate annual demand of the REC members (Demand) distributed by the sources of supply: sourcing from the grid contract electricity tariff of each REC member (Grid Supply), self-consumption from the renewable generation in each REC member (Own Self-Consumption), supply from BESS installed in each REC member (BESS Discharging), and energy shared with each member by the other REC members (REC Supply). Results were computed for the ISC and CSC settings for the same three scenarios of BESS CAPEX previously presented.

Table 4 presents the aggregate annual renewable generation of the renewable generation distributed by the destination: replacing electricity from the grid by self-consumption from renewable generation (Own-Self Consumption), sharing renewable generation with other REC members (Share with REC), charging the battery with surplus of renewable generation (BESS Charging), and selling additional renewable surplus to the grid (Surplus to Grid). As in Table 3, results were computed for the ISC and CSC settings for the three scenarios of BESS CAPEX.

From the simulation results it is observed that, at the current level of BESS development with a CAPEX of 500 €/kWh and a 90% roundtrip efficiency, it is not profitable to invest in BESS in the REC under study neither in ISC nor in CSC (see BESS in Table 2, Scenario 1).

However, with the development of BESS that will reduce the CAPEX from 500 €/kWh (Scenario 1) to 200 €/kWh (Scenario 2), and even further to 100 €/kWh (Scenario 3), batteries would become economically viable in the context of this REC. In particular, the increase in BESS capacity is more pronounced in the CSC than in the ISC setting (see BESS installed capacity in Table 3). This means that a REC is more prone to explore higher levels of BESS installation when compared to the ISC.

It is also observed that the increase in BESS is followed by the increase in renewable capacity and generation (see Renewables in Table 3 and Renewable Generation in Table 4). This trend is stronger in the CSC than in ISC, which highlights the complementarity of BESS with renewables, as well as a complementarity of BESS with the electricity sharing within the REC.

Table 3: Energy balance of the aggregate REC demand by source of supply, in ISC and CSC, for Scenario 1 (BESS CAPEX of 500 €/kWh), Scenario 2 (BESS CAPEX of 200 €/kWh), and Scenario 3 (BESS CAPEX of 100 €/kWh).

	Demand	**Grid Supply**	**Own Self-Consumption**	**BES Discharging**	**REC Supply**
Scenario 1					
ISC (MWh)	12 642	6 926	5 716	0	0
	100%	*55%*	*45%*	*0%*	*0%*
CSC (MWh)	12 642	5 912	6 185	0	545
	100%	*47%*	*49%*	*0%*	*4,3%*
Scenario 2					
ISC (MWh)	12 642	6 727	5 797	118	0
	100%	*53%*	*46%*	*0,9%*	*0%*
CSC (MWh)	12 642	5 698	6 246	125	572
	100%	*45%*	*49%*	*1,0%*	*4,5%*
Scenario 3					
ISC (MWh)	12 642	5 325	6 034	1 283	0
	100%	*42%*	*48%*	*10%*	*0%*
CSC (MWh)	12 642	3 928	6 200	1 593	920
	100%	*31%*	*49%*	*13%*	*7,3%*

In fact, the cumulative outcome of installing BESS and sharing electricity among REC members enables a reduction of the grid supply from 55% to 31% (see Grid Supply in Table 3 for Scenario 1 in ISC versus Scenario 3 in CSC).

This is achieved by the increase of renewable generation (see installed renewable capacity in Table 3 and the corresponding renewable generation in Table 4) that is used for individual self-consumption and sharing with other REC members, which can occur either synchronously or in differed time with the support of BESS, as well as the share of renewable energy (see self-consumption, share with REC, and BESS charging in Table 4).

Because of a better integration of renewables, due to the cumulative effect of BESS and REC, the overall surplus of renewables sold to the grid decreases both in absolute and relative terms, reducing from 18% in ISC with no BESS to 10% in CSC with BESS (see surplus to grid in Table 4).

To complement the BESS integration analysis in the REC it was computed the BESS acceptance zone for the ISC and CSC settings as a function of the CAPEX and roundtrip efficiency, as presented in Figure 3.

As seen in Figure 3, the maximum economic threshold that triggers investment in BESS corresponds to the limit of 100% efficiency and equals 378 €/kWh, for the ISC, and 295 €/kWh, for the CSC. This means that under no circumstance in terms of roundtrip efficiency will BESS be economically viable with CAPEX higher than these threshold values in the context of the REC under study. Computing the threshold CAPEX for the entire range of efficiency corresponds to the acceptance curves presented in Figure 3 for the ISC and CSC settings. Below these curves BESS are unprofitable (rejection zone) and above these curves BESS become profitable (acceptance zone). It is clear from the results that Scenario 1 is in the rejection zone, so that no BESS is installed neither in ISC nor in CSC (see also BESS in Table 2). On the other hand, Scenario 2 and Scenario 3 are in the acceptance zone and the optimal investment decision computed by the proposed model foresees BESS in both scenarios, with increasing capacity as scenarios go deeper in the acceptance zone (more BESS capacity in Scenario 3 than in Scenario 2, as presented in Table 2).

