

# Beyond Self-Consumption: Unlocking Battery Storage Value in Energy Communities via Ancillary Services

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**Abstract.** This research investigates the economic and operational advantages of combining Renewable Energy Communities (RECs) with shared Battery Energy Storage Systems (BESS) to participate in Ancillary Service Markets (ASMs). The investigation seeks to assess whether ASMs can boost the profitability of BESS investments in RECs, explicitly addressing the constraints of BESS when utilized exclusively for self-consumption. Through detailed financial assessment, the research demonstrates that while BESS investments typically lack profitability for self-consumption purposes alone, their financial feasibility is enhanced considerably with ASM participation. Critical financial indicators, including the Internal Rate of Return (IRR) and Net Present Value (NPV), indicate that ASMs generate supplementary revenue streams, enabling BESS to provide grid support services such as frequency regulation, resulting in notable reductions in electricity costs and improved investment returns. The study emphasizes the significance of accounting for the BESS's yearly cycle threshold, directly affecting its durability and capacity for ASM participation. These results indicate that supportive policies and regulatory structures are necessary to foster REC engagement in ASMs, unlocking substantial economic advantages and improving the financial appeal of renewable energy initiatives. The knowledge gained from this investigation benefits policymakers, grid operators, and investors, as it illustrates the vital function of ASMs in advancing wider adoption and integration of distributed energy resources, ultimately contributing to more robust and adaptable energy infrastructures.

## 1 Introduction

The rise of distributed generation in the electricity system is a significant disruption the system operator must prepare to leverage [1]. One of its most significant characteristics is the flexibility contribution, particularly when coupled with energy storage systems. Battery energy storage systems (BESSs) not only benefit final users by utilising distributed generation surpluses, reducing peak demand, or providing price arbitrage [2], [3], but also offer grid benefits through generation backup, voltage control, and frequency regulation [4], [5]. This work explores the potential of renewable energy communities (RECs) with a

collective BESS to enhance the energy system by participating in ancillary service markets (ASMs), generating additional revenues for the final users.

RECs play a crucial role in the energy market, aggregating demand, generation, and storage capacities to a scale that allows them to participate in wholesale markets, including ancillary markets [6]. As per RED II [7], RECs are defined as legal entities that are optional, user-controlled organisations near renewable energy projects they own or operate. These entities, which can be natural persons, SMEs, or municipalities, are not just profit-driven but also aim for social, economic, or environmental outcomes. According to RED II, RECs have the right to self-arrange sharing of renewable energy and to access all suitable energy markets directly or through aggregation in a non-discriminatory manner.

Operation services are the backbone of the electricity system, ensuring the continuity and security of supply and the coordination of the generation-transport set. They play a vital role in maintaining controlled voltage and frequency values at all points in the system. These services are designed to adapt the production schedules from the daily and intraday markets to the technical needs of quality, reliability, and security required for the electricity supply. In Spain, these services are assigned by the system operator (REE) through mandatory or market mechanisms, leading to the creation of operation markets. These operation services, including Primary Regulation (FCR), Secondary Regulation (aFRR), Tertiary Regulation (mFRR), and Reserves (RR), are instrumental in ensuring a reliable and secure electricity supply.

Of these services, Primary Regulation, unlike in other countries, is mandatory in Spain and has to be provided as a requirement to be a generator. The rest of the services are allocated through the market. In order to be able to participate in this type of market, it is necessary to have a generator with the permits to access and connect to the grid and register as a participant in balancing services. This procedure involves applying for a permit from Red Eléctrica de España (REE) or the regional distributor to have the right to evacuate energy through the electricity infrastructure. Following Royal Decree Law 1183/2020 [8], a basic project design is required to obtain connection permits that demand a '*financial guarantee for an amount equivalent to € 40/kW installed*'.

This work explores the benefits obtained by a REC for participating in ASMs. To do so, we have developed a mathematical model that simulates and optimises the operation of a REC involving a PV generation system, a collective BESS, and aggregated residential and commercial charges.

