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Optimal energy management strategies for aggregators in renewable energy communities

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ABSTRACT

First introduced in European directives and recently incorporated into the Italian legal framework, Renewable Energy Communities (RECs) are described as innovative organisations that can promote collaboration between active and passive users engaged in the production, sharing and consumption of locally produced energy, according to creative management schemes. The aim of this study is the implementation of Mixed-Integer Linear Programming (MILP) models to build Energy Management Systems (EMSs) for an aggregator managing a REC. The REC includes Renewable Energy Sources (RESs), Battery Energy Storage Systems (BESSs), AC and DC charging points for Electric Vehicles (EVs), and also considers the use of Vehicle-to-Building (V2B). Specifically, the "Centralised" EMS managed by the aggregator has the aim of maximising the energy shared within the REC, while minimising BESS and EV battery degradation. The optimal profiles of active power exchanges with the network are provided as reference inputs to the local EMSs of the users. Two scenarios are considered, a week in May and a week in December, to investigate the impact of different RES productions and electricity demands on energy sharing mechanisms. Through the definition of appropriate Key Performance Indicators (KPIs), this work shows that an optimal operation of the distributed energy technologies can improve the REC performance, leading to Shared Energy Index (SEI) up to 92.42% for the considered week of May. Further scenarios are investigated considering mid-season weeks (March and October) and analysing the trade-off between maximising the shared energy and minimising battery degradation of BESSs and EVs. Finally, the impact of the users' cooperative or non-cooperative behaviour on the global energy sharing is investigated through the analysis of multiple scenarios, varying the centralised EMS awareness about REC members' behaviour and the configuration in terms of cooperative/non-cooperative users.

1. Introduction

1.1. Motivation and background

One way to support the democratisation, decarbonisation and decentralisation of the energy sector across Europe is the creation of Renewable Energy Communities (RECs). The European Renewable Energy Directive 2018/2001 (RED II) [1] defines a REC as a legal entity with the ability to produce, consume, store, and exchange renewable energy between geographically adjacent private individuals, governmental entities, and small and medium-sized businesses. The goals of RECs are to improve community members' economic, environmental, and social well-being and to raise local support for renewable energy initiatives. RECs are vital in supporting citizens and local authorities in their efforts to invest in Renewable Energy Sources (RESs), coupled to Battery Energy Storage Systems (BESSs), and improve energy efficiency. Additionally, RECs play a crucial role in promoting the decentralisation of the energy system, so easing a shift towards sustainable energy within society [2]. Moreover, RECs may include flexible devices and facilities, like Electric Vehicles (EVs), heat pumps and Microgrids (MGs), in order to help the stabilisation of the power system.

Given the complexity of a REC, its design, operational management and maintenance may be assigned to third parties, like aggregators or Energy Service Companies (ESCOs). Literature on aggregators typically concentrates on the optimal scheduling of a group of users to yield collective benefits, such as lower energy costs through market hedging or bidding, occasionally including Demand Response (DR) or Demand

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Nomenclature

Acronym

AC	Alternating Current
BESS	Battery Energy Storage System
CHP	Combined Heat and Power
cVPP	community-based Virtual Power Plant
DC	Direct Current
DR	Demand Response
DSM	Demand Side Management
DSO	Distribution System Operator
EMS	Energy Management System
ESCO	Energy Service Company
EV	Electric Vehicle
HEMS	Home Energy Management System
KPI	Key Performance Indicator
LP	Linear Programming
LV	Low-Voltage
MG	Microgrid
MILP	Mixed-Integer Linear Programming
MPC	Model Predictive Control
MV	Medium-Voltage
POD	Point Of Delivery
PSCI	Physical Self-Consumption Index
PV	Photovoltaic
REC	Renewable Energy Community
RES	Renewable Energy Source
SEI	Shared Energy Index
SSR	Self-Sufficiency Rate
V2B	Vehicle-to-Building
VSCI	Virtual Self-Consumption Index

Symbol

C	Rated capacity [kWh]
D	Electrical demand [kW]
E	Energy [kWh]
F	Energy consumption of the EVs [kWh]
H	Number of hours over the optimisation horizon [-]
M	Big number [-]
P	Active power [kW]
SOC	State of Charge [-]
T	Number of time intervals over the optimisation horizon [-]
U	Number of REC users [-]
V_u	Number of EVs for each user [-]
X, x, y	Binary decision variable [-]
p	Electricity purchase price [€/kWh]
r	Electricity selling price [€/kWh]
Δ	Time interval duration [h]
α	Constant coefficient [-]
η	Efficiency [-]
ε	Binary parameter [-]
Φ	Weight coefficient [-]

Superscript

BESS	Battery Energy Storage System
EV	Electric Vehicle
PV	Photovoltaic
REC	Renewable Energy Community
WIND	Wind
b	Bought
ch	Charging
dch	Discharging
el	Electrical
fin	Final
grid	Grid
ini	Initial
max	Maximum
min	Minimum
s	Sold
sh	Shared
sum	Sum
tot	Total

Side Management (DSM). The majority of research studies assumes that aggregators act in a way that maximises the social welfare of the users, sometimes disregarding the possibility that the aggregator's objectives differ from those of the users. However, this misalignment may have an impact on the optimal operation of RECs [3]. Indeed, innovative local aggregation solutions should be applied to RECs, due to their peculiar structures: for example, households' untapped flexibility potential could be directed towards energy efficiency and energy saving goals or it could be used to offer self-balancing services for RECs and ancillary services to grid operators. While the directives validate the pooling of household assets via RECs and aggregators across the European Union, the opportunities for household flexibility remain largely unexplored on a global scale [4].

In a community-based Virtual Power Plant (cVPP), RECs can manage their energy production and consumption collectively, creating a win–win situation for both the community and its members, as well as the grid operators. The core of a cVPP is the Energy Management System (EMS), a smart tool which coordinates and schedules the operations of distributed RESs and flexible assets (e.g. BESSs, EVs and heat pumps) in a smart way, allowing to fulfil REC energy objectives and to provide active support strategies for the power system.

Among flexible solutions, an important role will also be played by EVs: the potential of the relationship between buildings and EVs is explored in [5] through the proposal of various EMSs and advanced energy control techniques, while [6] investigates EV smart-charging strategies in facilities that integrate RESs and electric mobility. Paper [7] proposes a methodology that utilizes rooftop PV-based households, aggregated into RECs, to offer renewable energy support to the green hydrogen production for refuelling stations satisfying fuel cell EVs. Regarding Vehicle-to-Building (V2B) applications, it is important to highlight the research published in [8], which assesses the advantages of EVs serving as storage systems in buildings that operate in islanded mode, as well as the analyses conducted in [9] and [10], which look into how V2B can enhance a prosumer building's energy and economic key performance indicators.

1.2. Literature review

The operation of RECs is subject of a large number of studies, with various distinctions based on the technologies that are taken into consideration. The most widely utilised techniques are those involving optimisation modelling: typically, mathematical programming techniques such as Linear Programming (LP) or Mixed-Integer Linear Programming (MILP) models are used to carry out the optimisation.

The available studies distinguish between three topics: community interactions with the external grid or services provided to it, individual building operation, and flexibility and energy sharing in RECs to maximise collective self-consumption.

Within the first framework, the authors of [11] suggest an EMS in the context of the management of REC's energy storage systems for load-generation balancing schemes, although focusing on the minimization of energy from the grid specifically during high load peak conditions. In particular, the proposed EMS aims at peak load shaving and load shifting, considering PV forecast updates. Paper [12] adds to the extensively debated methods for optimising self-consumption and fully utilising RESs in RECs by presenting RECs as virtual aggregators that offer grid services. This includes DSM, reduction of energy losses and enhancement of voltage quality. The authors of [13] quantify the impact of a REC grid service that, with the use of PV systems, BESSs, and flexible loads, reduces the peak power exchange between the community and the electric grid with an optimised grid-friendly operation, thus providing further revenues. Study [14] explains how RECs with PV plants and BESSs can greatly lower peak power exchange and low-voltage grid loading. Nevertheless, heat pumps and EVs are not taken into account in the paper as flexible loads that could further reduce peaks.

Within the second study framework, the sharing of rooftop PV generation in multi-apartment buildings is studied in [15]. In apartment complexes with various arrangements, the maximization of self-consumption by PV-BESS deployment has been researched in [16]. A game theoretic model with a welfare maximization has been suggested by [17] for the shared usage of a solar PV and energy storage system in multiapartment building. These previously mentioned papers only look at the application of renewable energy transfer in apartment buildings. In a similar way, paper [13] focuses also on the correlation between members' sharing in rural, suburban and urban grid topologies, economic benefits, and grid-friendly operation of flexible assets. Nevertheless, to have a true concept of a REC setup, it is important to incorporate a variety of end-users and diversify the application of the optimisation models. In order to implement different energy sharing systems, it also critical for a REC to include a mix of prosumers and consumers.

Within the framework of energy sharing, a significant part of the literature addresses economic issues of RECs. In fact, the energy sharing mechanism can be profitable if the REC self-consumption of renewable electricity is increased: moreover, in some scenarios, like the Italian one, the shared energy is the one being remunerated [18]. Indeed, the cash flows for each member of the REC are one of the primary economic factors that must be taken into account during the management phase. RECs may lower the overall electricity expenses incurred by participants as presented in [19]: this goal is achieved by performing load aggregation and increasing community self-consumption, benefitting from reduced grid tariffs for the exchanged electricity and by lowering REC electricity costs. The authors of [20] proposed a Shapley value-based approach to allocate a portion of the community's income to members. The results showed the efficacy of this management scheme and added benefit of motivating members to adopt energy efficient practices.

A linear optimisation model with various prosumers (apartments, businesses, etc.) in a REC concept for energy sharing under willingness-to-pay criteria, is examined in the work [21]. Fixed retail electricity prices are the basis of the energy tariffs that were considered in [21] for the purchase and sale of energy to the grid and inside the community. A two-stage optimisation approach for renewable energy sharing among prosumers and consumers in a REC setup is considered in the study [22]. The optimisation model implemented by the authors is based on a single day, i.e., 24-hours time horizon and takes into account time-of-use tariffs only. Both [21] and [22] do not consider demand charges and variable market signals, including feed-in tariffs, but they assume that all community members (prosumers and consumers) pay the same energy prices. Therefore, the application of such optimisation models is limited and different electricity tariff scenarios and market signals should be taken into consideration to achieve real-life community MG setups.

A further approach for managing BESSs in RECs is provided in [23], where the authors considered a mix of PV and BESS units, focusing on the participation of RECs in ancillary services markets. The proposed approach helps in maximizing the profits of the REC, while from the energy point of view the self-consumption, either physical or virtual, might be penalised.

