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# A new smart batteries management for Renewable Energy Communities

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ABSTRACT

Based on the European Directive, the Italian Government has recently published the technical rules for accessing the service for valorizations and incentivizing shared electricity, kick-starting the setting-up of Renewable Energy Communities (RECs).

A techno-economic analysis is performed based on a real case in the city of Florence to show the benefits that the creation of a REC can bring to the stakeholders: consumers, prosumers, the national grid operator and third-party companies. Moreover, this study focuses on the role of batteries within a REC by comparing three different battery management systems (BMS).

The standard BMS (StBMS) is developed for individual prosumer self-consumption (SC) and not for REC collective-self-consumption (CSC), which is thus penalized by the presence of batteries. For that reason, a new smart BMS (SmBMS) based on REC real-time data monitoring is proposed. This solution guarantees the same level of CSC as in the case without batteries, and compared to the StBMS, it ensures greater REC energy independence from the national grid and leads to more incentives for all stakeholders, causing only a negligible economic loss for prosumers, as their individual SC slightly decreases.

The optimal BMS (OpBMS), based on deterministic knowledge of demand and production curves, could guarantee even greater REC energy independence and a better investment for all REC participants, but since it cannot be implemented, it is calculated only to be used as a benchmark to assess other BMSs and to explore the potential of forecasting based methods.

StBMS and SmBMS are simulated by Multi Energy System Simulator (MESS) while OpBMS by a Mixed-integer linear programming model (MILP).

## 1. Introduction

The concepts of REC and collective-self-consumption (CSC) have been introduced in Italy by the Regulatory Authority for Energy Networks and Environment [1], the ministry of economic development [2] and the ministry of justice [3] adopting Articles 21 and 22 of the European REDII Directive [4].

The Italian energy services operator (GSE) was appointed by the Italian Government to define the technical rules necessary for setting up a REC [5].

The REC is a legal entity composed of users belonging to the same low-voltage network that share the electricity produced by one or more systems powered by renewable sources, in this specific study photovoltaic panels. Open and voluntary participation in a REC is allowed for individuals, local or public authorities and small and medium-sized enterprises.

All configurations allowed for RECs involve the interaction with the electricity grid (Fig. 1), as it is not allowed to develop private grids for peer-to-peer energy transactions. All energy produced which is not self-consumed behind the meter of each utility is fed into the low voltage (LV) grid and it is paid based on 'Ritiro Dedicato' (RD) rates by GSE ([5]).

Part of this energy can also be recognized as CSC on which 110 €/MWh incentives are paid plus 8 €/MWh for the restitution of costs, not incurred for the management of the electrical system. The remaining energy ends up in the medium voltage (MV) grid. Each utility pays all the electricity withdrawn from the meter at

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**Abbreviations**

| | |
|---|---|
| CF | Cash flow |
| CSC | Collective-self-consumption |
| EnCo | 'Energia Collettiva' (Third-party company name) |
| GSE | 'Gestore Servizi Energetici' (Italian energy service operator) |
| LV | Low voltage |
| MESS | Multi-energy system simulator |
| MILP | Mixed-Integer Linear Programming |
| MV | Medium voltage |
| NPV | Net present value |
| PV | Photovoltaic panels |
| RAMP | Rural area multi-energy profile generator |
| RD | 'Ritiro Dedicato' (GSE rate for energy fed into the grid) |
| REC | Renewable Energy Community |
| SC | Self-consumption |
| SmBMS | Smart battery management system (scenario) |
| StBMS | Standard battery management system (scenario) |
| OpBMS | Optimal battery management system (scenario) |
| PVrec | PV are installed in a REC, no batteries (scenario) |

the price established with its distributor, whether it comes from MV or LV (CSC).

CSC corresponds to the energy produced and self-consumed by the entire REC on an hourly basis. It is defined as the minimum, in each hourly timestep, between the electricity fed into the grid by production systems and the electricity withdrawn from the grid by the end customers of the REC.

The purpose of RECs is to encourage the production of energy from renewable sources and to create social, environmental and economic benefits for the participants.

### *Literature review*

The first operative Italian REC is located in the town of Magliano Alpi [6] and it consists of four public buildings, one commercial service and three residences. Photovoltaic panels are installed on the roof of the City Hall for a total of 19.4 $kW_p$ and currently, no battery energy storage system is used. The developers claim to have obtained social, environmental, and economic benefits for all participants and emphasize the importance of developing smart control systems for the integrated management of generation sources and batteries to create more efficient and flexible scenarios.

Another Italian REC is in Monticello d'Alba, with a similar composition to the one in Magliano Alpi. It includes three municipal buildings, where PV panels are installed and ten dwellings. Its feasibility study [7] focused on two main aspects: the sizing of a single PV system and battery for the entire REC and the economic assessment of three business models defined based on a different distribution of the initial costs and revenues. All economic evaluations have been made from the point of view of the REC as a whole and as a third-party company, without investigating the economics of single prosumers and consumers. Moreover, the possibility that PV or batteries are installed in a single dwelling is not considered.

In both studies, demand profiles are obtained from synthetic load profiles based on general appliances usage statistics on a minute basis and then aggregated to hourly time steps.

A different approach to load forecasting, based on actual REC participant's consumption, was described and used in a study on the constitution of a REC from condominiums [8]. The work investigates a case study in Valle d'Aosta, a mountainous region in Northern Italy, and performs a techno-economic sizing of centralized PV panels, batteries and heat pumps. Results underline the importance of assessing the economic investment of individual citizens because, in the absence of the right forms of incentive, they may opt for an economic benefit rather than an environmental one, jeopardizing the potential benefit of energy community initiatives.

Starting from the Italian experience, a set of recent works dealing with battery management systems in RECs has been compiled and summarized in Table 1, whereas a thorough review on the topic has been conducted by Hossain Lipu et al. [9]. Each work has been distinguished from the others based on the following characteristics. First, whether the energy sources of the REC (be it PV, wind, or others) and the batteries are installed in a centralized (C) or decentralized (D) configuration. In the former case, a single energy source and battery system are serving the whole energy community, while in the latter each participant might install its own production and storage assets.

A distinction is then made on the Battery Management System (BMS), which is based on a set of predefined rules or mathematical optimization. In line with the definition given by Casalicchio et al. [10], REC can be virtual (Vir) or physical (Phy). Virtual RECs are in line with the Italian normative, and energy is always exchanged with the grid. CSC depends on contextual injection and extraction of energy from the grid from two distinguished REC participants. Physical RECs are composed of microgrids where energy is shared among participants and a single point of connection to the grid is present. Each work can then be focused either on energy management (Man), components' sizing (Siz), or both. Finally, the reference country for the analysed study case and the major modelling approaches employed in each work are listed in the last two columns.

RECs analyses are often divided into two approaches: rule-based simulation and optimization [11]. In the first, the energy balances of the system are solved with an established energy management system (e.g., [8,12,13]), while in the latter a deterministic linear or mixed-integer linear programming (MILP) is applied to find the optimal energy dispatch (e.g., [7,10,14–17]).

Rule-based battery control strategy compared with an optimization-based battery control can lead to a lower cost for prosumer both in the case of shared battery storage [18] and in the case of an energy communities involving decentralized storage system [19].

The main role of battery management for a REC is to perform self-consumption and collective self-consumption, but energy arbitrage and services to the local grid can also be considered, such as load levelling [20] and smoothing [21] and peak shaving [22]. Moreover, ancillary services to the national grid could also be provided [23] in order to maximize the exploitation of available storage capacity and increase economic returns. Nevertheless, this study focuses only on ensuring self-consumption and collective self-consumption.