## 2 Mathematical model

The optimisation consists of a MILP model that optimises battery operation and participation in ASMs. This optimisation can be performed for a variable period; in this work, all optimisations have been performed over one year. The model favours self-consumption and assumes that demand is inflexible. This model is programmed in Julia, using the JuMP package and the optimisation software Gurobi. The output of this optimisation is made in Excel spreadsheets containing for each time step of the simulation the energy use, the participation in the secondary regulation markets of the system, the load states of the storage system, the degree of self-consumption and the purchase of electricity from the grid.

These Excel files are then processed in Matlab for data processing. In Matlab, the economic evaluation of the project is carried out by calculating savings and revenues, the Internal Rate of Return (IRR) or the Net Present Value (NPV). In addition, optimisation strategies for the installation are analysed, and the number of cycles performed by the battery system in each situation is evaluated. All this is used to perform the final analysis of the proposal.

Therefore, this model optimises the system's operation rather than the investment, as the installation costs and economic KPIs are considered afterwards. To estimate which investments offer the best economic results, we include sensitivity analyses by varying the size of the PV installation and the storage capacity of the batteries.

From this point, the mathematical model used to optimise the operation of the self-consumption installation with participation in secondary markets is presented.

## 2.1 Objective function

First, we define the objective of the optimisation function using Equation (1). The optimisation objective is to minimise the energy cost to the system (consumer cost and secondary share). The cost is the sum of the cost of the contracted power in the electricity tariff ( $CONT \cdot \pi_{CONT}$ ), the energy purchased from the grid ( $RED_t \cdot \pi_{RED_t}$ ), the energy purchased in the downward secondary market ( $ASd_t \cdot \pi_{d_t}$ ), and the cost of errors, which is defined as 50% of the cost of secondary at that instant,  $((\varepsilon_{u_t} \cdot \pi_{u_t} + \varepsilon_{d_t} \cdot \pi_{d_t}) \cdot 1.5)$ , minus the revenues that include the participation in the secondary band  $((band_{u_t} + band_{d_t}) \cdot \pi_{band_t})$  and the sale of energy in upward activities ( $ASu_t \cdot \pi_{u_t}$ ). In addition, a battery usage cost is included to avoid excessive system degradation ( $BC_t \cdot B^{LCOS}$ ); the battery will only be used in situations that provide more value than its cost.

$$\min Cost = CONT \cdot \pi_{CONT} + \sum_{t=1}^T (RED_t \cdot \pi_{RED_t} - (band_{u_t}^u + band_{d_t}^d) \cdot \pi_{band_t} - AS_t^u \cdot \pi_{u_t} + AS_t^d \cdot \pi_{d_t} + (\varepsilon_{u_t}^u \cdot \pi_{u_t}^u + \varepsilon_{d_t}^d \cdot \pi_{d_t}^d) \cdot 1.5 + B_t^C \cdot B^{LCOS}) \quad (1)$$

To minimise this cost, the model decides what to do with the solar generation at each moment, how to use the batteries and the energy they store, or at which moments to offer to the band and participate in secondary markets. These decisions are made for each simulation step (hourly, in this case) to obtain the best possible economic results.

## 2.2 Energy balances

This section will describe the energy balances that occur during system operation and the associated constraints.

Equation (2) represents the system's energy balance, which equalises inputs and outputs or final consumption. Thus, the inputs are the PV generation ( $PV_t$ ), the purchase of energy from the grid ( $RED_t$ ), the discharge of the storage system ( $BD_t \cdot \eta_{B,D}$ ), with its respective efficiency, or the purchase of energy in downstream shares in secondary markets ( $ASd_t$ ). On the other hand, the energy outputs of the system are the prosumer's electricity demand ( $D_t$ ), the charging of the batteries ( $BC_t / \eta_{B,C}$ ) and the participation in upstream actions in secondary regulation markets ( $ASu_t$ ).