Reference [24] provides a focus on the flexibility offered by REC members, especially those with smart home appliances, helping to optimise self-consumption and shared energy, thereby increasing economic revenues from incentive schemes. These algorithms consider the flexibility offered by users and aim to minimize the cost of electricity for each member.

Regarding the development and operation of EMS aggregators for RECs, the paper [25] introduces a bi-level multi-objective EMS specifically designed to maximise self-consumption within an energy community while considering the welfare of its members. Based on the aggregator participation in the day-ahead market, this work focuses on optimising self-consumption as a primary objective at the aggregator level, distinguishing it from approaches primarily driven by profit or grid flexibility. The role of REC manager is discussed in [26], proposing a single-level EMS for the optimal management of REC composed of multiple residential members. The REC manager is in charge of the operation of a PV plant and of a solid-oxide fuel cell, coupled to a hydrogen tank, aiming to maximize the economic benefit of the REC. Reference [27] proposes a two-level distributed energy management scheme for a residential community that leverages coordination at both the aggregator level and customer levels. The objective is to lower the peak-to-average ratio of demand and facilitate the integration of local RESs to the electricity network. The authors in [28] present a three-level framework for energy community management involving Distribution System Operators (DSOs), aggregators and Home Energy Management Systems (HEMSs), incorporating a flexibility-based incentive program. The aggregator acts as a facilitator, collecting and managing flexibility from users by rescheduling household appliances to leverage both upward and downward flexibility. Finally, the study [29] presents a multi-timescale optimal operation strategy for an energy community aggregator managing heterogeneous distributed flexible resources. A multi-timescale rolling optimal dispatch model is proposed, combining day-ahead dispatch with Model Predictive Control (MPC) to achieve fine-grained rolling adjustments of power dispatch instructions for distributed resources with different time scales.

Some papers also explore various aspects of optimising energy systems across different scales, from individual smart homes to community energy storage and multi-carrier energy networks. A common thread is the application of advanced modelling and optimisation techniques to enhance efficiency, sustainability, and user satisfaction while addressing inherent uncertainties and flexibilities within these systems.

In [30], the focus is on the interaction between community energy storage owners and prosumers in a local energy market, proposing a bi-level optimisation model based on Stackelberg game theory. In this model, the community energy storage owner acts as the leader, aiming to maximize operational profit through energy trading with the network and local prosumers. Simultaneously, the prosumers are the followers, seeking to minimize their billing costs while maintaining their preferred comfort levels. The paper [31] presents a flexibility-oriented hybrid multi-objective model for the operation of local multi-carrier energy systems. The primary objective is to simultaneously minimize operational costs and environmental emissions in energy communities encompassing electrical, water, gas, and heat energies, integrating various components like hydrogen fuel stations, power-to-gas units, and Combined Heat and Power (CHP) units.

The authors in [32] propose a bi-level optimal management model for a multi-carrier energy network that integrates energy communities. At the upper level, the multi-carrier network operator seeks to maximize its profit by trading energy with energy communities and participating in upstream markets, while, at the lower level, energy community managers aim to minimize the operating costs for end-users within their communities. The paper also conducts a sensitivity analysis to evaluate the impact of price and renewable resources' variations. Finally, the study [33] introduces a flexibility-constrained smart home energy management framework designed to optimise energy costs, end-user satisfaction, and self-sufficiency preferences. The smart home model includes technologies such as CHP units, PV, BESS, and EVs, and the results demonstrate the significant impact of flexibility limits on energy costs and how the priority order of the MILP problem's objective functions affects the outcomes.

To conclude this subsection and with the aim of providing a summary of the literature review, Table 1 summarises the main features of each paper studied in this subsection, highlighting the existing literature gap. Indeed, most of the papers do not consider wind turbines and EVs within REC configuration. The absence of wind turbine production makes the sharing of energy possible only during daylight hours (since RECs would mainly rely on PV production), while neglecting the impact of EVs would restrict the application of the approaches present in literature to future scenarios. Moreover, many papers provide a single level EMS approach that could limit the adherence to real-world management of RECs, since the interaction between REC aggregator and REC members would be not comprehensively modelled. Finally, only few papers consider the concept of energy sharing within RECs.

1.3. Paper contribution and novelty

Within this state of art, the study described in the present paper aims at providing insights on RECs optimisation by practically integrating advanced EMS strategies for both the whole community and its members, whose interests can differ and for whom it's necessary to find a good trade-off in terms of energy, economic and environmental objectives.

In particular, the study is focused on the formulation of a centralised EMS used by an aggregator which is supposed to manage the REC, whose members are residential, commercial and industrial users, some of them prosumers and some of them just consumers.

The developed MILP model takes into account a REC consisting of different members equipped with different technologies, among which PV plants, wind turbines, BESSs and EV charging stations at the users' facilities. The centralised EMS has been conceived to maximise the collective self-consumption in the community, thus contributing to the reduction of transmission losses, and to optimise the usage of the entire community's production, by an objective function aiming at maximising the energy shared within the REC, i.e. the energy produced by a REC production unit and virtually shared between two or more units of consumption that are not directly connected to the production plant, configurating a virtual self-consumption scheme.

From the REC management perspective, the aggregator provides to the REC members reference signals of power to be exchanged with the network: if members are able to follow these signals, the maximization of the shared energy is ensured. Nevertheless, the objectives of the single members may differ from the simple energy sharing, especially in non-cooperative approaches.

Therefore, the main novelties of the paper are:

- setting up of an innovative REC management architecture, modelling the interaction between the centralised EMS, managed by REC's aggregator, and the local EMSs of the single participants, whose goals may differ from social welfare ones, depending on the chosen approach (cooperative/non-cooperative);
- analysis of an innovative case study, considering different types of end-users of a REC, in particular an industrial MG, not only exploiting common RESs and BESSs but also the V2B application for enabled EVs;
- definition of real-use Key Performance Indicators (KPIs) used by the aggregator to assess the operational efficiency and energy performances of the REC;
- development of sensitivity analyses aimed at assessing the impact that the centralised EMS awareness of the REC users' behaviour (cooperative or non-cooperative) has on the energy shared within the REC.

The proposed EMS is applied to a REC located in the North of Italy, thus implementing the energy sharing mechanism provided by the Italian legislation: changing the constraints related to the shared energy incentivisation, the method has a general validity and can be applied to any case study community.

The paper is organised as follows: Section 2 describes the MILP mathematical model for the centralised EMS by reporting the objective function and all the constraints and decision variables; all the input data are accurately defined in Section 3 to provide a detailed overview of the study case community and its members; the main results of the application of the developed model to the REC are reported in Section 4, considering first two different scenarios, namely a week in December and a week in May, and then expanding the analyses assessing how energy sharing is affected by BESS and EV batteries' degradation minimization and by users' behaviour uncertainty. Finally, Section 5 draws the main conclusions and future developments of the work.

Table 1
Summary of the literature review on EMSs for RECs.

Reference	PV	Wind turbine	BESS	EVs	Multi-energy	Optimisation model	EMS structure[c]	Energy sharing
[11]	✓[a]	✘[a]	✓	✘	✘	LP	1L	✘
[13]	✓	✘	✓	✘	✘	LP	1L	✘
[14]	✓	✘	✓	✘	✘	LP	1L	✘
[16]	✓	✘	✓	✘	✘	?[a]	1L	✓
[17]	✓	✘	✓	✘	✘	?	1L	✓
[21]	✓	✘	✓	✘	✘	LP	1L	✓
[22]	✘	✓	✓	✘	✘	LP	2L	✘
[23]	✓	✘	✓	✘	✘	?	1L	✘
[24]	✓	✘	✘	✓	✘	MILP	1L	✓
[25]	✓	✘	✘	✘	✘	NLP[b]	2L	✘
[26]	✓	✘	✘	✘	✘	NLP	1L	✓
[27]	✓	✘	✓	✘	✘	NLP	2L	✘
[28,29]	✓	✘	✓	✓	✘	MILP + NLP	3L	✘
[30]	✓	✘	✓	✘	✓	MILP	2L	✘
[31]	✓	✓	✘	✘	✓	MILP	2L	✘
[32]	✓	✓	✘	✘	✓	MILP	2L	✘
[33]	✓	✘	✓	✓	✓	MILP	1L	✘
This study	✓	✓	✓	✓	✘	MILP	2L	✓

[a] ✓=included, ✘=not included, ?=not disclosed in the paper.
[b] NLP=Non-linear programming.
[c] 1L = one level, 2L = two level, 3L = three level.

2. The mathematical model of the centralised EMS

In this section, a detailed insight into the mathematical model of the centralised EMS is provided. The optimisation problem has been modelled as a MILP problem, that considers both continuous and binary decision variables, with linear constraints and a linear objective function.

2.1. Methodology overview

The proposed methodology is represented schematically in Fig. 1. Through the centralised EMS, the REC's aggregator defines the optimal power exchange profile of the community members that would ensure the maximization of the energy shared within the REC. As presented in [34], each REC member equipped with a local EMS receives as input from the aggregator the desired profiles of active power to be exchanged with the external network in order to maximize the energy shared within the REC.

To understand the concept of shared energy in RECs, it is important to distinguish between physical self-consumption and virtual self-consumption. Physical self-consumption refers to the case in which a power plant is directly connected to the electrical load, so that the end-user instantly consumes part of the energy locally produced. The portion of the production that is not locally consumed is injected into the distribution network, remaining available for virtual self-consumption schemes. These ones define the concept of shared energy, which is virtually currently incentivised in REC configurations.

More in detail, a day-ahead centralised EMS model is developed for the aggregator considering the whole REC, which receives several data as inputs, including the electrical energy purchase and selling prices, the forecasted production profiles of the RES plants, the estimated electrical load profiles, information about the community's EV fleet, storage systems, PV plants and wind turbines. The centralised EMS, whose objective is to maximise the energy shared within the REC, in turn interacts with the local EMSs (referring to a few community members that are not simple consumers or simple producers), which manage more in detail the operational strategy of RES plants, BESSs and EV charging points, and the energy exchange with the external distribution network. These EMSs installed locally, whose description is not reported in the present paper, follow a multi-objective approach, aiming, on the one hand, to follow the desired power exchange profile with the distribution network provided by the Centralised EMS (cooperative approach) and, on the other hand, to minimise the operating costs of the user (non-cooperative approach). The complexity of the local EMSs strongly depends on the installed technologies at the users' sites. Only the users with dispatchable sources need a local EMS which is used to optimally schedule their operation (PV curtailment, charging/discharging of BESSs, flexible loads management, reactive power management, etc.). Consequently, an increased number of installed technologies determines a higher grade of complexity of the EMSs.