### *Aims and elements of novelty*

None of the works cited addressed the main problem described in this study: installing batteries in an REC penalizes CSC if they are managed by StBMS. Therefore, this work aims to investigate how different BMS affect the energy balances and the economics of RECs. The Italian regulatory context is taken as a reference and a real-world case study is considered, as to ground the analysis on realistic assumptions and obtain new insights into the regulation itself by considering all stakeholders point of view: prosumers, consumers, third-party companies and national grid.

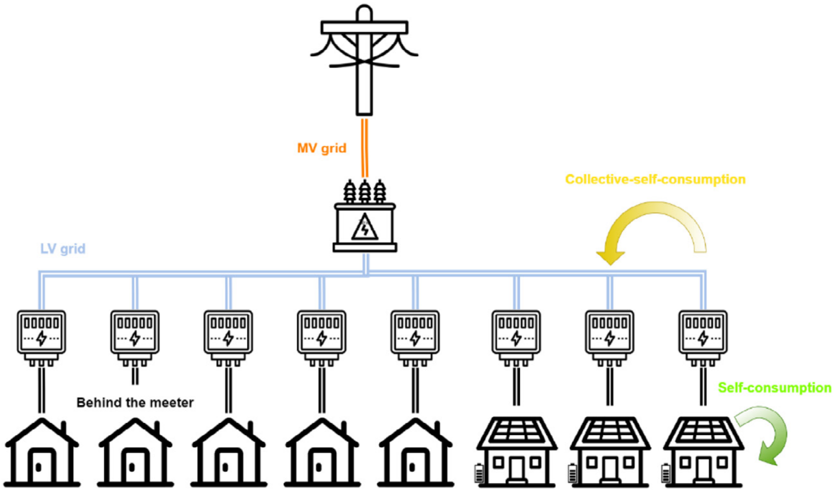

**Fig. 1.** Study case grid diagram.

**Table 1**
Literature review.

| Ref. | Energy source | Battery | BMS | Phy/Vir | Man/Siz | Country | Methods |
|---|---|---|---|---|---|---|---|
| Ascione et al. [24] | C | C, D | Rule-based | Vir | Siz | Italy | Energy Plus<br>Exhaustive search |
| Casalicchio et al. [10] | D | D | Optimization | Phy, Vir | Man, Siz | Italy | MILP |
| Cielo et al. [7] | C | C | Optimization | Vir | Man | Italy | MILP |
| Fernandez et al. [25] | C, D | C | Optimization | Phy | Man | Australia | MILP Bi-level optimization (Stackelberg game) |
| Fina et al. [12] | D | – | – | Phy | Man | Austria | Simulation |
| Fioriti et al. [26] | D | D | Optimization | Phy | Man, Siz | Italy | MILP Game theory |
| Gul et al. [27] | C | C | Optimization | Phy | Man, Siz | Italy | SAM optimization |
| Henni et al. [28] | D | D | Rule-based | Phy | Man | Germany | Simulation |
| Korjani et al. [29] | D | C | Optimization | Phy | Man | IEEE 906-bus | Genetic algorithm |
| Minuto et al. [8] | C | C | Rule-based | Vir | Siz | Italy | Simulation |
| Mustika et al. [19] | D | D | Rule-based Optimization | Vir | Man | France | Simulation YALMIP |
| Norbu et al. [18] | C | C | Rule-based Optimization | Phy | Man, Siz | UK | Simulation MILP |
| Roberts et al. [30] | C | – | – | Phys | Man | Australia | Simulation |
| Secchi et al. [31] | D | D | Rule-based | Phys | Man, Siz | IEEE 906-bus | Simulation<br>Non-dominated Sorting Genetic Algorithm-II |
| Weckesser et al. [17] | D | D | Optimization | Phys | Man, Siz | Denmark | LP |
| Present work | D | D | Rule-based Optimization | Vir | Man, Siz | Italy | Simulation MILP |

Key novelties of this study are:

- Demonstrate that the presence of batteries in a REC penalizes the CSC if they are managed with a StBMS.
- New SmBMS for RECs.
- Comparing different BMSs for RECs.
- Comparison between simulation and MILP optimization methods.
- Assessment of a REC with a decentralized storage system, in which each prosumer has its own battery.
- Focus on each stakeholder's investment.
- New method to generate load profiles.

## 2. Materials and methods

### 2.1. Reference study cases

The REC considered in this study is a residential neighbourhood, aiming to become an energy community, located in the countryside of Florence. The community consists of 3 prosumers and 5 consumers (Fig. 1). The project is under development by the start-up "Energia Collettiva" (EnCo), through which participants' data are collected.

The PVs sizes are determined based on the space available on a car park roof, whose angle of inclination is 10° and azimuth is 0°. Lithium-ion batteries sizing are performed to maximize each prosumer's investment, as explained in 3.1.

Table 2 summarizes case study information.

### 2.2. Load forecasting

The meters installed in the eight dwellings considered are old generation, so load profiles are not available, and it is necessary to generate them using a forecasting technique. Thanks to the collaboration with EnCo it was possible to submit a survey to the REC participants asking them about their habits in using household appliances. These kinds of information are used as input for a bottom-up simulation programme to simulate loads. After that, the generated profiles have been top-down validated and corrected according to the electricity bill of the participants.

***Bottom-up simulation***

Each household is subjected to a survey, in which it is asked what appliances are present in the dwelling and how often they are used. In addition, it is asked an average of at what time these are used. This information is used as input for a bottom-up simulation software [32] that simulates, minute by minute

**Table 2**
Study case information.

| Stakeholder name | Role | Annual demand [kWh] | PV size [kW$_p$] | Battery size [kWh] |
|---|---|---|---|---|
| p1 | Prosumer | 1891 | 4.5 | 2.5 |
| p2 | Prosumer | 10 341 | 6.0 | 10.0 |
| p3 | Prosumer | 1695 | 4.5 | 3.0 |
| c1 | Consumer | 1232 | – | – |
| c2 | Consumer | 1374 | – | – |
| c3 | Consumer | 2743 | – | – |
| c4 | Consumer | 2791 | – | – |
| c5 | Consumer | 1378 | – | – |
| EnCo | Service provider and REC manager | | | |
| | Total REC demand: 23 070 kWh | | | |
| | Total REC production: 20 840 kWh | | | |