In the acceptance zone, not only BESS becomes economically viable but also additional renewable energy can be integrated within the REC in a competitive way. Accordingly, more renewable capacity is installed in all REC members (except REC 4, which is prevented to install renewable capacity due to site specific constraints), both in solar PV and Wind.

To understand the differences among REC members in the adoption of BESS each members' acceptance curve is computed both for ISC and CSC, as presented in Figure 4 and Figure 5, respectively.

Table 4: Aggregate renewable generation of the REC by destination, in ISC and CSC, for Scenario 1 (BESS CAPEX of 500 €/kWh), Scenario 2 (BESS CAPEX of 200 €/kWh), and Scenario 3 (BESS CAPEX of 100 €/kWh).

	Renewable Generation	**Own Self-Consumption**	**Share with REC**	**BES Charging**	**Surplus to Grid**
Scenario 1					
ISC (MWh)	6 955	5 716	0	0	1 239
	100%	*82%*	*0%*	*0%*	*18%*
CSC (MWh)	8 049	6 185	545	0	1 319
	100%	*77%*	*6,8%*	*0%*	*16%*
Scenario 2					
ISC (MWh)	7 151	5 797	0	132	1 223
	100%	*81%*	*0%*	*1,8%*	*17%*
CSC (MWh)	8 251	6 246	572	144	1 289
	100%	*76%*	*6,9%*	*1,7%*	*16%*
Scenario 3					
ISC (MWh)	8 563	6 034	0	1 428	1 100
	100%	*70%*	*0%*	*17%*	*13%*
CSC (MWh)	9 950	6 200	920	1 802	1 028
	100%	*62%*	*9,2%*	*18%*	*10%*

For the ISC setting (Figure 4) it is observed that the threshold CAPEX for BESS adoption is 300 €/kWh for REC 3, the first do adopt BESS, 279 €/kWh for REC 2, the second do adopt BESS, and 250 €/kWh for REC 1, the last REC member do adopt BESS.

Moreover, the cumulative BESS installation of the overall REC members increases with the BESS declining CAPEX, as it also increases the cumulative installation of renewable generation capacity (PV and Wind), showing the complementarity for BESS with renewables.

For the CSC setting (Figure 5) it is observed that the threshold CAPEX for BESS adoption is 278 €/kWh for REC 3, the first to adopt BESS, 266 €/kWh for REC 2, the second do adopt BESS, and 184 €/kWh for REC 1, the last REC member do adopt BESS. In comparison with the ISC setting this represents a later adoption, that is it is required lower BESS CAPEX for the adoption of batteries in the CSC. This is a natural result as the added value of sharing electricity in the CSC setting is a substitute for the storage. In fact, sharing electricity surplus among members is economically superior that storing

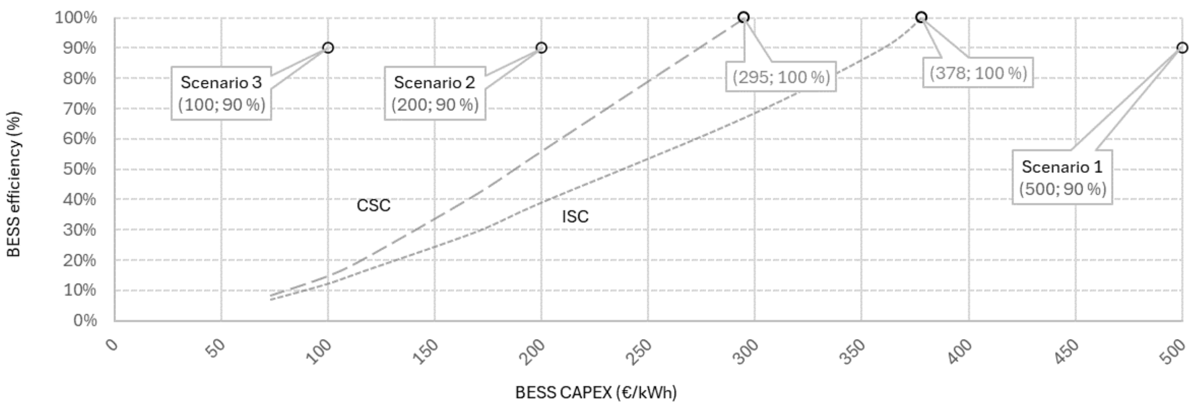

Figure 3: BESS acceptance curves for the ISC (dashed line) and CSC (solid line) as a function of the BESS CAPEX (x-axis) and BESS efficiency (y-axis).