2.2. Input data

The optimisation horizon consists of T time intervals, each one with a duration corresponding to Δ.

The main sets are:

- $t = 1\dots T$: set of time intervals;
- $u = 1\dots U$: set of users joining the REC, where U is the number of REC's users;
- $h = 1\dots H$: set of the hours of the day, where H is the number of hours of the considered time horizon;
- $v = 1\dots V_u$: set of EVs for each $u \in U$, where V_u is the number of EVs owned by user u.

All the input data related to the centralised EMS are reported as follows with the corresponding definitions:

- $D^{el}_{u,t}$: electrical load profile of user u at time t [kW];
- $p^{el}_{u,t}$, $r^{el}_{u,t}$: electricity purchase and selling prices for user u at time t [€/kWh];
- $P^{PV}_{u,t}$: active power production of the PV plants of user u at time t [kW];

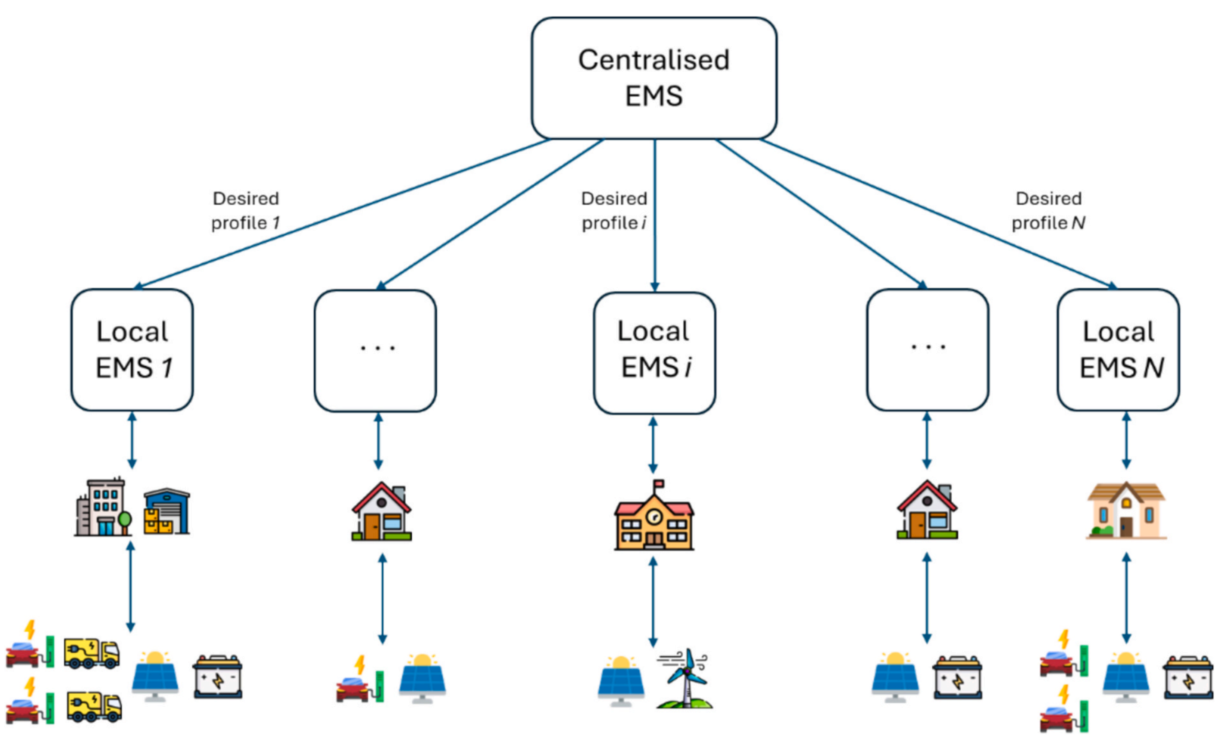

Fig. 1. Schematic representation of the implemented methodology.

- $P_{u,t}^{WIND}$: active power production of the wind turbines of user u at time t [kW];
- C_u^{BESS}: rated capacity of the BESS owned by user u [kWh];
- $P_u^{BESS,ch,max}$, $P_u^{BESS,dch,max}$: maximum charging and discharging power of the BESS owned by user u [kW];
- $\eta_u^{BESS,ch}$, $\eta_u^{BESS,dch}$: charging and discharging efficiency of the BESS owned by user u [-];
- $SOC_u^{BESS,min}$, $SOC_u^{BESS,max}$: minimum and maximum state of charge of the BESS owned by user u [-];
- $SOC_u^{BESS,min,fin}$, $SOC_u^{BESS,max,fin}$: final ($t = T$) minimum and maximum state of charge of the BESS owned by user u [-];
- $SOC_u^{BESS,ini}$: initial ($t = 1$) state of charge of the BESS owned by user u [-];
- $C_{u,v}^{EV}$: rated capacity of the v-th EV's battery owned by user u [kWh];
- $P_{u,v}^{EV,ch,max}$, $P_{u,v}^{EV,dch,max}$: maximum charging and discharging power of the v-th EV owned by user u [kW];
- $\eta_{u,v}^{EV,ch}$, $\eta_{u,v}^{EV,dch}$: charging and discharging efficiency of the v-th EV's battery owned by user u [-];
- $\varepsilon_{u,v,t}^{EV}$: equal to 1 when the v-th EV owned by user u is parked and can be connected to its charging point at time t [-];
- $SOC_{u,v}^{EV,min}$, $SOC_{u,v}^{EV,max}$: minimum and maximum state of charge of the v-th EV's battery owned by user u [-];
- $\alpha_{u,v}^{EV,ini,min}$, $\alpha_{u,v}^{EV,ini,max}$: constant coefficients used to define the minimum and maximum value of the initial ($t = 1$) state of charge of the v-th EV's battery owned by user u [-];
- $F_{u,v}^{EV,tot}$: weekly total energy consumption of the v-th EV owned by user u [kWh];
- $F_{u,v}^{EV,max}$: maximum energy consumption of the v-th EV owned by user u during a single time interval of duration Δ [kWh];
- $P_u^{grid,b,max}$, $P_u^{grid,s,max}$: maximum power that can be withdrawn/injected from/into the distribution network by user u, related to the committed power [kW].

It is important to remark that electricity purchase and selling prices ($p_{u,t}^{el}$ and $r_{u,t}^{el}$) are not used in the proposed centralised EMS, since the focus of the analysis is on the energy performance of the REC, neglecting operational costs. On the other hand, they are input data for the local EMSs, which also aim to the minimization of the net operational costs of the single REC members.

2.3. Decision variables

The decision variables, both continuous and binary, associated with the centralised EMS can be defined as follows:

- $P_{u,t}^{grid,b}$, $P_{u,t}^{grid,s}$: active power absorbed/injected from/into the local distribution network by user u at time t [kW];
- $x_{u,t}^{grid,b}$, $x_{u,t}^{grid,s}$: binary variables equal to 1 when user u is buying or selling electricity at time t, respectively [-];
- $P_{u,t}^{BESS,ch}$, $P_{u,t}^{BESS,dch}$: charging and discharging active power of the BESS owned by user u at time t [kW];
- $x_{u,t}^{BESS,ch}$, $x_{u,t}^{BESS,dch}$: binary variables equal to 1 when the BESS owned by user u is being charged or discharged at time t, respectively [-];
- $X_{u,t}^{BESS,ch}$, $X_{u,t}^{BESS,dch}$: binary variables equal to 1 if there's a change in the operative states of the BESS owned by user u at time t, respectively, $x_{u,t}^{BESS,ch}$ and $x_{u,t}^{BESS,dch}$, linked to the start or end of a charging or discharging phase, when compared to the previous time interval $t - 1$ [-];
- $SOC_{u,t}^{BESS}$: state of charge of the BESS owned by user u at time t [-];
- $P_{u,v,t}^{EV,ch}$, $P_{u,v,t}^{EV,dch}$: charging and discharging active power of the v-th EV owned by user u at time t [kW];
- $x_{u,v,t}^{EV,ch}$, $x_{u,v,t}^{EV,dch}$: binary variables equal to 1 when the v-th EV owned by user u is being charged or discharged at time t, respectively [-];
- $X_{u,v,t}^{EV,ch}$, $X_{u,v,t}^{EV,dch}$: binary variables equal to 1 if there's a change in the operative state of the v-th EV's battery owned by user u at time t, respectively, $x_{u,v,t}^{EV,ch}$ and $x_{u,v,t}^{EV,dch}$, linked to the start or end of a charging or discharging phase, when compared to the previous time interval $t - 1$ [-];
- $SOC_{u,v,t}^{EV}$: state of charge of the v-th EV's battery owned by user u at time t [-];
- $F_{u,v,t}^{EV}$: energy consumption of the v-th EV owned by user u at time t [kWh];
- $E_h^{REC,grid,b}$: electrical energy purchased by the whole REC during the h-th hour [kWh];
- $E_h^{REC,grid,s}$: electrical energy sold by the whole REC during the h-th hour [kWh];
- $E_h^{REC,sh}$: electrical energy counted as shared energy of the whole REC during the h-th hour [kWh];
- $y_h^{REC,sh}$: binary variable equal to 1 when the REC's shared energy at hour h coincides with the energy purchased from the distribution network and equal to 0 when it coincides to the energy sold to the distribution network [-].

While the time interval duration Δ can be chosen arbitrarily for the developed model, the shared energy has to be calculated on hourly basis according to the Italian regulatory framework, but the relative constraints can be easily adapted to compute it in a different way.