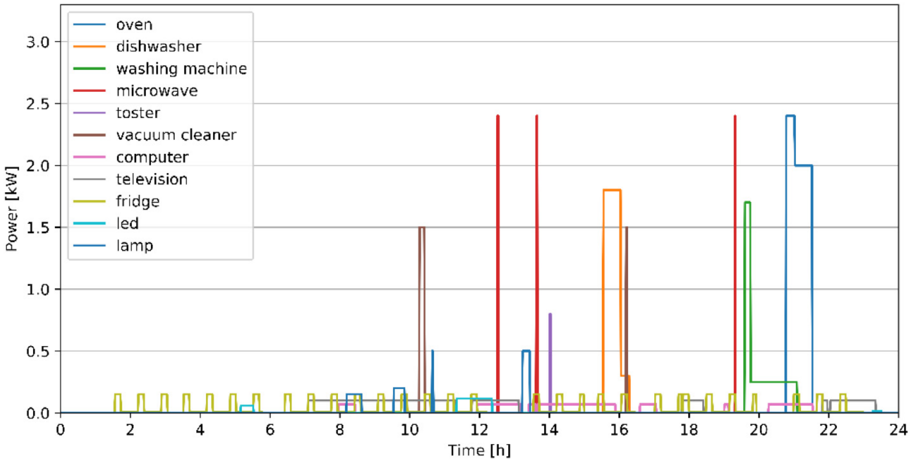

**Fig. 2.** Daily load simulation minute by minute of each appliance.

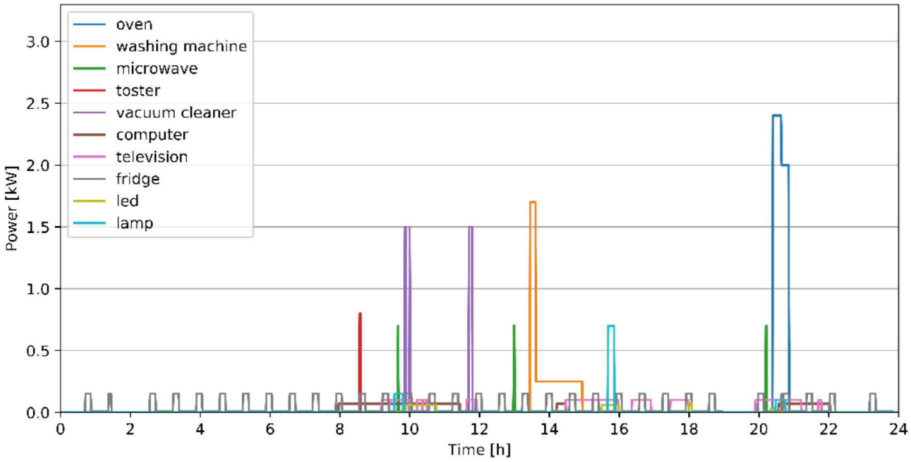

**Fig. 3.** Another daily load simulation minute by minute of each appliance.

throughout the year, the switch on and the switch-off of each appliance with a degree of randomness. The curves that the software can generate are shown in Fig. 2, Fig. 3, Fig. 4, and Fig. 5 using as example p1 simulation data.

Figs. 2 and 3 show how a daily load can be composed. Each appliance requires a different power and its switches on and switches off happen considering both survey information and a certain degree of randomness. For that reason, every day is different, the times in which the appliances are used change and some of them could also not be used.

By increasing the number of simulations, it is possible to observe the characteristics of the electrical demand of each dwelling, in terms of the average curve and required powers. These characteristics reflect survey information. Figs. 4 and 5 show, with a blue line, the medium load minute by minute of p1; the first figure considering a one-week simulation and the second one a whole year. The skylines are the daily profiles overlapping.

Average profiles, power required, and total energy demand are different from dwelling to dwelling because each one has different appliances and uses them at different times and frequency.

The main advantage of using a bottom-up method like this is that it allows replacing the random behaviour of people inside the dwellings by generating realistic loads. Moreover, the non-contemporaneity of each dwelling load, is a fundamental aspect

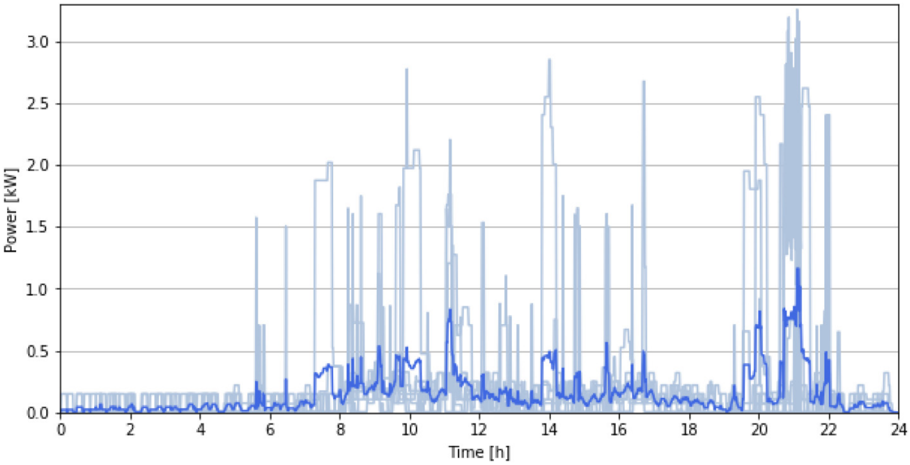

**Fig. 4.** Weekly load simulation: average curve and overlapping days.

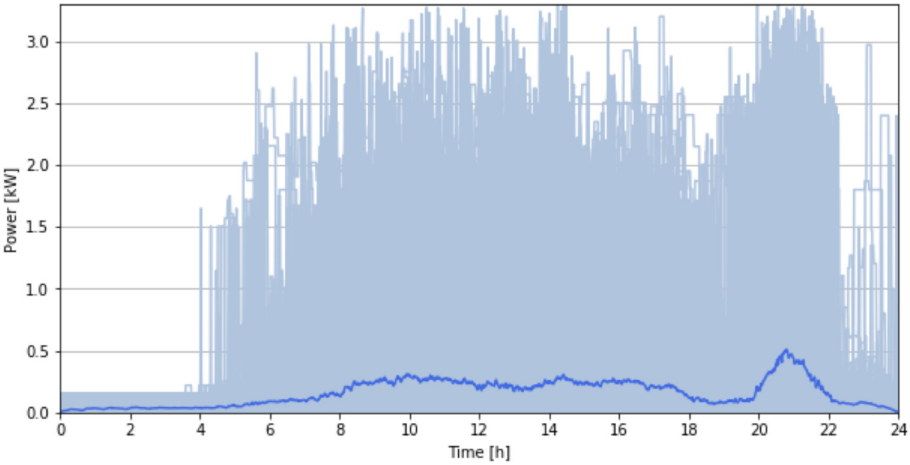

**Fig. 5.** Yearly load simulation: average curve and overlapping days.

| Hours | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Week days | F3 | F3 | F3 | F3 | F3 | F3 | F3 | F2 | F1 | F1 | F1 | F1 | F1 | F1 | F1 | F1 | F1 | F1 | F1 | F1 | F2 | F2 | F2 | F2 |
| Saturday | F3 | F3 | F3 | F3 | F3 | F3 | F3 | F2 | F2 | F2 | F2 | F2 | F2 | F2 | F2 | F2 | F2 | F2 | F2 | F2 | F2 | F2 | F2 | F2 |
| Sunday | F3 | F3 | F3 | F3 | F3 | F3 | F3 | F3 | F3 | F3 | F3 | F3 | F3 | F3 | F3 | F3 | F3 | F3 | F3 | F3 | F3 | F3 | F3 | F3 |

**Fig. 6.** Time slots according to Italian legislation.

to calculate the CSC. On the other hand, this approach does not include seasonality, it is subjected to errors due to initial assumptions, and the validity of the generated curves strictly depends on survey reliability, which varies from case to case. To adjust these sources of unreliability a top-down validation method is also used.

### *Top-down validation*

Bottom-up simulation results are compared with electricity bills information, i.e., the consumption of each month, divided into the three time slots, defined by Italian law: F1, F2 and F3 as they are defined in Fig. 6.

Therefore, for each dwelling, 12 *x* 3 (month *x* timeslot) values are used to validate simulation results and correct them making consumption more realistic. As an example, Table 3 shows the p1 simulation results and p1 bill for some months of the year.

Starting from the simulated loads, the energy required in each time slot for each month is calculated, and these values are compared with those of the bills. Consequently, it is calculated where and how much energy to add or remove to make the simulated curve balance consistent with the bill information. These energies are randomly distributed on an hourly basis, as shown for a single day in Fig. 7. For instance, in the case represented, demand in F1 is overestimated, while in F2 and F3 it is underestimated.

The aggregation of the time step from minute to hour is a computational necessity of the following simulations. It is also justifiable considering that the CSC, which is the main object of this study, is defined on an hourly basis. The hourly profiles, averaged over a simulation year, are shown in Fig. 8. Total demands reflect electricity bill information and profiles result from survey information. Each dwelling has a different load, some concentrate the demand in the morning and during the evening while others have a more distributed demand. Due to the presence of electric vehicles, p2 demand is greater than the others and it is also high during the night hours, as verified in the bill.