Equation (3) is a version of the above balance that constrains how demand can be met. Thus, demand is inflexible and does not participate in the secondary market. Equation (4) limits the energy the system can acquire from the system to the sum of demand and battery charge. Finally, Equation (5) indicates that the contracted power ( $CON_T$ ) will always be sufficient to acquire the required power at any time.

$$PV_t + RED_t + B_t^D \eta^{B,D} + AS_t^d = D_t + \frac{B_t^C}{\eta^{B,C}} + AS_t^u \quad \forall t \in T \quad (2)$$

$$PV_t + RED_t + B_t^D \eta^{B,D} = D_t \quad \forall t \in T \quad (3)$$

$$RED_t \leq D_t + B_t^C / \eta^{B,C} \quad \forall t \in T \quad (4)$$

$$CONT \geq RED_t \quad \forall t \in T \quad (5)$$

### 2.3 BESS behaviour

This section will characterise the operation of the energy storage system of the installation consisting of lithium-ion batteries. Equation (6) defines the battery's state of charge (BSOC<sub>t</sub>) and how it evolves over time. The state of charge always starts from the state of charge in the previous step (BSOC<sub>t-1</sub>) plus the energy charged (BC<sub>t-1</sub>η<sup>B,C</sup>) or minus the energy discharged (BD<sub>t-1</sub>/η<sup>B,D</sup>) during that step time, considering the efficiency of the batteries appropriately. The battery is assumed to have a nominal charge and discharge power equivalent to the maximum storage capacity. Therefore, the charging power of the batteries (BC<sub>t</sub>) is limited by Equation (7) as the difference between the maximum capacity (BMAX) and the current state of charge (BSOC<sub>t</sub>). Equation (8) limits the discharge power (BD<sub>t</sub>) to the current stored energy.

$$B_t^{SoC} = B_{t-1}^{SoC} + B_{t-1}^C \eta^{B,C} - \frac{B_{t-1}^D}{\eta^{B,D}} \quad \forall t \in T \quad (6)$$

$$B_t^C \leq B^{MAX} - B_t^{SoC} \quad \forall t \in T \quad (7)$$

$$B_t^D \leq B_t^{SoC} \quad \forall t \in T \quad (8)$$

$$\frac{\sum_{t=1}^T B_t^C}{B^{MAX}} = B_{lim}^{cycles} \quad (9)$$

### 2.4 ASM participation

This section describes how participation in secondary markets is performed considering the actual market instructions, the possibility of failing to respond to these secondary markets, and the fact that one cannot simultaneously participate in upstream and downstream work. Equation (10) describes that the fraction of the bidding band (θ<sub>t</sub><sup>u</sup>) requested for upward activities (band<sub>t</sub><sup>u</sup>) is equal to the energy delivered upward (ASu<sub>t</sub>) plus the energy missed at that time (εu<sub>t</sub>). Equation (11) defines the participation in downward secondary market activities equivalently. Finally, Equation (12) prevents simultaneous participation in upside and downside actions.

$$AS_t^u + \varepsilon_t^u = band_t^u \theta_t^u \quad \forall t \in T \quad (10)$$

$$AS_t^d + \varepsilon_t^d = band_t^d \theta_t^d \quad \forall t \in T \quad (11)$$

$$AS_t^u AS_t^d = 0 \quad \forall t \in T \quad (12)$$

## 3 Case Study

The case study consists of a Renewable Energy Community (REC) in Valencia, Spain, integrating a photovoltaic (PV) solar installation, a collective Battery Energy Storage System (BESS), and an aggregation of residential and commercial loads. We conduct simulations across various combinations of PV system power and BESS capacity to explore the optimal configuration for the community. The PV system power is varied across five design scenarios with capacities of 0, 125, 175, 225, and 275 kWp. The BESS capacity is explored in six increments: 0, 50, 100, 150, 200, and 250 kWh.