2.4. Constraints

Constraints from (1) to (3) define the interaction between the users and the distribution grid, while ensuring the non-simultaneity between purchase and selling of electrical energy.

$$0 \le P_{u,t}^{grid,b} \le P_u^{grid,b,max} \cdot x_{u,t}^{grid,b} \quad \forall u = 1 \ldots U, \forall t = 1 \ldots T \tag{1}$$

$$0 \le P_{u,t}^{grid,s} \le P_u^{grid,s,max} \cdot x_{u,t}^{grid,s} \forall u = 1 \ldots U, \forall t = 1 \ldots T \tag{2}$$

$$x_{u,t}^{grid,b} + x_{u,t}^{grid,s} \le 1 \forall u = 1 \ldots U, \forall t = 1 \ldots T \tag{3}$$

For BESSs and EVs, power during charge and discharge is typically limited, so further constraints from (4) to (9) need to be introduced, compelling the two powers to be different from zero only one at a time and obviously according to the presence of the EV at the user facility.

$$0 \le P_{u,t}^{BESS,ch} \le P_u^{BESS,ch,max} \cdot x_{u,t}^{BESS,ch} \forall u = 1 \ldots U, \forall t = 1 \ldots T \tag{4}$$

$$0 \le P_{u,t}^{BESS,dch} \le P_u^{BESS,dch,max} \cdot x_{u,t}^{BESS,dch} \forall u = 1 \ldots U, \forall t = 1 \ldots T \tag{5}$$

$$x_{u,t}^{BESS,ch} + x_{u,t}^{BESS,dch} \le 1 \forall u = 1 \ldots U, \forall t = 1 \ldots T \tag{6}$$

$$\begin{gathered} 0 \le P_{u,v,t}^{EV,ch} \le P_{u,v}^{EV,ch,max} \cdot x_{u,v,t}^{EV,ch} \\ \forall u = 1 \ldots U, \forall t = 1 \ldots T, \forall v = 1 \ldots V_u \end{gathered} \tag{7}$$

$$\begin{gathered} 0 \le P_{u,v,t}^{EV,dch} \le P_{u,v}^{EV,dch,max} \cdot x_{u,v,t}^{EV,dch} \\ \forall u = 1 \ldots U, \forall t = 1 \ldots T, \forall v = 1 \ldots V_u \end{gathered} \tag{8}$$

$$x^{EV,ch}_{u,v,t} + x^{EV,dch}_{u,v,t} \leq \varepsilon^{EV}_{u,v,t} \quad \forall u = 1...U, \forall t = 1...T, \forall v = 1...V_u \tag{9}$$

The constraints from (10) to (13) and from (14) to (17) impose a change in the decision variables' values related to the start or end of a charging or discharging phase when BESSs' and EVs' charging and discharging operative states switch from 0 to 1 or vice versa.

$$X^{BESS,ch}_{u,t} \geq x^{BESS,ch}_{u,t} - x^{BESS,ch}_{u,t-1} \forall u = 1...U, \forall t = 2...T \tag{10}$$

$$X^{BESS,ch}_{u,t} \geq -x^{BESS,ch}_{u,t} + x^{BESS,ch}_{u,t-1} \forall u = 1...U, \forall t = 2...T \tag{11}$$

$$X^{BESS,dch}_{u,t} \geq x^{BESS,dch}_{u,t} - x^{BESS,dch}_{u,t-1} \forall u = 1...U, \forall t = 2...T \tag{12}$$

$$X^{BESS,dch}_{u,t} \geq x^{BESS,dch}_{u,t} - x^{BESS,dch}_{u,t-1} \forall u = 1...U, \forall t = 2...T \tag{13}$$

$$X^{EV,ch}_{u,v,t} \geq x^{EV,ch}_{u,v,t} - x^{EV,ch}_{u,v,t-1} \quad \forall u = 1...U, \forall t = 2...T, \forall v = 1...V_u \tag{14}$$

$$X^{EV,ch}_{u,v,t} \geq -x^{EV,ch}_{u,v,t} + x^{EV,ch}_{u,v,t-1} \quad \forall u = 1...U, \forall t = 2...T, \forall v = 1...V_u \tag{15}$$

$$X^{EV,dch}_{u,v,t} \geq x^{EV,dch}_{u,v,t} - x^{EV,dch}_{u,v,t-1} \quad \forall u = 1...U, \forall t = 2...T, \forall v = 1...V_u \tag{16}$$

$$X^{EV,dch}_{u,v,t} \geq -x^{EV,dch}_{u,v,t} + x^{EV,dch}_{u,v,t-1} \quad \forall u = 1...U, \forall t = 2...T, \forall v = 1...V_u \tag{17}$$

The content of the BESS and EV batteries follow the energy balances (18) and (19). The constraints related to the batteries' SOC, (20) and (21), imply a feasible range between a minimum and maximum value. Instead, for the EVs' battery, the initial SOC has to be limited between two properly chosen values to satisfy the user needs at the beginning of the week, according to (22). In order for the SOC of the BESSs at the end of the analysed week to be at a plausible value, i.e. BESSs have been properly charged and discharged by the community members, a restriction is imposed on the variation of the final SOC by the constraint (23).

$$SOC^{BESS}_{u,t+1} = SOC^{BESS}_{u,t} + \frac{\Delta}{C^{BESS}_{u}} \cdot \left(P^{BESS,ch}_{u,t} \cdot \eta^{BESS,ch}_{u} - \frac{P^{BESS,dch}_{u,t}}{\eta^{BESS,dch}_{u}} \right) \quad \forall u = 1...U, \forall t = 1...T-1 \tag{18}$$

$$SOC^{EV}_{u,v,t+1} = SOC^{EV}_{u,v,t} + \frac{\Delta}{C^{EV}_{u,v}} \cdot \left(P^{EV,ch}_{u,v,t} \cdot \eta^{EV,ch}_{u,v} - \frac{P^{EV,dch}_{u,v,t}}{\eta^{EV,dch}_{u,v}} \right) - \frac{F^{EV}_{u,v,t}}{C^{EV}_{u,v}} \quad \forall u = 1...U, \forall t = 1...T-1, \forall v = 1...V_u \tag{19}$$

$$SOC^{BESS,min}_{u} \leq SOC^{BESS}_{u,t} \leq SOC^{BESS,max}_{u} \forall u = 1...U, \forall t = 1...T \tag{20}$$

$$SOC^{EV,min}_{u,v} \leq SOC^{EV}_{u,v,t} \leq SOC^{EV,max}_{u,v} \quad \forall u = 1...U, \forall t = 1...T, \forall v = 1...V_u \tag{21}$$

$$SOC^{EV,min}_{u,v} + \alpha^{EV,ini,min}_{u,v} \leq SOC^{EV}_{u,v,1} \leq SOC^{EV,min}_{u,v} + \alpha^{EV,ini,max}_{u,v} \quad \forall u = 1...U, \forall v = 1...V_u \tag{22}$$

$$SOC^{BESS,min,fin}_{u} \leq SOC^{BESS}_{u,T} \leq SOC^{BESS,max,fin}_{u} \forall u = 1...U \tag{23}$$

Constraints (24) limit the energy consumption of each EV in a single time interval, while constraints (25) define the total energy consumption over the considered time horizon.

$$0 \leq F^{EV}_{u,v,t} \leq F^{EV,max}_{u,v} \cdot \left(1 - \varepsilon^{EV}_{u,v,t}\right) \quad \forall u = 1...U, \forall t = 1...T, \forall v = 1...V_u \tag{24}$$

$$\sum_{t=1}^{T} F^{EV}_{u,v,t} = F^{EV,tot}_{u,v} \forall u = 1...U, \forall v = 1...V_u \tag{25}$$

Considering the REC as a scheme where local RES plants, BESSs, EV charging points and the end-users interact each other to increase local self-consumption, the constraints (26) are introduced to represent the active power balance of the whole system that has to be respected for each time interval t.

$$P^{PV}_{u,t} + P^{WIND}_{u,t} + P^{grid,b}_{u,t} + P^{BESS,dch}_{u,t} + \sum_{v=1}^{V_u} P^{EV,dch}_{u,v,t} = P^{grid,s}_{u,t} + P^{BESS,ch}_{u,t} + \sum_{v=1}^{V_u} P^{EV,ch}_{u,v,t} + D^{el}_{u,t} \quad \forall u = 1...U, \forall t = 1...T \tag{26}$$

The remaining set of constraints, from (27) to (34), focuses on the link between the REC shared energy and the total hourly amount of purchased and sold energy (calculated over the sum of all users), always ensuring that the shared energy corresponds to the minimum value between the energy purchased and sold from/to the external network, by exploiting the *Big M* technique where M is arbitrarily chosen equal to a high number.

$$E^{REC,sh}_{h} \leq E^{REC,grid,b}_{h} \forall h = 1...H \tag{27}$$

$$E^{REC,sh}_{h} \leq E^{REC,grid,s}_{h} \forall h = 1...H \tag{28}$$

$$E^{REC,sh}_{h} \geq E^{REC,grid,s}_{h} - M \cdot y^{REC,sh}_{h} \forall h = 1...H \tag{29}$$

$$E^{REC,sh}_{h} \geq E^{REC,grid,b}_{h} - M \cdot \left(1 - y^{REC,sh}_{h}\right) \forall h = 1...H \tag{30}$$

$$E^{REC,grid,s}_{h} \leq E^{REC,grid,b}_{h} + M \cdot y^{REC,sh}_{h} \forall h = 1...H \tag{31}$$

$$E^{REC,grid,b}_{h} \leq E^{REC,grid,s}_{h} + M \cdot (1 - y^{REC,sh}_{h}) \forall h = 1...H \tag{32}$$

$$E^{REC,grid,b}_{h} = \Delta \cdot \sum_{u=1}^{U} \sum_{t=\frac{h-1}{\Delta}+1}^{\frac{h}{\Delta}} P^{grid,b}_{u,t} \forall h = 1...H \tag{33}$$

$$E^{REC,grid,b}_{h} = \Delta \cdot \sum_{u=1}^{U} \sum_{t=\frac{h-1}{\Delta}+1}^{\frac{h}{\Delta}} P^{grid,b}_{u,t} \forall h = 1...H \tag{34}$$

The optimisation problem follows a multi-objective approach: the first objective is related to the maximization of total energy accounted as shared within the REC, in order to obtain the highest possible incentive. A second objective is introduced to minimise the number of BESS and EVs charging and discharging cycles over the time horizon: to this purpose, the sum of the corresponding decision variables, multiplied by a proper weight coefficient ϕ^{sum}, is included in the objective function. Finally, the objective function to be minimised is defined as follows:

$$Obj = -\sum_{h=1}^{H} E^{REC,sh}_{h} + \phi^{sum} \cdot \left(\sum_{u=1}^{U} \sum_{t=1}^{T} X^{BESS,ch}_{u,t} + \sum_{u=1}^{U} \sum_{t=1}^{T} X^{BESS,dch}_{u,t} + + \sum_{u=1}^{U} \times \sum_{v=1}^{V_u} \sum_{t=1}^{T} X^{EV,ch}_{u,v,t} + + \sum_{u=1}^{U} \sum_{v=1}^{V_u} \sum_{t=1}^{T} X^{EV,dch}_{u,v,t} \right) \tag{35}$$

3. Case study description

The case study refers to a REC in Italy. Before introducing the main input data of the optimisation problem for this specific case study, it is necessary to introduce the main elements of the Italian regulatory framework for RECs in order to explain the calculation of the shared energy implemented within the optimisation model. In particular, the main reference is the so-called *CACER* Decree no. 414 issued on the 7th of December 2023 [35], which has defined the new modalities of granting incentives to the energy shared within RECs. The energy virtually shared, on which the calculation of the incentive as well as of the valorisation fee (that considers the avoided losses on the transmission network) is carried out, is calculated for each hour as the minimum between the energy injected into the public distribution network by the set of plants that participate in a REC (net of physical self-consumption of possible loads connected "behind the meter" directly to generation plants) and the energy withdrawn from the set of Points of Delivery (PODs) of the REC. All the PODs involved in a REC must underly the same primary substation.