**Table 3**
Case study p1 bottom-up simulation results vs bill information [kWh].

| Month | F1 | | F2 | | F3 | |
|---|---|---|---|---|---|---|
| | Simulation | Bill | Simulation | Bill | Simulation | Bill |
| January | 58 | 70 | 56 | 66 | 39 | 96 |
| February | 51 | 49 | 42 | 49 | 46 | 60 |
| … | … | … | … | … | … | … |
| December | 51 | 55 | 50 | 56 | 48 | 72 |
| Total | 612 | 531 | 549 | 590 | 522 | 770 |

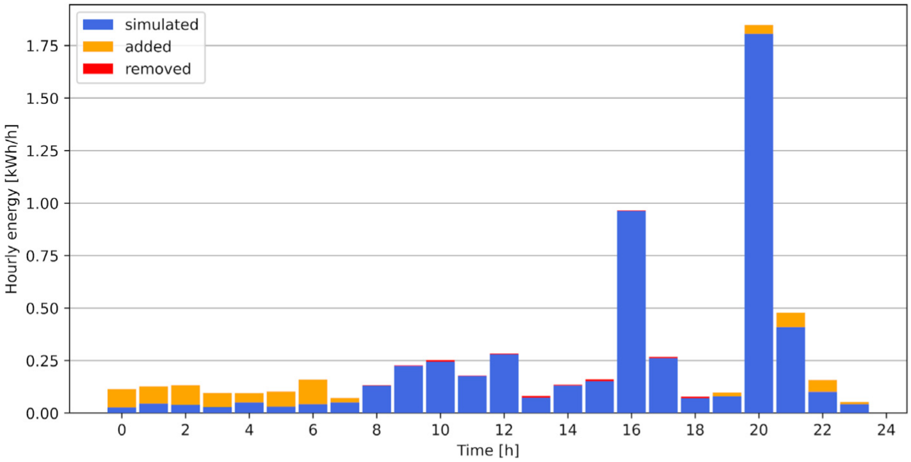

**Fig. 7.** One-day load curve correction.

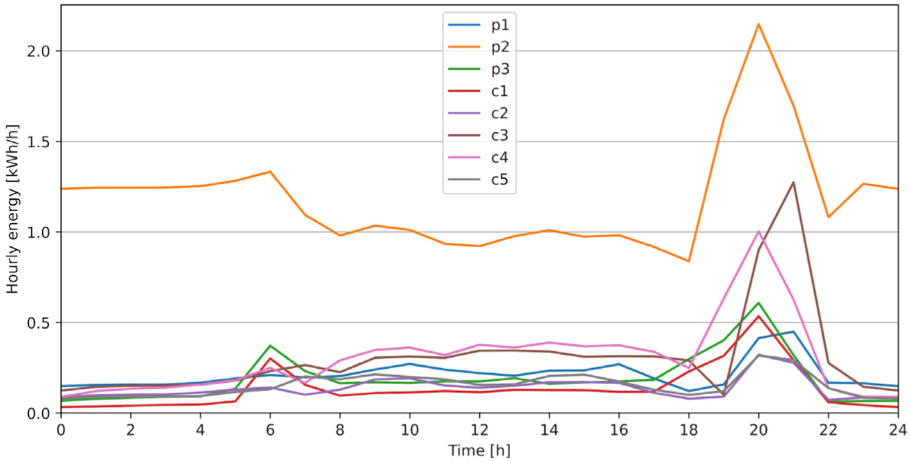

**Fig. 8.** Average daily profiles of each user dwelling.

### 2.3. Economics

The cost of PVs and batteries is covered by prosumers, who own them. Consumers, on the other hand, have no cost to bear either for the installations or for being able to participate in the REC and use the surplus of prosumer's energy. Their participation in the REC allows for an increase in CSC and the associated incentive, which is then distributed among both prosumers and consumers, as explained in paragraph 2.4.

The economic assessment of prosumers' investment is based on the Net Present Value (NPV), calculated for 20 years (y) using Eq. (1). Evaluating the evolution of the NPV over the years allows an accurate assessment of the investment by considering the $NPV_{20}$ (Eq. (2)) and the payback time.

$$NPV_y = NPV_{y-1} + CF_y/(1+i)^y \tag{1}$$

$$NPV_{20} = -NPV_0 + \sum_{y=1}^{20} CF_y/\,(1+i)^y \tag{2}$$

$$CF = Into\ grid \cdot RD + SC \cdot E_{price} + CSC \cdot CSC_{rate} - O\&M \tag{3}$$

$NPV_0$ is the initial investment, $CF_y$ is the cash flow of one year, and i is the annual interest rate set at 4%.

The initial investment is calculated according to the costs in Table 4 which are indicated by EnCo and therefore represent the Italian market as of September 2022; prices include main and additional components and installation costs. The 50% of the investment is refunded by the Italian Government in 10 annual instalments. In most cases the client can assign this credit to the seller, thus paying only half or a little more, of the initial investment cost.

The cash flow is calculated with Eq. (3), according to the rates in Table 5, and against the "business as usual" scenario in which

**Table 4**
Total installation cost of components.

| Component | Total installation cost* |
|---|---|
| PV | 1400 €/kW$_p$ |
| Battery | 800 €/kWh |

*50% of total installation costs are refunded.

no renewable energy system is installed, and each household purchases all electricity from the grid and receive no incentives. Therefore, the cash flow related to a prosumer's investment is composed of the energy fed into the grid and therefore sold to the GSE at the RD tariffs, and of the self-consumed (SC) energy that is not purchased from the grid at energy price ($E_{price}$), as in business as usual.

Part of the energy fed into the grid is recognized as CSC on which incentives of 0.118 €/kWh [5] are disbursed and then distributed among REC members.

O&M can be considered zero for a residential installation.

The medium rate of RD is estimated at 0.15 €/kWh in March 2023 [33]; consequently the energy purchase tariffs is estimated to be at least 0.40 €/kWh. This last assumption is made by comparing the historical prices RD and the costs in participants' bills. Despite these estimates, the values used for the economic analysis are lower (fourth column of Table 5) so as to make the analysis more robust by simulating a 'worst-case' scenario. Obviously, making an accurate estimate of these prices is impossible, but it is worth noting that the economic gains reported below could be even much higher in scenarios of high prices, such as those experienced in 2022 due to geopolitical conditions.

### 2.4. Redistribution of collective-self-consumption incentives

CSC is calculated as follows:

$$CSC = \sum_{h} min(into\ grid_h, from\ grid_h) \quad (4)$$

Where into grid$_h$ and from grid$_h$ are electricity fed to and withdrawn from the grid by the entire REC at each hour (h). The total is multiplied by the value of the incentive and redistributed among the participants of the REC according to rules defined during its establishment. In this study, a meritocratic method that rewards who contributes most to CSC is proposed.

CSC$_h$ is attributable both to producers and to consumers: for example, if 10 kWh are recognized as CSC$_h$, this means that at least 10 kWh are fed into the grid and at least 10 kWh are withdrawn from the grid. The contribution of the 10 kWh fed into the grid is divided between the households that fed energy into the grid at hour h, in proportion to how much each fed. And the 10 kWh withdrawn are proportionally attributed to the dwellings that withdrew energy at hour h. Based on this principle, it is possible to calculate for each household how much it contributes to CSC as a consumer and how much as a producer. Consumers can only contribute as consumers, while prosumers can contribute both as producers and as consumers.

Consequently, the incentives are distributed according to how much everyone contributes, but first the share of the contribution as a producer and the share of the contribution as a consumer must be established.

Moreover, a part will be probably retained by the REC operator. In this study, a division of 60% to consumers, 20% to prosumers and 20% to the REC operator is initially proposed. Later, the operator's share is further discussed.