**Table 1.** REC residential and commercial loads.

REC annual demand (kWh)	Residential loads	Residential annual demand, average (kWh)	Commercial loads	Commercial annual demand, average (kWh)
880,748	130	3,535	35	12,013

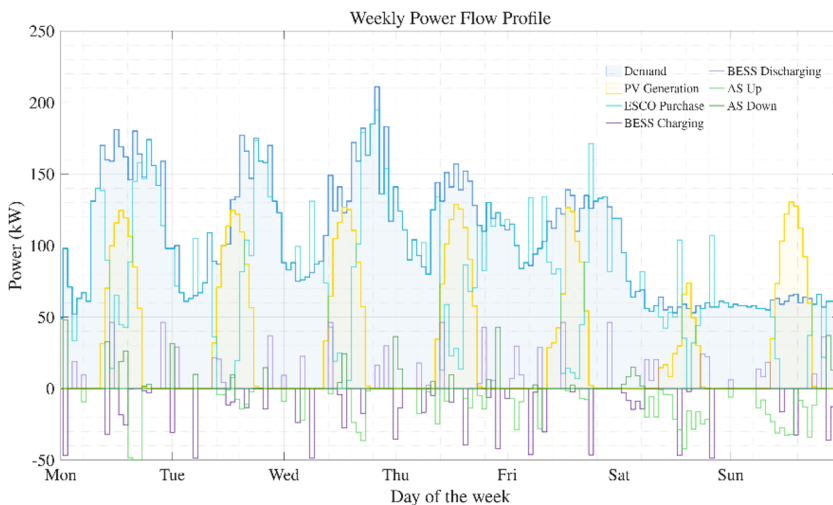
For each combination of PV power and BESS capacity, simulations were run to estimate solar generation, energy storage performance, and grid interaction. The solar generation data accounts for Valencia’s specific solar irradiance levels based on real capacity factors observed over one year.

Hourly load profiles for residential and commercial participants during a year were obtained through smart meters, providing detailed insights into energy consumption. The community integrates 130 residential loads and 35 commercial premises as indicated in **Table 1**. It has a total annual consumption of 880,748 kWh, and the peak load is 239 kW. Electricity market prices are obtained from ESIOS, the official platform of the Spanish electric grid operator (REE).

To ensure consistency across scenarios, a set of economic assumptions was applied in the evaluation. These include technology-specific capital and operational expenditures, a fixed interest rate, and a ten-year project horizon. **Table 2** summarizes the key parameters used in the financial analysis.

**Table 2.** Economic assumptions for the techno-economic analysis.

Variable	Value	Units
CAPEX PV	650	€/kW
CAPEX BESS	500	€/kWh
OPEX PV	10	€/kW/year
OPEX BESS	15	€/kWh/year
Interest rate	10%	–
Project lifetime	10	years



**Figure 1.** Winter day energy balances to illustrate REC’s operation.

## 4 Results and discussion

This section exposes the main results of this work. **Figure 1** represents REC’s operation on a typical winter day. Apart from how self-consumption reduces the electricity purchased at central hours, it shows how the REC participates in Ancillary Service Markets (ASMs).

Namely, downward operations charge the BESS at 2, 11, 14, and 15 AM. Later, it gets discharged to cover electric demand and reduce the electric bill, except at 6 AM when the REC participated in an upward AS operation.

To assess the economic performance of each REC configuration, we use the Internal Rate of Return (IRR) and Net Present Value (NPV), which are standard indicators for evaluating investment profitability and long-term value creation. These metrics were chosen for their relevance in energy project assessments, particularly in comparing scenarios with varying investment sizes and cash flow profiles. In addition, we analyse the number of annual BESS cycles to evaluate the impact of operation on battery lifespan and its implications for system durability. Finally, we compare all configurations both with and without participation in ASM to quantify the added value of accessing these markets.