The incentive tariff is recognised by the energy services operator, in Italian "*Gestore dei Servizi Energetici*" (GSE), for 20 years on the base of the energy virtually shared. The incentive is differentiated according to the rated power and to the technologies of RES power plants and it is composed of a fixed and of a variable part: this latter part reduces as the zonal market clearing price increases, until it reaches zero for a price equal to 180 [€/MWh] or more. Compensation for sites having lower solar radiation is also provided (4 or 10 [€/MWh]), according to the installation region of the PV plant. As aforesaid, in addition to this tariff, for each kWh of energy virtually shared, the GSE recognises a unitary fee, defined as a valorisation contribution, related to avoided transmission network losses.

3.1. Additional constraints for the case study

For RECs in Italy, the optimisation mathematical model presented in Section 2.4 needs the two additional sets of constraints (36) and (37) to prevent the discharging of BESSs and EVs when active power is injected into the external network. Indeed, in the Italian regulatory framework, it is not still clear whether the discharged active energy would be taken into account or not for the calculation of the REC shared energy, as the stored energy could have been previously withdrawn from the external grid, rather than being locally generated by RESs plants. In particular, constraints (36) impose EVs to discharge exclusively to satisfy the local electrical demand of the owners.

$$x_{u,t}^{BESS,dch} + x_{u,t}^{grid,s} \leq 1 \forall u = 1 \ldots U, \forall t = 1 \ldots T \quad (36)$$

$$x_{u,v,t}^{EV,dch} + x_{u,t}^{grid,s} \leq 1$$

$$\forall u = 1 \ldots U, \forall v = 1 \ldots V_u, \forall t = 1 \ldots T \quad (37)$$

These constraints have been added to adopt a conservative approach: indeed, the current lack of further clarifications by the Italian regulating authority limits the role of BESSs and V2G-enabled EVs in enhancing virtual self-consumption in RECs. In this case, storage technologies can only contribute to shared energy by storing renewable energy produced by the members of the REC, that can be then used only to satisfy the local "behind-the-meter" demand.

3.2. Dataset description

The optimisation problem is solved over a one-week time frame (number of intervals T equal to 672), with a time interval duration equal to a quarter of hour ($\Delta = 0.25[h]$), taking into consideration two distinct seasons of the year, namely one week in December and one week in May, so as to investigate the impact of two different scenarios in terms of load demand and renewable energy production on energy sharing mechanisms. The examined REC includes eight different members, as represented in Fig. 2, that are connected in Low-Voltage (LV) or Medium-Voltage (MV) to the same portion of the grid underlying the same primary electrical substation whose perimeter broadens inside the municipality of Savona in the North of Italy.

By using the *Icograms Designer* [36] online drawing tool, it was also possible to design an ideal 3D map of the REC under analysis from the scratch, including all the eight members located within the primary electrical substation perimeter, as shown in Fig. 3.

As provided by Table 2, REC participants are distinguished between residential and industrial/commercial users, with quite different characteristics in terms of RES plants capacity, BESS and EV types, and committed power.

The remaining specifications for BESSs were defined from the corresponding data sheets, reported in [37] and [38], respectively for user no. 1 and no. 6. When not present in the technical specifications, the BESS charging and discharging efficiencies were assumed equal to 0.95 [-].

The industrial user, consisting of an office building with a 10 [kWp] PV plant and two warehouses with a 100 [kWp] PV plant each, owns two EV charging stations of 150 [kW] DC each (*Power Choice 150X*) [39] and one EV charging station of 44 [kW] three-phase AC with two plugs up to 22 [kW] (*Enel X Way WayPole2*) [40]. The industrial user's facilities are arranged in MG configuration, as highlighted in [34], but for the

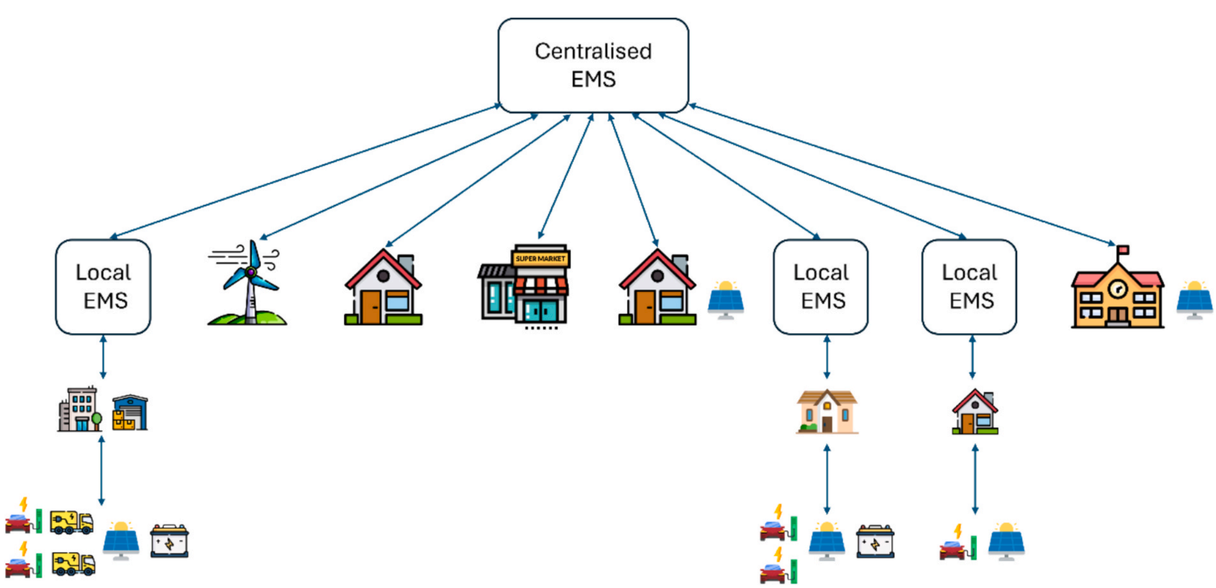

Fig. 2. Schematic representation of the case study REC.

Fig. 3. Graphic illustration of the REC.

Table 2
Technical specifications of the REC users.

User	Type	PV size	Wind turbine size	BESS size	EV models	Annual energy consumption	Committed power
1	Industrial prosumer	210 [kW]	–	250 [kWh] / 180 [kW]	2 Renault Zoe +2 DAF XD Electric trucks	490,000 [kWh]	800 [kW]
2	Producer	–	225 [kW]	–	–	–	250 [kW]
3	Residential consumer	–	–	–	–	2,500[kWh]	3 [kW]
4	Supermarket	–	–	–	–	260,000 [kWh]	80 [kW]
5	Residential prosumer	2.7 [kW]	–	–	–	4,300[kWh]	6 [kW]
6	Residential prosumer	8.1 [kW]	–	13.5 [kWh]/5 [kW]	1 Renault Zoe +1 VW ID 4.1 Pro	25,000 [kWh]	30 [kW]
7	Residential prosumer	3.6 [kW]	–	–	1 Renault Zoe	4,700[kWh]	6 [kW]
8	School building	20 [kW]	–	–	–	107,000 [kWh]	40 [kW]

purposed of the aggregator and of the Centralised EMS, the MG is represented through a single busbar model.

The Renault Zoe EVs should arrive at the office building at 9 A.M. and leave at 6 P.M. on weekdays. In addition, one of the two Zoe is present at the facility from 9 A.M. to 6 P.M. on Saturday. The two DAF XD Electric trucks are V2B-enabled and are assumed to be used for freight delivery. One truck is not available at the facility from 8 A.M. and to 5 P.M. during working days and on Saturday, while on Sunday it is connected at the facility for the whole day, with a weekly total energy consumption estimated to be equal to 680 [kWh] (evaluated on the distance that the truck is supposed to travel over the week).

The availability of the other electric truck at the facility is described in Fig. 4, where 1 means that the truck is connected to the charging station and 0 means that it is not present at the facility. Its weekly total energy consumption is assumed to be equal to 640 [kWh]. The maximum quarter-hour energy consumption is estimated to be equal to 18 [kWh] for both the electric trucks. All the other input data for EVs are specified in [41,42] and [43], for the Renault Zoe, the V2B-enabled Volkswagen ID 4.1 Pro and DAF XD Electric trucks, respectively.

For all the users, the EV presence at the facilities and the corresponding input data are assumed the same for both December and May. It is important to highlight that hypotheses have been done on the transportation demand of EVs in order to emulate the real behaviour of people. As shown in the mathematical model section, a deterministic approach has been followed to model the EVs interaction with the REC, since the focus of the work is to assess the operational management of the REC and not to focus on charging strategies details.

For the supermarket and the industrial MG all the input data about the buildings' hourly electrical demand were imported from the HOMER Pro ® software [44] (version 3.15.3) and properly scaled according to the maximum power that can be exchanged with the external network by the user.

	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Monday	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
Tuesday	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wednesday	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
Thursday	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Friday	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Saturday	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Sunday	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Fig. 4. DAF XD Electric truck's availability at the industrial site (green when available, red when not available). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The school building's consumptions were obtained from the electrical demand data of the Savona Campus, and then properly scaled and referred to the time interval Δ, since the original data were available per minute [45]. All the residential users' electrical demands were determined with the *LoadProfileGenerator* (LPG) tool [46], which uses a desire-driven agent simulation to model in detail the behaviour of the residents and generate load profiles with high temporal resolution up to 1 min for residential energy consumption, primarily electricity and domestic hot water [47]. The PV input data were exported from the *Photovoltaic Geographical Information System* (PVGIS) online tool [48]. Since this tool also makes available data about 10-meter total wind speed, it was possible to estimate the wind turbine power production knowing its power curve and hub height from [49].

The annual energy consumptions of the REC members, reported in Table 2, have been compared with the average annual electricity consumption reported by several sources and articles, among which [50,51,52,53,54] and [55], about electricity consumption in the building sector, depending on the end use of the facility, its location and the occupation level. Regarding household users, the Italian Regulatory Authority for Energy, Networks, and the Environment (ARERA) website [56] allows to visualise the average electricity consumption of domestic customers measured monthly, whose data can be collected by selecting the region, municipality, committed power, market, and, if applicable, the residence of the end customer. The comparison has shown that the values provided in Table 2 are coherent with actual facilities.