### 2.5. Simulation and optimization models

***MESS***

MESS (Multi-Energy System Simulator) is a simulation model based on an analytical programming approach, meaning that it is based on a set of pre-defined rules and priorities applied at each timestep. The simulation approach and the modular development of the tool, allow to consider different strategies for the same component and to define more realistic management strategies to account for real-life, unoptimized behaviours of energy systems [11]. A more detailed description of the tool can be found in previous works of the authors, where the tool has been applied to residential energy systems with heat pumps [34] or considering battery ageing [35]. For this work, a new BMS (defined as smart BMS, or SmBMS) is introduced. MESS is an open source software published on GitHub [36].

***MILP***

The optimization model used to benchmark the performance of two different BMS has already been presented for an optimal scheduling problem in a precedent work of the authors [14]. In this study, the optimal dispatch of PV, batteries, heat pumps and electric vehicle (EV) chargers is calculated to minimize costs. An extension of this model, with the addition of the optimal investment planning to the optimal dispatch problem, was presented in [15]. This updated model is used in this study for the evaluation of one of the possible BMS to implement in the REC, with the only addition of the extra revenue stream coming from CSC. The main advantage of using a fully deterministic optimization approach is that, by giving the best possible solution, it can be used as a benchmark for evaluating the results of another approach that could be more easily implemented in real-life conditions. On the other hand, a control based on perfect foresight cannot be implemented in real-life conditions.

### 2.6. Simulated scenarios

Table 6 summarizes the scenarios simulated, their acronyms and the tool used to simulate them. The graphs in Fig. 9 are examples of a daily balance of a single prosumer and are useful to display the distinct roles of the battery according to different BMS, which are also described in Table 7.

In the PVrec scenario there are not batteries, so all the PV surplus is fed into the LV grid and part of it can be used by the REC and recognized as CSC, the remaining ends up in the MV grid.

If a battery is present and managed with a standard battery management system (StBMS), PV surplus is first used to charge the battery and then fed into the LV grid. Because of this, the prosumer SC increases but REC CSC decreases.

This happens with StBMS, but a different management rule can be used (SmBMS) which gives priority to fed energy into the grid to create CSC instead of charging the battery. SmBMS allows to obtain the same CSC of the PVrec scenario, but the

**Table 5**
Cash flow components.

| Energy balance | Rate in 2022 €/kWh | Rate in 03/2023 €/kWh | Rate used €/kWh |
|---|---|---|---|
| Into grid | 0.50 (RD) | 0.15 (RD) | 0.10 (RD) |
| Self-consumption | 1.20 ($E_{price}$) | 40 ($E_{price}$) | 30 ($E_{price}$) |
| Collective-self-consumption | 0.118 (to share) | 0.118 (to share) | 0.118 (to share) |

**Table 6**
Simulated scenarios.

| Acronym | Scenario | Tool |
|---|---|---|
| PVrec | No batteries | MESS |
| StBMS | Standard battery management system | MESS |
| SmBMS | Smart battery management (real-time data monitoring) | MESS |
| OpBMS | Optimal battery management (perfect forecasting) | MILP |

**Table 7**
Batteries management system in the simulated scenarios.

| StBMS | SmBMS |
|---|---|
| If there is energy surplus<br>Charge the battery<br>If there is still energy surplus<br>Fed energy into the grid<br>Calculate CSC | If there is energy surplus<br>If REC members are withdrawing energy<br>Fed the energy they need into the grid (this create CSC)<br>If there is still energy surplus<br>Charge the battery<br>If there is still energy surplus<br>Fed energy into the grid<br>Calculate CSC |
| **PVrec (no batteries)** | **OpBMS** |
| If there is energy surplus<br>Fed energy into the grid<br>Calculate CSC | Calculate the optimal scheduling based on perfect foresight to maximize REC profits.<br>Calculate CSC |

**Table 8**
REC annual energy balances in **PVrec** scenario.

| Energy balance | Value [kWh] | Value/production [%] | Value/load [%] |
|---|---|---|---|
| SC | 3824 | 18.35 | 16.57 |
| CSC | 3594 | 17.24 | 15.58 |
| Into MV grid | 13 423 | 64.41 | 58.18 |
| From MV grid | 15 654 | 75.11 | 67.85 |

SC of each prosumer is slightly lower than the StBMS scenario because the battery does not always have the necessary energy to be charged as in StBMS. Unlike StBMS, SmBMS requires real-time data monitoring because it considers the energy balances of all the REC members.

Introducing one-year perfect production and consumption forecasts OpBMS can be performed, which calculates the optimal batteries' scheduling to maximize REC profits, that is the sum of the profits of all members. This results in solving the contrast between CSC and SC without establishing a priority but maximizing the former without reducing the latter. OpBMS guarantees the same SC as the StBMS but allows a greater CSC because, in some hour battery charging is delayed. This also ensures that less energy is fed into the MV grid. Unfortunately, OpBMS it cannot be implemented, so it is only used as a benchmark to evaluate other BMSs.

## 3. Results

Firstly, batteries are sized and secondly, results of the different BMS scenarios are analysed by comparing the different energy balances and their economic performances. The aim is to quantify the benefits that can be achieved by establishing a REC, installing batteries, and managing them with different BMS. At last, the third-party company point of view is also discussed.

### 3.1. Battery sizing

Each prosumer's battery is sized to maximize his $NPV_{20}$ considering StBMS; results are shown in Fig. 10. Due to the difference in PV nominal power, total electrical demand and load profiles, the sizing is different for each prosumer. P2 needs a 10 kWh battery as its demand is significantly higher and so is the PV capacity; for p1 and p3, smaller batteries of 2.5 kWh and 3 kWh respectively are the best solution.

### 3.2. Energy balances

Fig. 11 and Fig. 12 are graphical representations of the annual energy flows in PVrec and StBMS scenarios. Looking from left to right diagrams show energy produced by prosumers' PV which becomes SC, CSC or energy fed into the MV grid. From right to left, the demand for electricity is met by energy from the MV grid, from the LV grid (CSC) or from PV or batteries (self-consumption).

To create a national grid that is powered by renewable sources and at the same time stable, the amounts of energy that a REC withdraws from the MV grid and feeds into the MV grid must be minimal. In other words, the REC and so the LV grid should be as independent as possible. This also reduces energy losses due to MV transport.

StBMS is used as an example for all the three scenarios in which batteries are installed, as the differences would not be appreciable in this type of graphs.

Tables 8–11 summarize the main results of the four scenarios. Comparing PVrec with StBMS, the latter scenario increases the independence of the REC. This results in a drop of 26.4% of energy fed into the MV grid and a fall of 17.3% of energy withdrawn from the MV grid. This happens because the batteries increase the SC by 95.6%. Unfortunately, StBMS also leads to a 26.3% decrease in CSC, which is a symptom of an inefficient REC.

SmBMS is developed to solve this problem, indeed, it guarantees the same CSC as the PVrec scenario. As a consequence, the REC independence increases further: compared to the StBMS, the energy fed into the grid MV decreases by an additional 3.9% and the energy withdraws from the MV grid by an additional 3.8%. The only problem with this scenario might be that SC decreases by 6.1% penalizing individual prosumers. This will be investigated from the economic point of view in the next section.

OpBMS aims to find the optimal scheduling in terms of cost, which results in maximizing SC, reaching the same amount of StBMS, but with an additional increase of 20% of CSC. The total grid interaction in the OpBMS scenario also decreases further compared to StBMS, with a 5.4% reduction of energy fed into the MV grid and a 4.1% reduction of energy withdrawn.

Fig. 13 gives a summary of the total energy flows. In general, the MV grid remains the biggest contributor to the annual demand, followed by the SC, while CSC represents the smallest contribution in all the scenarios.