IRR (%)	BESS Capacity (kWh)						
	PV (kWp)	0	50	100	150	200	250
125		11.66	10.04	7.47	5.15	3.16	1.35
175		9.58	8.82	7.03	5.27	3.68	2.22
225		7.09	7.14	6.04	4.74	3.50	2.33
275		4.26	4.82	4.29	3.48	2.64	1.80

2a. REC does not participate in ASM.

IRR (%)	BESS Capacity (kWh)						
	PV (kWp)	0	50	100	150	200	250
0			12.69	23.88	23.18	22.83	23.37
125		11.66	17.85	20.21	20.37	22.03	22.39
175		9.58	15.33	17.09	19.83	20.87	22.34
225		7.09	13.09	15.24	18.17	19.64	21.45
275		4.26	10.32	13.23	16.40	18.38	19.88

2b. REC participates in ASM.

$\Delta$ IRR (%)	BESS Capacity (kWh)						
	PV (kWp)	0	50	100	150	200	250
125		-	7.81	12.74	15.22	18.86	21.04
175		-	6.51	10.06	14.56	17.18	20.12
225		-	5.95	9.20	13.43	16.14	19.12
275		-	5.50	8.94	12.92	15.74	18.07

2c. Increment from participating in ASM.

**Figure 2.** IRR obtained for the different REC configurations.

Starting with the IRR, **Figure 2a** shows that BESS is not a profitable investment for self-consumption, but it turns out to be beneficial when participating in ASM is an option (**Figure 2b**). IRR increases in all scenarios, as **Figure 2c** shows.

NPV (€)	BESS Capacity (kWh)						
	PV (kWp)	0	50	100	150	200	250
125		5,868 €	175 € -	13,921 € -	31,028 € -	49,608 € -	69,929 €
175		2,020 € -	6,956 € -	20,283 € -	36,559 € -	54,359 € -	73,543 €
225		17,749 € -	20,440 € -	32,107 € -	47,414 € -	64,322 € -	82,476 €
275		41,607 € -	43,018 € -	52,930 € -	66,507 € -	81,641 € -	98,093 €

3d. REC does not participate in ASM.

NPV (€)		BESS Capacity (kWh)				
PV (kWp)	0	50	100	150	200	250
0	- €	2,958 €	33,145 €	47,003 €	60,855 €	79,541 €
125	5,868 €	38,235 €	62,463 €	75,611 €	102,861 €	120,847 €
175	2,020 €	33,270 €	52,920 €	86,300 €	108,786 €	139,312 €
225	17,749 €	23,377 €	46,224 €	83,057 €	110,291 €	146,072 €
275	41,607 €	2,834 €	32,680 €	73,648 €	107,561 €	139,571 €

3e. REC participates in ASM.

ΔNPV (€)		BESS Capacity (kWh)				
PV (kWp)	0	50	100	150	200	250
125	- €	38,061 €	76,384 €	106,639 €	152,468 €	190,776 €
175	- €	40,226 €	73,203 €	122,858 €	163,144 €	212,855 €
225	- €	43,817 €	78,331 €	130,472 €	174,612 €	228,548 €
275	- €	45,852 €	85,610 €	140,154 €	189,202 €	237,665 €

3f. Increment from participating in ASM.

Figure 3. NPV obtained for the different REC configurations.

The NPV results (Figure 3) show similar behaviours to the IRRs, proving that BESS is cost-effective only when participating in ASM is possible. NPV is calculated with a 10% discount market for ten years to avoid repowering considerations with the uncertainty regarding the BESS and grid prices in ten years.

Regarding the BESS's annual cycles (Figure 4), participating in ASM increments them as is expected. However, we limited the annual cycles to 683 to ensure a ten-year lifespan. This ceiling is never reached when self-consuming, but limits ASM participation if a large storage system is not employed. This behaviour indicates that participation in ASM is very profitable, and the system tries to do it as much as possible; however, raising the limit would lead to reduced BESS life and the REC would participate in less cost-effective activities.