4. Optimisation results

This section discusses the results of the optimisation model. The EMS has been implemented in the Matlab R2023B/Yalmip R20230622 [57] environment and solved with Gurobi solver [58].

The results from the centralised EMS are representative of the maximization of the shared energy within the REC, both for week of May and December. These two periods have been chosen in order to analyse the performance of the REC in different operating conditions in terms of RESs production. Relevant results are shown in Subsections 4.1 and 4.2. In Subsection 4.3, the KPI analysis is extended by considering two additional weeks, one in March and one in October. Finally, Subsection 4.4 analyses the trade-off between the maximization of the energy shared within the REC and the minimization of BESS and EV battery degradation.

The CPU model used to run the centralised EMS is an Intel ® Xeon ® Platinum 8160 CPU @2.10 GHz. The gap of the optimal solution, the number of decision variables and constraints, as well as the time necessary to generate input data, constraints and to optimise the day-ahead model are reported in Table 3.

4.1. Week of May

Regarding the week of May, Fig. 5 and Fig. 6 show the optimal active power dispatchment of two REC members, where the produced active power is represented on the positive y-axis, while absorbed active power is shown on the negative y-axis. In the graphs, the scale of values on the y-axis is related to the user's committed power.

All the figures report the days on the x-axis; the number of quarter-hourly time intervals at the end of each day are reported as ticks. In Fig. 5, the PV active power production of the industrial user follows an almost constant trend until Thursday, when it decreases suddenly in the central hours of the day, due to some clouds. On Monday and on Sunday, the low industrial demand allows for the surplus of PV production to be sold to the external grid and to be shared with the other members of the REC. Due to the significant power production from the wind turbine in the central hours on Wednesday and on Saturday that is injected into the external grid, the power absorption of the industrial user reaches its peaks on those days, as shown in Fig. 5, charging BESS and EVs, in particular the trucks, to maximise the shared energy. In some intervals, BESS discharging and partly V2B are able to satisfy the electrical demand, either coupled with PV production during peak hours or on their own during off-peak hours.

The wind turbine active power production is represented in Fig. 6. The high production between Tuesday and Wednesday, and on Sunday, allows for the sale of active power to the external network and the consequently purchase by the REC members to exploit it as virtual self-consumed energy, which is incentivised as shared energy.

Fig. 7 and Fig. 8 show the reference profiles of active power to be exchanged with the local distribution network (both in purchase and sale phases) for users no.1 and no.6. These profiles are the inputs that the REC aggregator provides to the local EMSs in order to ensure the maximization of the energy that is shared within the REC. Then, local EMSs choose whether or not to try to follow the reference profile, depending on whether the user adopts a cooperative or non-cooperative approach. Regarding user no.1, whose profiles are represented in Fig. 7, the reference active power purchase profile shows some peaks in correspondence of EV trucks charging, in turn needed to virtually share the wind turbine production and to satisfy the transportation demand. On the other hand, the reference active power sale profile follows the trend of the PV production, especially when trucks are not present at the facility. Similar considerations are valid for user no.6, whose profiles are represented in Fig. 8, in which some peaks of suggested power purchasing appear in correspondence of EVs charging, while sale suggestions are evident when PV production cannot be locally physically self-consumed.

The main numerical results of the centralised EMS for the week of May are reported in Table 4. As expected, the industrial user is the most involved in the power exchanges, since its electrical demand and active power production are the highest within the REC. Only the supermarket and the school building are comparable to the industrial MG in terms of purchased energy over the week. The energy involved in BESSs and EVs charging and discharging cycles during this week is quite small for most of the users, apart from the industrial one who owns high-capacity BESS and EVs able to be usefully exploited to maximise the shared energy. The BESS owned by user no. 6 is still required to operate in charging and discharging mode to satisfy partly the electrical demand, whose value is the highest among the residential users.

Table 5 shows other significant results related to the total RESs production, overall electrical consumption and shared energy within the REC.

The profile of the shared energy over the week of May is represented in Fig. 9. Its peaks are at the central hours on Wednesday and Saturday, when the wind turbine injects a significant amount of its active power production into the distribution grid, which is in turn absorbed and virtually self-consumed by the other community members. On Thursday, energy sharing is basically not exploited since the wind turbine production is extremely low and the PV production of user no.1 is physically self-consumed, thus preventing the industrial user from contributing to the net injected energy.

4.2. Week of December

In December, the differences compared to the previous scenario concern the input data about RESs active power production and the

Table 3
Model computational details for the day-ahead centralised EMS.

	May	December
Gap [%]	1.29	3.93
Continuous variables [-]	126,840	126,840
Binary variables [-]	118,440	118,440
Constraints [-]	463,544	463,544
Elapsed time for input data [s]	60.46	98.1
Elapsed time for constraints [s]	1,030.08	1,394.77
Elapsed time for optimisation [s]	1,466.03	2,131.12

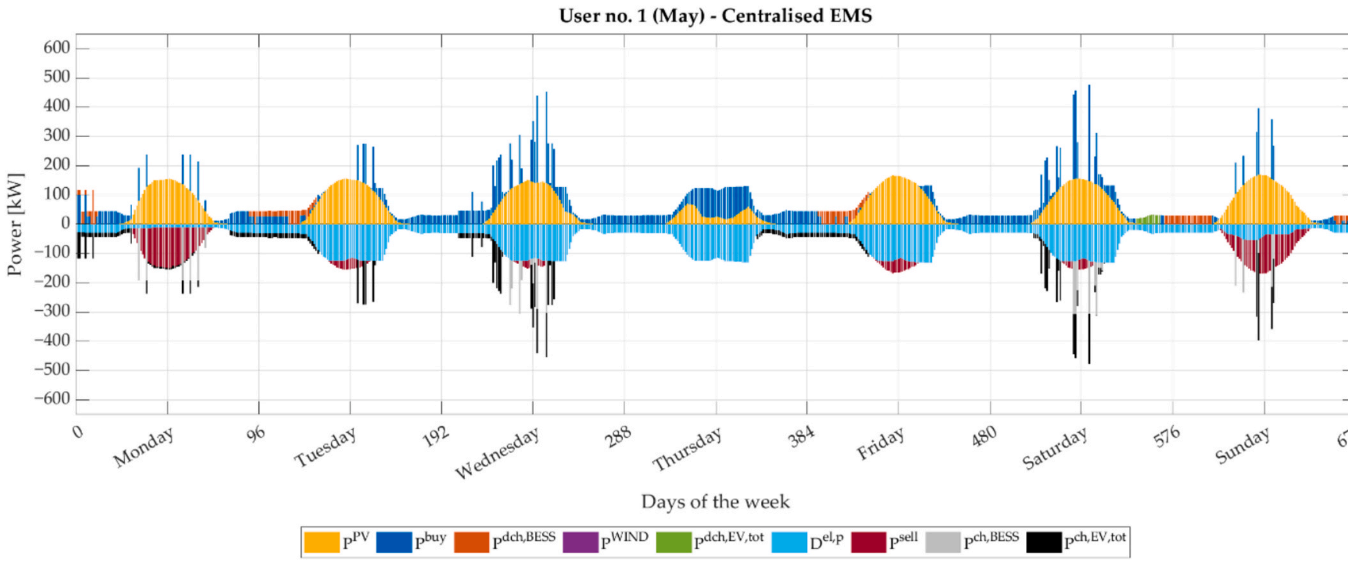

Fig. 5. Centralised EMS's active power results for the industrial user – May scenario.

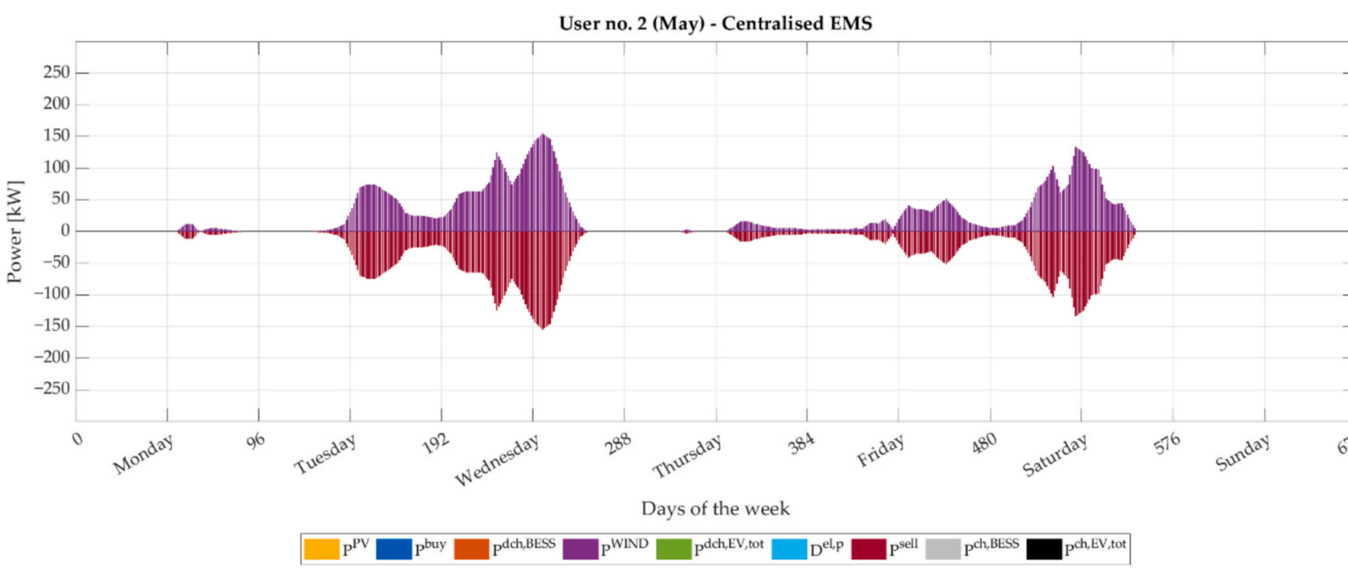

Fig. 6. Centralised EMS's active power results for the wind turbine – May scenario.

electrical demand of the REC members. Fig. 10 and Fig. 11 show the main results in terms of power exchanges in the December scenario for user no.1 and user no.2.

The industrial user's active power exchanges are reported in Fig. 10. The very low PV active power production leads to a significant absorption of power from the external network for the whole week to meet the electricity needs of the user and to charge properly BESS and EVs, thus also contributing to increase the energy sharing. In the nights between Friday and Saturday and between Saturday and Sunday, both or only one of the V2B-enabled electric trucks, being available at the facility, are used in discharging mode to satisfy the industrial load without needing to absorb power from the public grid.