### 3.3. Economic assessment

Each REC member's investment is evaluated over 20 years using as reference annual energy balances shown in the paragraph above. 20 years is the period for which the GSE guarantees incentives on CSC from the time of REC establishment and is also the minimum expected lifetime for PV and batteries. Fig. 14 and Fig. 15 show the evolution of each member's NPV for PVrec and StBMS scenarios, while Tables 12 and 13 describe the exact cash

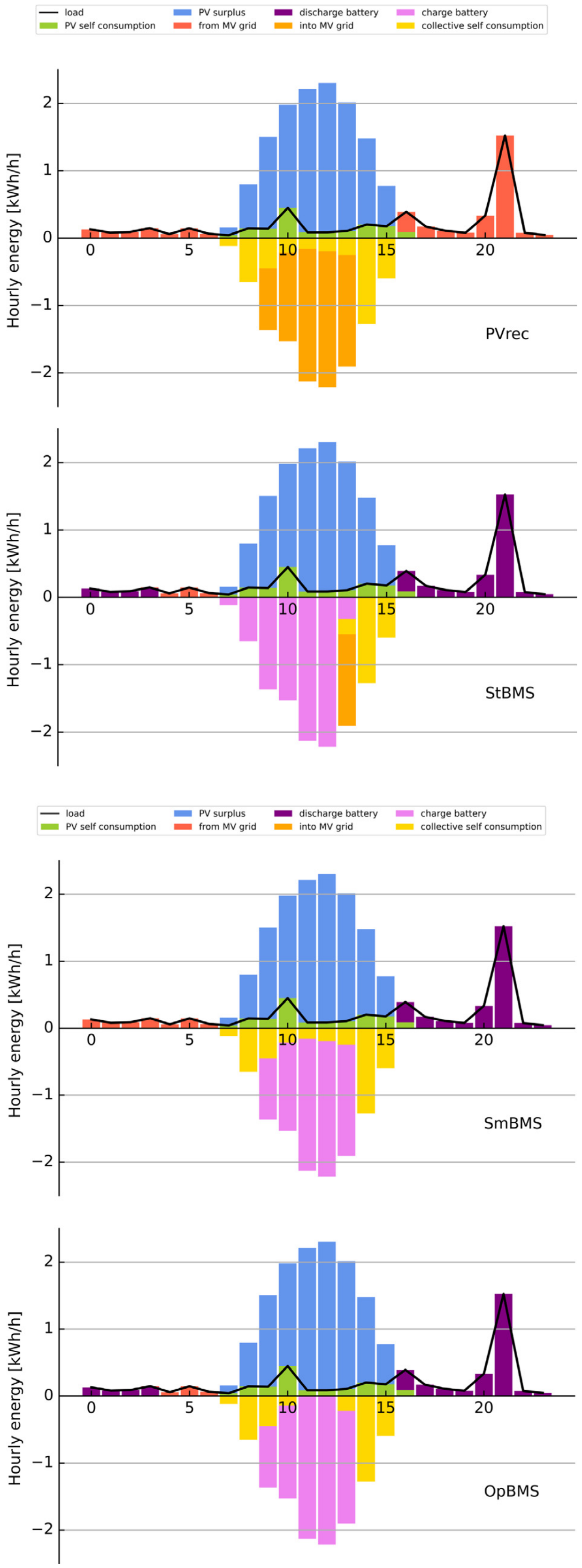

**Fig. 9.** Daily energy balances in different scenarios.

flow of prosumers and consumers respectively. Fig. 16 summarizes the prosumer's cash flow composition in different scenarios.

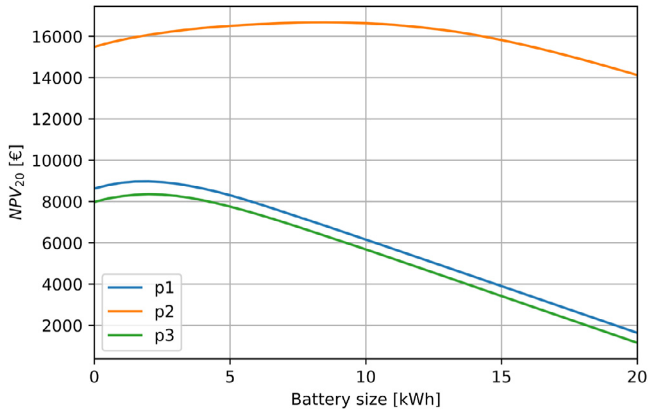

**Fig. 10.** Battery sizing.

**Table 9**
REC annual energy balances in the **StBMS** scenario.

| Energy balance | Value [kWh] | Vs PVrec [%] | Value/ production [%] | Value/ load [%] |
|---|---|---|---|---|
| SC | 7480 | +95.6 | 35.89 | 32.42 |
| CSC | 2648 | −26.3 | 12.71 | 11.48 |
| Into MV grid | 9872 | −26.4 | 47.37 | 42.79 |
| From MV grid | 12 945 | −17.3 | 62.11 | 56.10 |

Prosumers must repay the initial investment of PV and batteries, while consumers have no upfront expenses and receive for free their share of the incentive.

In PVrec scenario, p1 and p3 pay 6300 €, which they recover in 7 years, coming to get, after 20 years, about 8000 €and 7500 €respectively; the difference is obviously due to the ability to self-consume energy and thus to consumption profiles. P2 investment is different, as it has both higher demand and production. It has an initial investment of 8400 €, his payback time is about 5 years and after 20 years it gets more than 15,000 €. REC establishment provides the three prosumers with 39, 53 and 32 €of additional revenue per year and consumers with 25 to 68 €, depending on how much they contribute to CSC. These values would be much higher in REC composed of a larger number of members, capable of creating greater CSC.

In the StBMS scenario, income due to CSC incentives decreases for all members. Battery installation magnifies prosumer investment to 8300 €, 16,400 €and 8700 €respectively for p1, p2 and p3. P2 payback time increase for all three. But also, earnings increase: the magnitude of these depends on the difference between the cost of energy and the RD.

In SmBMS and OpBMS the variation in investments is very small compared to StBMS to be shown in NPV evolution over years (Figs. 14 and 15); it is therefore necessary to look at the detail of the cash flow components (Table 12 and Fig. 16).

In SmBMS, CSC incentives are the same as the PVrec scenario, but the prosumer's annual cash flow decreases by about 15 €. This happens because the increase in cash flow due to CSC and energy sold to RD does not compensate for the diminution of SC. This result proves that adapting an SmBMS that prioritize CSC rather than SC creates a negligible economic disadvantage for prosumers. This should, however, also be evaluated considering less usage and thus ageing of the batteries, assuming a refund for prosumers or simply considering it "a gift to the environment".

OpBMS guarantees the highest revenues for all three prosumers by optimally choosing between charging the battery and