BESS Cycles		BESS Cap (kWh)				
PV_Pnom (kWp)	0	50	100	150	200	250
125	-	630	603	578	551	521
175	-	624	592	565	536	505
225	-	629	589	557	525	493
275	-	622	582	546	514	483

4g. REC does not participate in ASM.

BESS Cycles		BESS Cap (kWh)				
PV_Pnom (kWp)	0	50	100	150	200	250
125	-	683.0	683.0	683.0	682.8	682.7
175	-	683.0	683.0	683.0	682.8	682.7
225	-	683.0	683.0	683.0	683.0	682.7
275	-	683.0	683.0	683.0	682.8	682.7

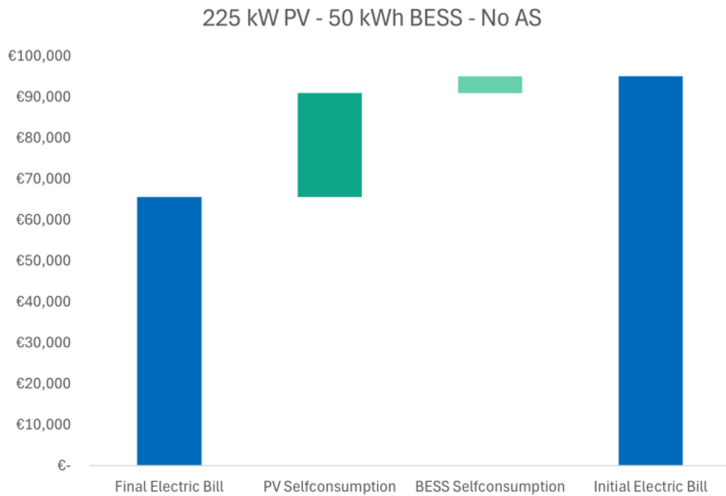
4h. REC participates in ASM.

ΔBESS Cycles		BESS Cap (kWh)				
PV_Pnom (kWp)	0	50	100	150	200	250
125	-	52.85	79.55	105.00	131.70	162.05
175	-	58.85	91.35	118.29	146.33	177.25
225	-	54.46	94.21	126.47	158.00	189.47
275	-	60.76	101.19	136.65	168.56	200.11

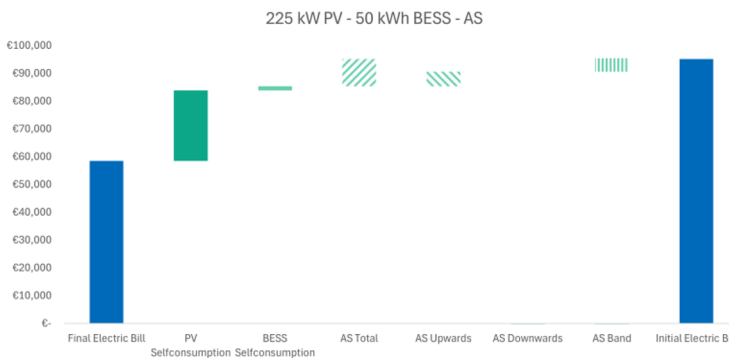
4i. Increment from participating in ASM.

Figure 4. Annual BESS cycles used for the different REC configurations.

Finally, we present a specific case to see how the electric bill is reduced using self-consumption and participating in ASMs. The aggregated initial electric bill of the REC is €95,055 for a year. Self-consumption alone (**Figure 5a**) reduces that bill to €65,583, mainly due to direct PV self-consumption, which is responsible for more than €25,000 out of the €30,000 savings. In **Figure 5b**, the REC reduces its bill further to €58,424 by participating in ASMs. Self-consumption is still the primary source of savings, as the model is programmed to prioritise it, but the AS revenues ascend to almost €10,000 yearly. The AS revenues come evenly from availability in band and upward activities, while the downward activities are almost negligible.