The wind turbine power production in December, as represented in Fig. 11, is much higher than in May, especially on Monday, on Friday and on Saturday. Since the objective function of the EMS is always to maximise the shared energy within the REC, this active power production is virtually self-consumed by the other members through the distribution grid. A significant contribution is provided by user no.1.

Reference profiles of active power exchange to be provided as input to local EMSs appear in Fig. 12 and Fig. 13 for users no.1 and no.6, respectively. Differently from May scenario, in December scenario the reference active power sale profile is always 0, since the reduced PV production is always physically self-consumed. On the other hand, the reference active power purchase profile reaches significant values and is variable, trying to exploit as much as possible virtual energy sharing of the wind turbine production.

Table 6 and Table 7 show the results about the total energy exchanged within the REC and with the public network during the week of December. Compared to May, the total PV production is much lower as well as the energy sold to the external network by the industrial MG. Almost all the energy injected into the distribution network is provided by the wind turbine, and the corresponding amount counted as shared energy increases significantly with respect to the previous scenario. It can also be noticed a decrease in the total energy exchanged by the BESSs, both in charging and discharging mode (down to zero exchanged energy for the BESS of user no. 6) while the V2B-enabled EVs are called upon to operate more in the discharge mode. This limited operation of the BESS is also related to the minimization of the number of charging/discharging cycles, to avoid degradation.

As it is evident from the comparison between Table 5 and Table 7,

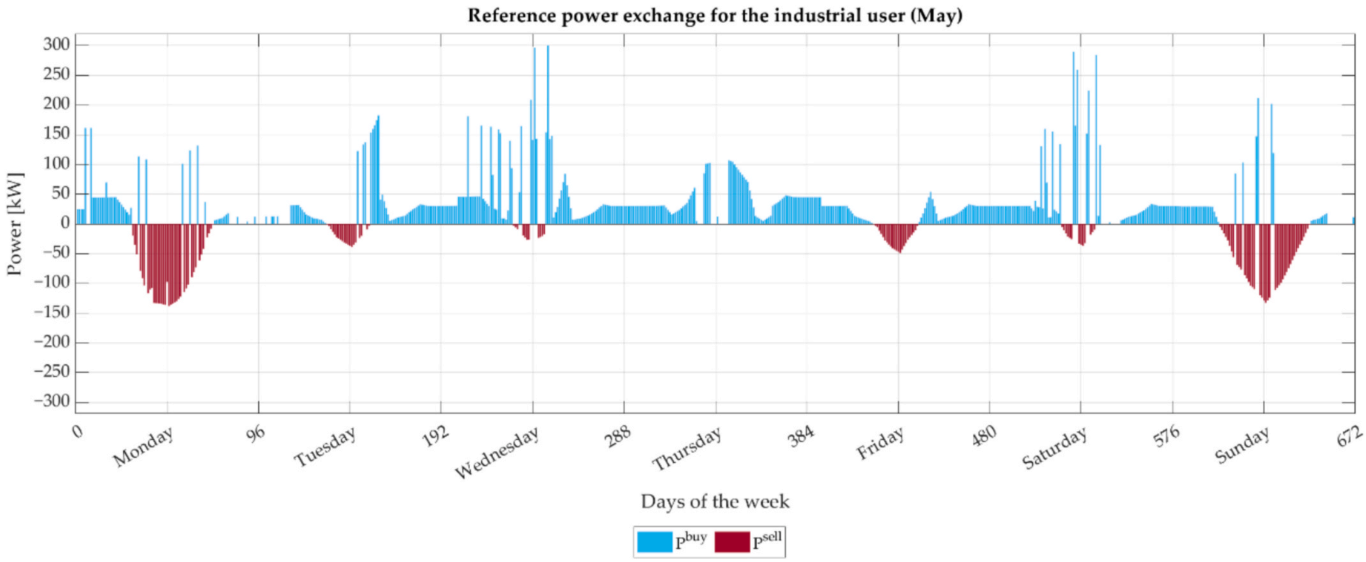

Fig. 7. Reference profile of power exchange with the distribution network for user no.1 – May scenario.

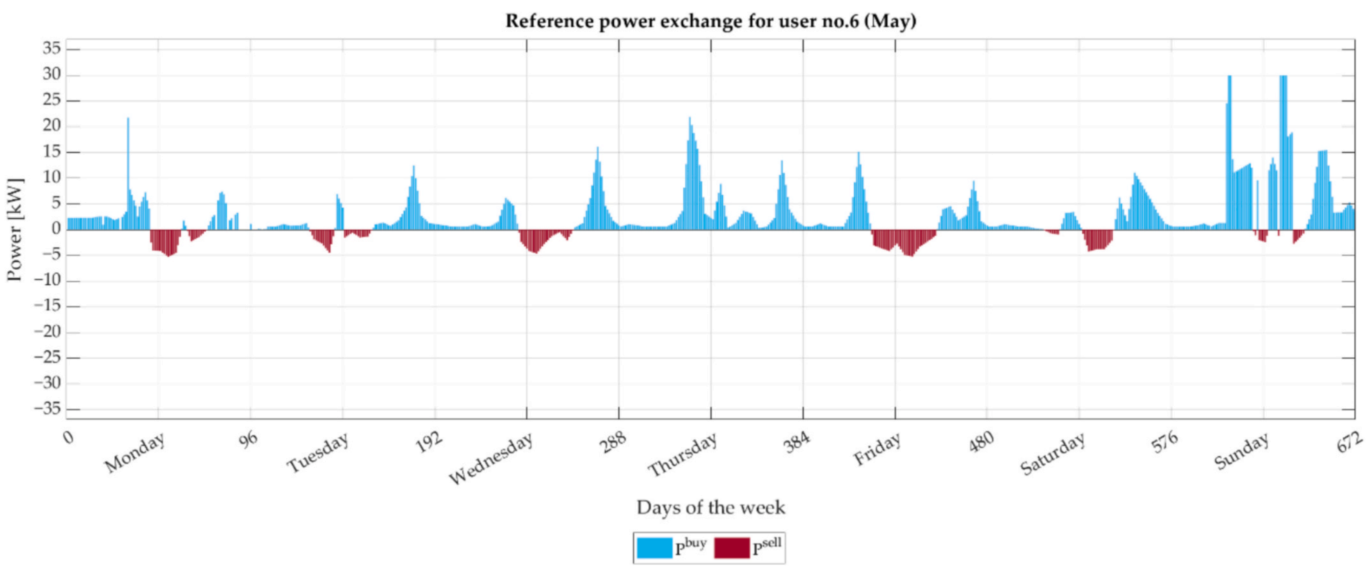

Fig. 8. Reference profile of power exchange with the distribution network for user no.6 – May scenario.

Table 4
Centralised EMS results – May scenario.

User	$E^{grid,b,tot}$ [kWh]	$E^{grid,s,tot}$ [kWh]	$E^{BESS,ch,tot}$ [kWh]	$E^{BESS,dch,tot}$ [kWh]	$E^{EVch,tot}$ [kWh]	$E^{EV,dch,tot}$ [kWh]
1	5,069	1,997.70	891.74	795.44	1,950.90	85.11
2	0	3,798.30	–	–	–	–
3	59.63	0	–	–	–	–
4	4,963.10	0	–	–	–	–
5	51.35	41.39	–	–	–	–
6	494.08	99.9	27	21.52	144.55	0
7	73	97.55	–	–	21.28	0
8	1,424.60	142.25	–	–	–	–
REC	12,134.76	6,177.10	918.74	816.96	2,116.73	85.11

Table 5
REC overall energy results – May scenario.

	$E^{PV,tot}$ [kWh]	$E^{WIND,tot}$ [kWh]	$E^{D^{el},tot}$ [kWh]	$E^{sh,tot}$ [kWh]
REC	9,277.40	3,798.3	16,900	5,708.6

the energy that is shared within the REC is higher in December, thanks to the higher production of the wind turbine, that increases in turn the virtual self-consumption by the other members.

The profile of the shared energy over the week of December is shown in Fig. 14. It reaches peaks higher than in May thanks to the higher wind turbine power production in this period, in particular on Friday afternoon.

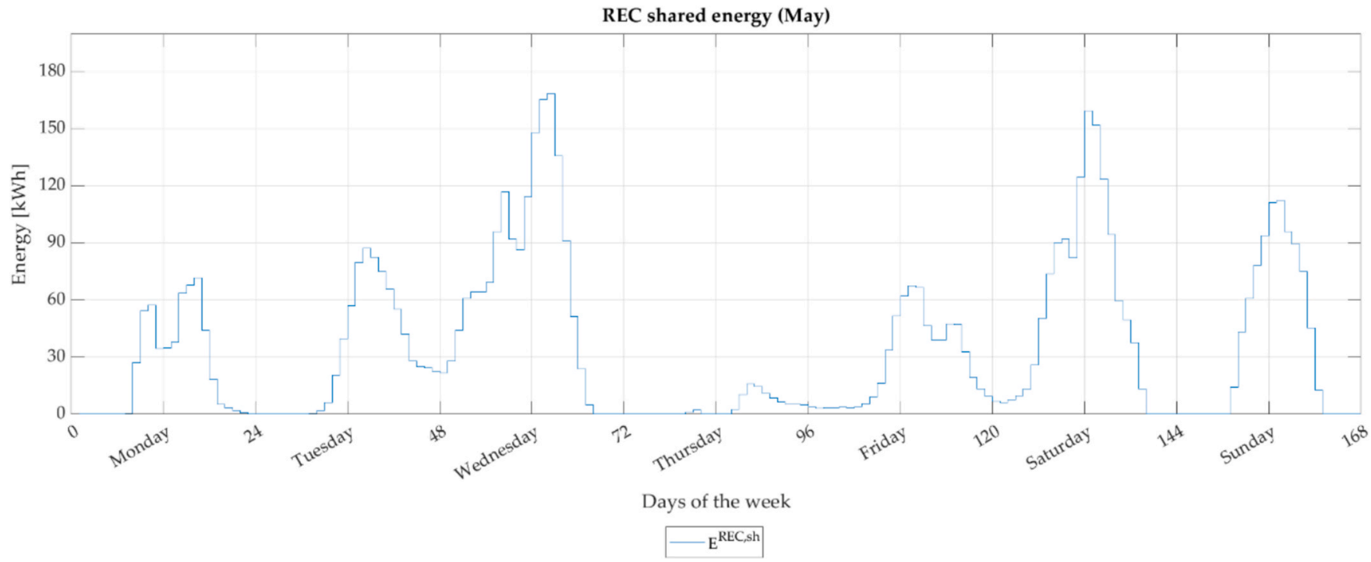

Fig. 9. Energy shared within the REC – May scenario.