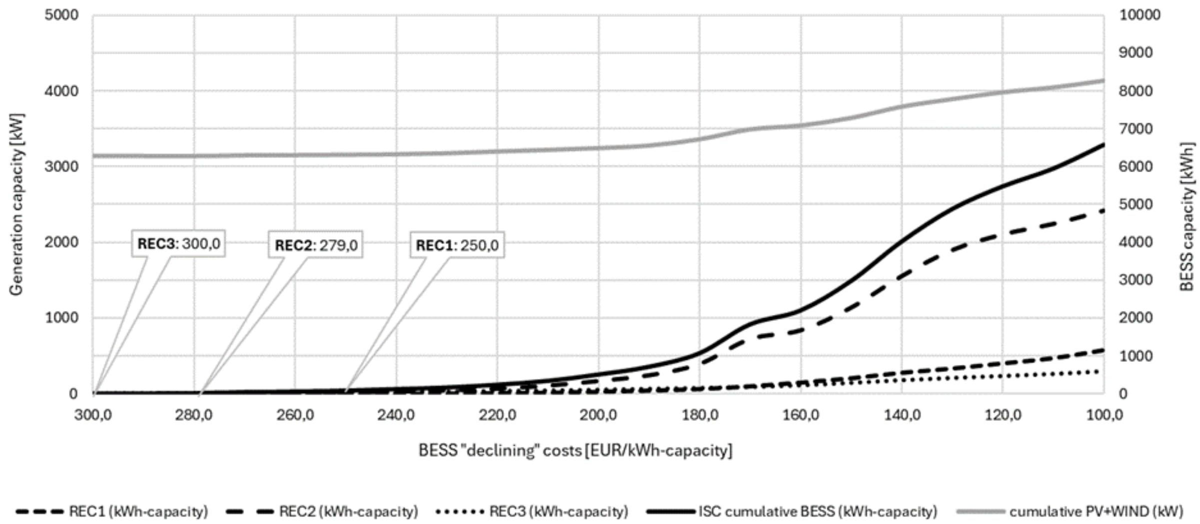

Figure 4: BESS installation capacity for REC1, REC2, REC3 and cumulative BESS and Renewable capacity in the ISC setting as a function of the BESS CAPEX declining costs.

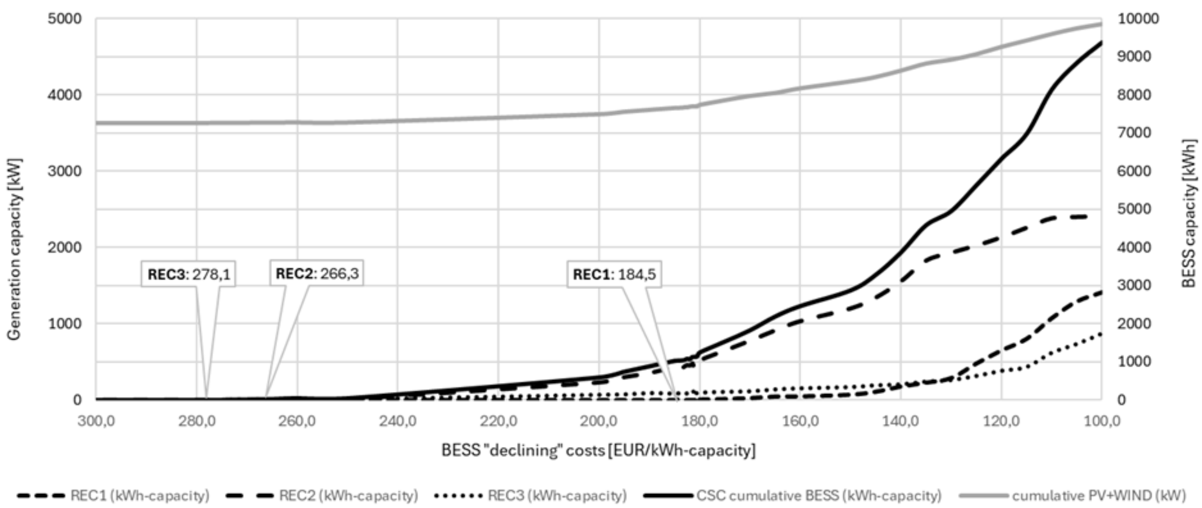

Figure 5: BESS installation capacity for REC1, REC2, REC3 and cumulative BESS and Renewable capacity in the CSC setting as a function of the BESS CAPEX declining costs.

electricity for later use, as in this case an investment and energy losses applies.