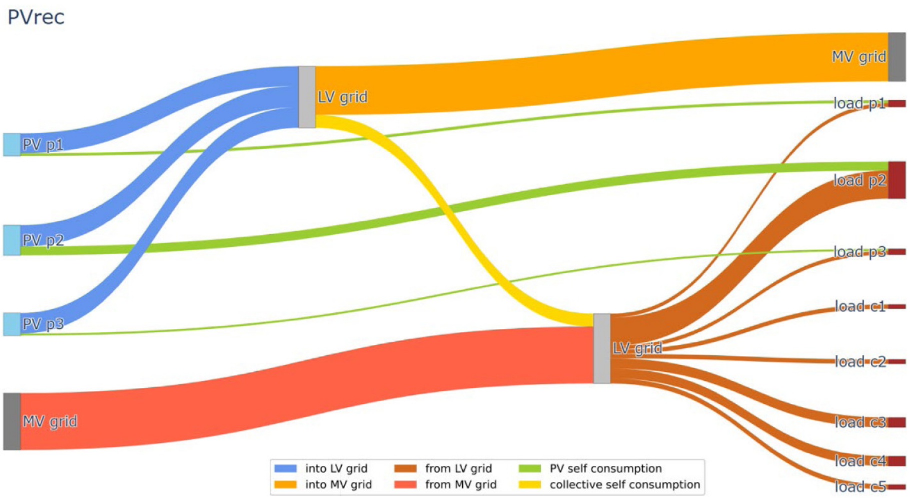

**Fig. 11.** Annual energy flows in **PVrec** scenario.

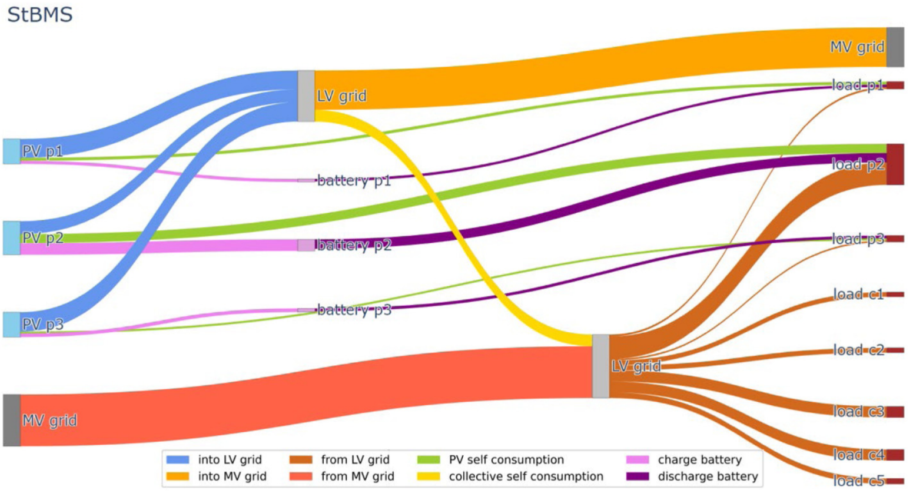

**Fig. 12.** Annual energy flows in the **StBMS** scenario.

**Table 10**
REC annual energy balances in **SmBMS** scenario.

| Energy balance | Value [kWh] | Vs StBMS [%] | Value/production [%] | Value/load [%] |
|---|---|---|---|---|
| SC | 7024 | −6.1 | 33.70 | 30.44 |
| CSC | 3594 | +35.7 | 17.24 | 15.58 |
| Into MV grid | 9490 | −3.9 | 45.54 | 41.13 |
| From MV grid | 12 455 | −3.8 | 59.76 | 53.98 |

**Table 11**
REC annual energy balances in **OpBMS** scenario.

| Energy balance | Value [kWh] | Vs StBMS [%] | Value/production [%] | Value/load [%] |
|---|---|---|---|---|
| SC | 7480 | −0.0 | 35.89 | 32.42 |
| CSC | 3178 | +20.0 | 15.25 | 13.77 |
| Into MV grid | 9342 | −5.4 | 44.91 | 40.48 |
| From MV grid | 12 415 | −4.1 | 59.55 | 53.79 |

selling electricity back to the grid, making it available for CSC. By doing this, OpBMS ensures the same SC as StBMS and at the same time makes it possible to achieve a higher level of CSC, providing more incentives to be shared among all parties.

### 3.4. Third-party company operator

Economic assessments above assume that the costs of setting up the REC are not borne by the participants but by a third-party company, in this case EnCo, who receives a percentage of the incentives on CSC to set up the REC and assumes the role of

**Table 12**
Prosumer's annual cash flow for different scenarios [€].

| Stakeholder name | Scenario | RD | SC | CSC | Tot |
|---|---|---|---|---|---|
| p1 | PVrec | 545 | 239 | 39 | 823 |
| | StBMS | 469 | 426 | 35 | 930 |
| | SmBMS | 482 | 394 | 39 | 915 |
| | OpBMS | 469 | 426 | 42 | 937 |
| p2 | PVrec | 588 | 736 | 52 | 1376 |
| | StBMS | 302 | 1434 | 17 | 1753 |
| | SmBMS | 329 | 1369 | 52 | 1750 |
| | OpBMS | 302 | 1434 | 20 | 1756 |
| p3 | PVrec | 568 | 171 | 32 | 771 |
| | StBMS | 481 | 384 | 24 | 889 |
| | SmBMS | 497 | 344 | 32 | 873 |
| | OpBMS | 481 | 384 | 29 | 894 |

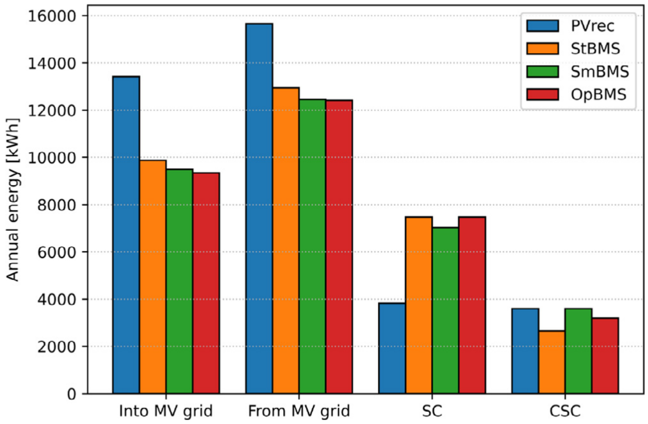

**Fig. 13.** REC annual energy balances comparing the four scenarios.

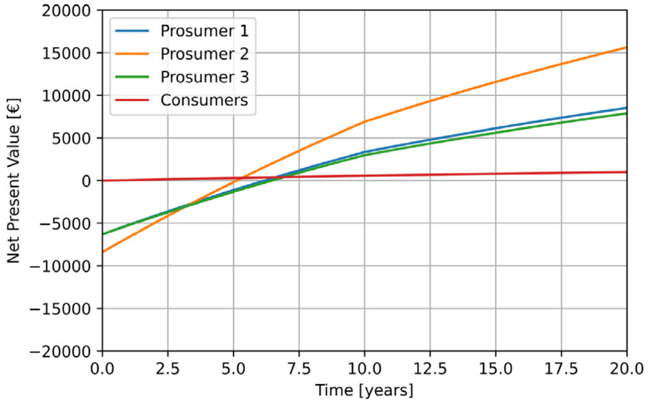

**Fig. 14.** Investment assessment of each REC member in **PVrec** scenario.

community manager. This income would like to be used partly to repay the initial investment and partly for public good works.

Table 14 summarizes the costs required to establish a REC. Here, it is evident how the role of a company like EnCo become very useful. In fact, due to legislation, to be operative a REC needs to be registered as legal entity to the authorities. Such a passage is full of bureaucracy and disincentive participants to deal with it. EnCo offers its support in matching the demand and the offer of service, like legal advisory. Furthermore, to properly allocate the generated tariff, EnCo installs a smart meter for each point of connection of the REC.