**j. REC does not participate in ASM.**



**k. REC participates in ASM.**

**Figure 5.** Comparison of the source of savings by doing only self-consumption

## 5 Conclusions

This study evaluated the potential benefits of integrating Renewable Energy Communities (RECs) with collective Battery Energy Storage Systems (BESS) in participating in Ancillary Service Markets (ASMs) to enhance economic returns and grid stability. Results showed that while BESS investments are not economically viable for self-consumption alone, they turn

profitable when RECs participate in ASMs, increasing both the Internal Rate of Return (IRR) and the Net Present Value (NPV). However, the BESS annual cycles also increased, reducing its lifespan. The study of a specific case showed that AS revenues come from both band availability and upward activities evenly.

These findings underscore the importance of policy and regulatory frameworks that facilitate REC participation in ASMs, as this can significantly enhance the economic viability of collective renewable energy projects involving more people and actors in the energy transition. The study's insights are particularly relevant for stakeholders in energy markets, including policymakers, grid operators, and renewable energy investors, as they highlight the potential of ASMs to drive broader adoption of distributed generation and storage. By demonstrating the financial and operational benefits of ASM participation, this work advocates for expanded integration of RECs into ancillary service markets, which could contribute to more resilient and flexible energy systems.

## References

- [1] G. Joos, B. T. Ooi, D. McGillis, F. D. Galiana, and R. Marceau, 'The potential of distributed generation to provide ancillary services', in *2000 Power Engineering Society Summer Meeting (Cat. No.00CH37134)*, Seattle, WA, USA: IEEE, 2000, pp. 1762–1767. doi: 10.1109/PESS.2000.868792.
- [2] H. Firoozi, H. Khajeh, and H. Laaksonen, 'Optimized Operation of Local Energy Community Providing Frequency Restoration Reserve', *IEEE Access*, vol. 8, pp. 180558–180575, 2020, doi: 10.1109/ACCESS.2020.3027710.
- [3] R. Rana, K. Berg, M. R. Brubaek, and O. B. Fosso, 'Ancillary services from a residential community - a Norwegian case study', in *2021 International Conference on Smart Energy Systems and Technologies (SEST)*, Vaasa, Finland: IEEE, Sep. 2021, pp. 1–6. doi: 10.1109/SEST50973.2021.9543330.
- [4] G. Brusco, D. Menniti, A. Pinnarelli, and N. Sorrentino, 'Renewable Energy Community with distributed storage optimization to provide energy sharing and additional ancillary services', *Sustain. Energy Grids Netw.*, vol. 36, p. 101173, Dec. 2023, doi: 10.1016/j.segan.2023.101173.
- [5] M. Elkazaz, M. Sumner, E. Naghiyev, Z. Hua, and D. W. P. Thomas, 'Techno-Economic Sizing of a community battery to provide community energy billing and additional ancillary services', *Sustain. Energy Grids Netw.*, vol. 26, p. 100439, Jun. 2021, doi: 10.1016/j.segan.2021.100439.
- [6] Y. Zhou, Z. Wei, G. Sun, K. W. Cheung, H. Zang, and S. Chen, 'A robust optimization approach for integrated community energy system in energy and ancillary service markets', *Energy*, vol. 148, pp. 1–15, Apr. 2018, doi: 10.1016/j.energy.2018.01.078.
- [7] European Union, 'Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources'. 2018. Accessed: Jun. 04, 2025. [Online]. Available: [https://joint-research-centre.ec.europa.eu/welcome-jec-website/reference-regulatory-framework/renewable-energy-recast-2030-red-ii\\_en](https://joint-research-centre.ec.europa.eu/welcome-jec-website/reference-regulatory-framework/renewable-energy-recast-2030-red-ii_en)
- [8] Spanish Official Gazette, 'Real Decreto 1183/2020, de 29 de diciembre, de acceso y conexión a las redes de transporte y distribución de energía eléctrica'. 2020.