Alike the ISC setting, the cumulative BESS installation of the overall REC members in the CSC setting increases with the BESS declining CAPEX, as it also increases the cumulative installation of renewable generation capacity (PV and Wind). However, the extend of BESS adoption is clearly higher in the CSC when compared with the ISC, as it is the cumulative renewable capacity installation (compare BESS and PV+Wind cumulative curves of ISC, in Figure 4, with CSC, in Figure 5).

We have also explored the model's reactions to 0,09€/kWh and 0,11€/MWh. Using 0,1€/MWh as a reference for grid costs we see that for lower values the total cost of the electricity sourced to the REC is lower

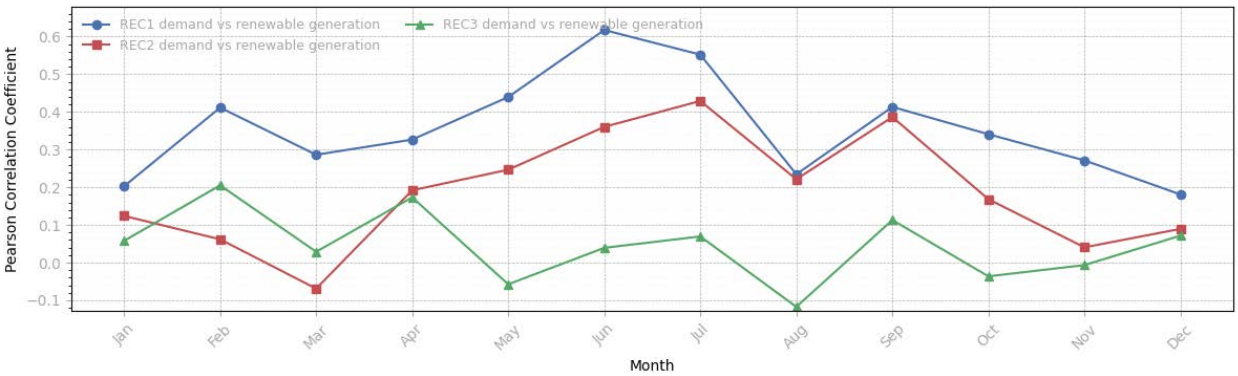

Figure 6: Monthly Pearson correlation coefficients between demand profile and renewable generation for each REC member (REC1, REC2, REC3).

and for higher values the total cost is higher, as expected. Also predictably, with a lower energy value to beat, the lower grid cost, the model recommends the installation of a reduced capacity in renewable energy and storage. In other words, it is harder to deploy Renewables. Conversely, for higher values of grid cost the model recommends the installation of more capacity in renewable energy and storage. Also notable, is the recommendation of storage capacity for higher values of battery CAPEX when facing higher values of grid costs.

To evaluate the drivers behind the results presented, the Pearson correlation coefficients between each REC member's demand profile and renewable generation is computed for a scenario of no BESS adoption, which are presented in Figure 6.

Figure 6 shows that each REC member's surplus, measured as the difference between its renewable generation and its demand in each period, is different among members. The highest correlation is observed for REC 1, followed by REC 2 and then by REC 3. This supports the previous results in which the adoption of BESS follows from the lowest correlation member (REC 3) to the second lowest (REC 2) and to the highest correlation (REC 1). This occurs because a higher surplus increases the willingness to adopt BESS.

5. Conclusions

This work proposes a model to support investment decisions in renewable energy communities and assess the techno-economic viability of battery energy storage systems. The model computes the optimal capacity of renewable generation technologies (solar PV and wind) and batteries, as well as the energy shared in each period, constrained by technical features. The model is used to evaluate investment and operational decisions in a real-world case of a REC with four members with an annual aggregate demand of 12.6 GWh.

At the current level of BESS development, with a CAPEX of 500 €/kWh and a 90% roundtrip efficiency, it was found that BESS is not economically viable neither in the individual self-consumption nor in the collective self-consumption settings. However, technological developments in BESS that would drive its capital costs down, creates an opportunity for the deployment of BESS at local level with benefits for the integration of renewables.

When economically viable, BESS increases the level of self-consumption, decreases the costs of electricity sourcing, increases the electricity sharing among REC members, and decreases the surplus of electricity.

Simulation results with scenarios of decreasing BESS CAPEX show an increase in BESS capacity that would also induce an increase in the renewable capacity and generation. This relationship is clearer in the REC setting than in individual self-consumption, which supports the conclusion of the complementarity of BESS with renewables as well as the complementarity of BESS with electricity sharing within the REC.

Moreover, the threshold for BESS adoption was analysed for each REC member. It was found that REC 3 is the first to adopt BESS, followed by REC 2 and then by REC 1. This sequence was supported by the Pearson correlation analysis carried out.

The comparison of the individual with the collective self-consumption settings showed that when electricity sharing is allowed the adoption of BESS is delayed, as the added value of sharing electricity is a substitute for the storage.

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