The cost of these meters and the constitution fee, visible in Table 14, are fully covered by EnCo to allow participants to enter the REC at zero cost. Administrative costs are mandatory and to be paid to GSE, therefore another support from third-party

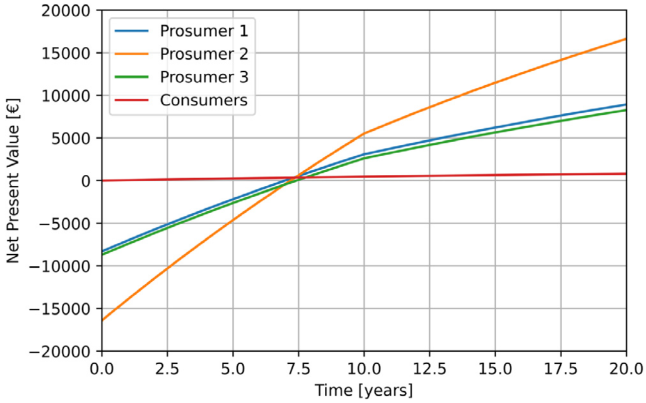

**Fig. 15.** Investment assessment of each REC member in the **StBMS** scenario.

**Table 13**
Consumer's annual cash flow for different scenarios [€].

| Stakeholder name | Scenario | CSC |
|---|---|---|
| c1 | PVrec | 25 |
| | StBMS | 20 |
| | SmBMS | 25 |
| | OpBMS | 24 |
| c2 | PVrec | 34 |
| | StBMS | 30 |
| | SmBMS | 34 |
| | OpBMS | 33 |
| c3 | PVrec | 63 |
| | StBMS | 55 |
| | SmBMS | 63 |
| | OpBMS | 61 |
| c4 | PVrec | 68 |
| | StBMS | 60 |
| | SmBMS | 68 |
| | OpBMS | 66 |
| c5 | PVrec | 42 |
| | StBMS | 36 |
| | SmBMS | 42 |
| | OpBMS | 40 |

companies like EnCo is to manage such transactions and covering this expense with its part of the incentive.

Fig. 17 describes third-party company investment varying the percentage of retained incentive and the scenarios.

Fig. 17 shows that, considering actual Italian regulation, an 8-member REC with such a configuration is a good investment for a third-party company only if they keep a substantial share of the incentive on CSC. Indeed, the figure shows that the costs of establishing and maintaining the REC require almost all CSC incentives to be repaid. Or, from another point of view, incentives

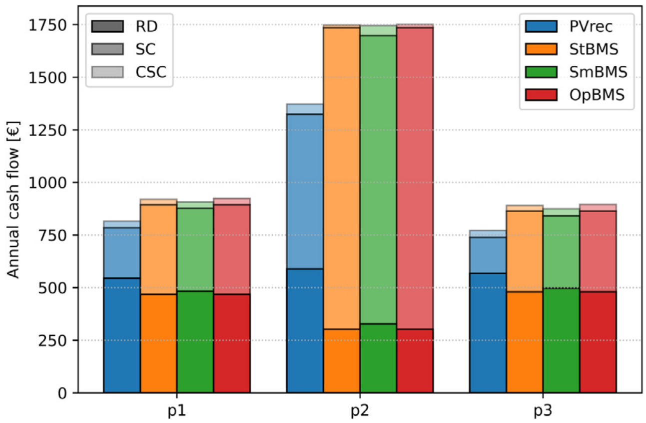

**Fig. 16.** Prosumer's annual cash flow composition for different scenarios.

**Table 14**
Costs of establishing and maintaining the REC.

| Initial investment* | |
|---|---|
| Constitution fee | 200 € |
| Meters | 150 €/component |
| Administrative costs | |
| Fixed fee | 4 €/component/y |
| Additional fee | 30 €/y |

*Deed is not necessary for a residential REC.

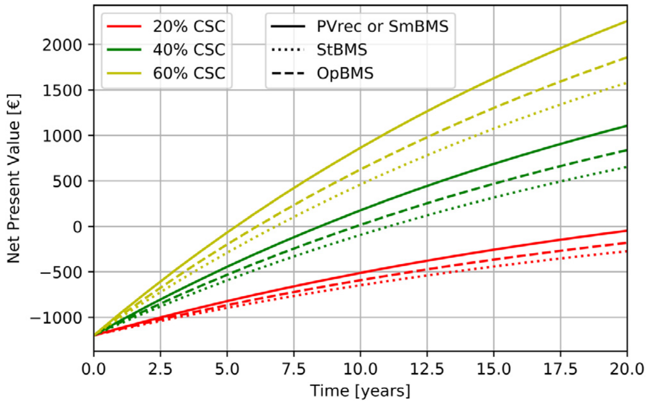

**Fig. 17.** Third-party company investment.

are too low. Despite this, the graph shows that a third-party manager should be incentivized to install SmBMS or to not install batteries because in these scenarios CSC is maximized and so is the incentive too. On the other hand, installing forecast-based systems to achieve the benchmark performance shown by the OpBMS should not be in the interest of a third-party company.

However, without any economic incentive SmBMS are still not economically convenient because of the costs of installing additional battery control systems. The government should incentivize them as they ensure greater stability of the national power grid.

## 4. Conclusions

A techno-economic assessment of a residential REC composed of 3 prosumers and 5 consumers is developed by comparing four different scenarios: PVrec, StBMS, SmBMS and OpBMS. PVrec does not include batteries; StBMS considers three batteries managed with a standard BMS which prioritizes SC; SmBMS considers a smart BMS which prioritizes CSC; and OpBMS finds the optimal operational schedule of batteries to minimize costs. The purpose is to assess different BMS benefits and problems from different points of view: prosumers, consumers, third-party company, and the national grid operator. The latter is interested in the development of REC as independent as possible from the MV grid, to reduce its instability and transport losses.

Results show that installing decentralized battery systems in a REC and managing them with a StBMS is a problem because CSC drop, and this limits the REC potential for energy independence from the MV grid. Therefore, the national grid operator should be interested in solving the problem through the addition of incentives to implement new BMSs. Also the stakeholders who only gain from the incentives that the GSE provides on CSC, consumers and third-party company, should be interested in finding a solution.

In this case study the decrease in CSC is 26.3%.

To solve the problem, it is necessary to manage batteries based on REC real-time data monitoring (SmBMS) or, even better, based on forecasts (OpBMS). The SmBMS proposed in this study guarantees to reach the same level of CSC of the case without batteries and compared to the StBMS allows greater REC independence: the energy fed into the MV grid decreases, as does the energy withdrawn. In this case respectively of the 3.9% and 3.8%. For those reasons third-party company, consumers and national grid operator should be interested in installing such a system. Only prosumers are slightly penalized by SmBMS as their SC decreases, but an accurate business model could provide reimbursement for this. According to these simulations, less than 15 €per year would be enough to reward them: a negligible amount.

To explore the potential of forecasting based methods the OpBMS based on the deterministic knowledge of production and consumption has been calculated as benchmark. This solution can guarantee no penalization for prosumers and a better REC independence from the MV grid, so the national grid operator should incentives such systems. But, from the point of view of consumers and a third-party company which earns by retaining a portion of the incentives on CSC, SmBMS remains the best system for managing batteries since it maximizes CSC. In addition, SmBMS is certainly less expensive than systems that require forecasting.

This proves for the umpteenth time that the economic interest and the environmental or population interest, are at odds. When that happens, governments have the responsibility to address it through the appropriate incentives. This study identifies a problem and uses a real case study to assess it and propose a solution by looking at both technical and economic perspectives. But energy and commodity markets are constantly evolving, as legislations and technologies; for that reason, studies such as these will always need to be updated. To facilitate this, MESS has been made open source on GitHub. The authors intend to follow the development of RECs around Europe and study new communities of different composition, not only residential one, by delving into topics such as centralized battery system and RECs as entities for the provision of multiple service to the grid. The REC that is the subject of this study will soon be realized and this will allow the SmBMS to be tested.

## CRediT authorship contribution statement

**Mattia Pasqui:** Term, Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualisation. **Alex Felice:** Term, Conceptualization, Methodology, Software, Validation, Formal analysis, Writing – review & editing. **Maarten Messagie:** Project administration, Funding acquisition. **Thierry Coosemans:** Project administration, Funding acquisition. **Tommaso Tiozzo Bastianello:**

Investigation, Resources, Writing – review & editing. **Duccio Baldi:** Investigation, Resources, Writing – review & editing. **Pietro Lubello:** Term, Conceptualization, Methodology, Validation, Formal analysis, Writing – review & editing. **Carlo Carcasci:** Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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