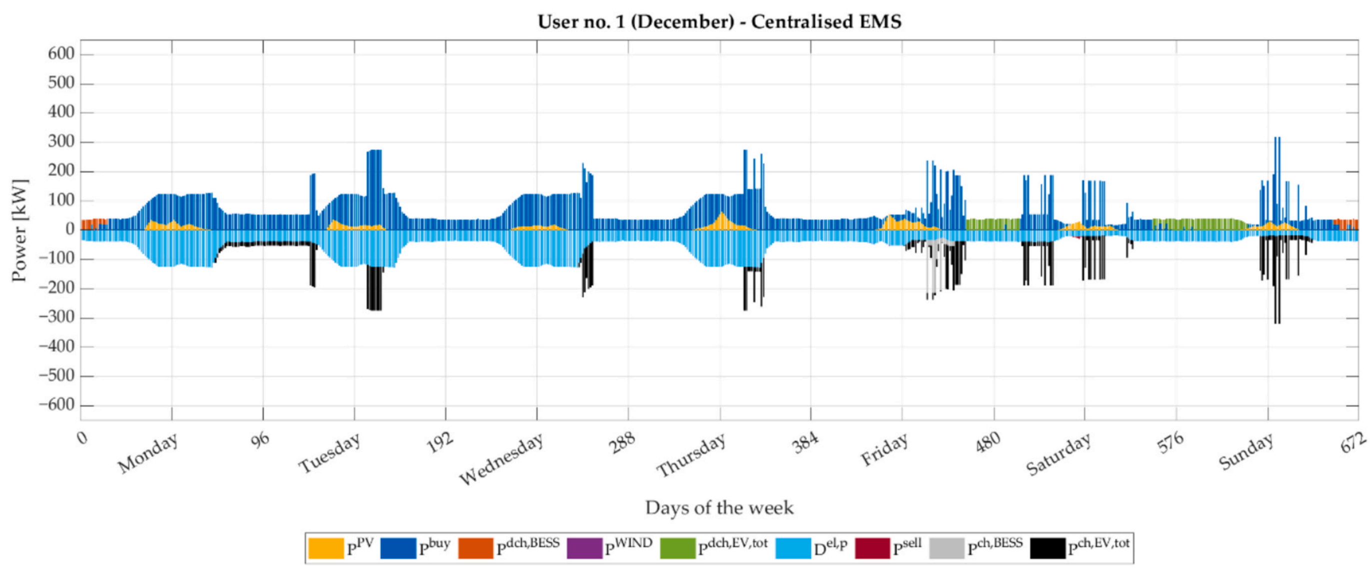

Fig. 10. Centralised EMS's active power results for the industrial user – December scenario.

4.3. Key performance indicators

In order to assess the operational efficiency of the REC, some KPIs need to be introduced to evaluate the economic and energy benefits on the community and its members. Some of them have been derived from [59].

Firstly, the Self-Sufficiency Rate (SSR) is calculated as follows:

$$SSR[\%] = \frac{E^{PV,tot} + E^{WIND,tot} + E^{BESS,dch,tot} + E^{EV,dch,tot} - E^{grid,s,tot}}{E^{D^{el},tot} + E^{EV,ch,tot} + E^{BESS,ch,tot}} \cdot 100 \quad (38)$$

The SSR describes the share of total energy demand of the REC, related to the satisfaction of the users' loads and to the charging of the EVs and the BESSs, covered by local resources, namely the PV plants, the wind turbine, BESSs discharging and the EVs in V2B mode.

Other two significant indicators for the REC monitoring are the Physical Self-Consumption Index (PSCI) and the Virtual Self-Consumption Index (VSCI), which are defined as follows:

$$PSCI[\%] = \frac{E^{PV,tot} + E^{WIND,tot} + E^{BESS,dch,tot} + E^{EV,dch,tot} - E^{grid,s,tot}}{E^{PV,tot} + E^{WIND,tot} + E^{BESS,dch,tot} + E^{EV,dch,tot}} \cdot 100 \quad (39)$$

$$VSCI[\%] = \frac{E^{sh,tot}}{E^{PV,tot} + E^{WIND,tot} + E^{BESS,dch,tot} + E^{EV,dch,tot}} \cdot 100 \quad (40)$$

On one hand, the PSCI shows the percentage of physical self-consumption over the local energy production, i.e., how much energy is produced and consumed directly by the electrical load downstream of the production plant and therefore not fed into the grid.

On the other hand, the VSCI allows to estimate the percentage of shared energy within the REC over the local energy production, i.e., how much renewable energy production is injected into the grid and withdrawn by consumers belonging to the REC during the same feed-in hour, calculated over the entire week.

To estimate the efficiency of the REC in terms of energy sharing, the Shared Energy Index (SEI) can be calculated as follows:

$$SEI[\%] = \frac{E^{sh,tot}}{E^{grid,s,tot}} \cdot 100 \quad (41)$$

The SEI evaluates, on the whole week, the percentage of total energy shared by the REC over the total energy injected into the external distribution network.

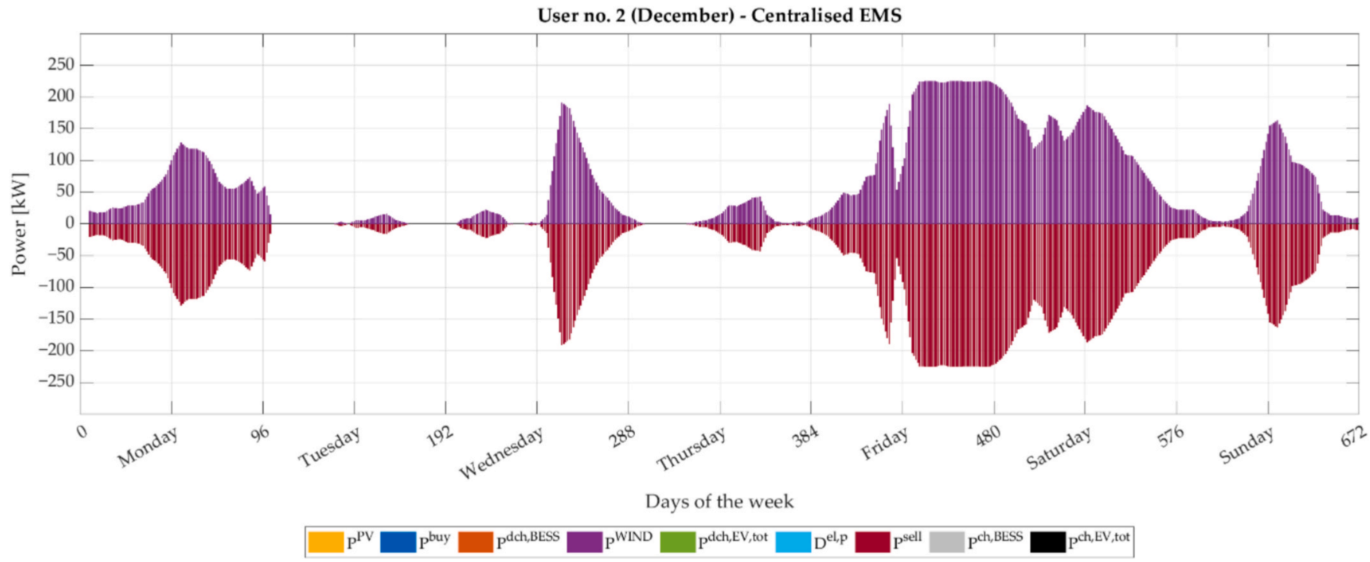

Fig. 11. Centralised EMS's active power results for the wind turbine – December scenario.

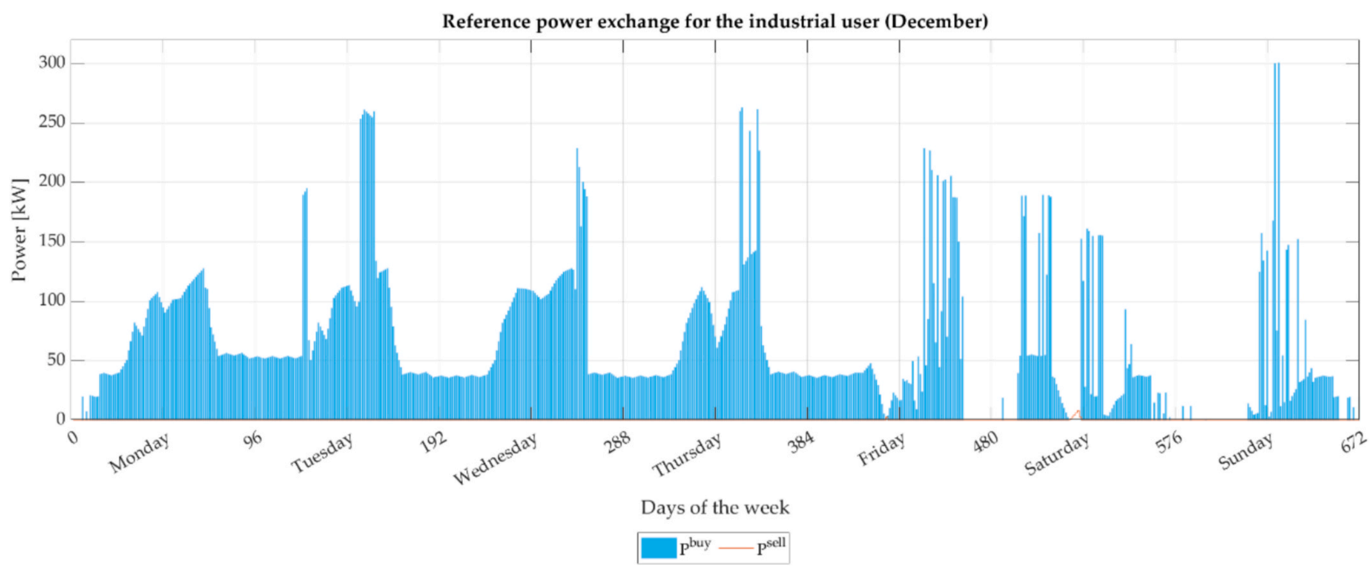

Fig. 12. Reference profile of power exchange with the distribution network for user no.1 – December scenario.

The results of the centralised EMS for these indicators are reported in Table 8, comparing the scenarios in December and in May.

The higher values of SSR, PSCI and SEI appear for the week of May. A significantly lower energy injected and withdrawn into/from the distribution network in May rather than in December, in conjunction with similar values of overall electrical demand and energy produced from RESs, and BESSs and EVs discharging, leads to a higher percentage of self-sufficiency, physical self-consumption and energy shared indices for the examined REC. Due to a lower shared energy within the REC in May, the percentage of the virtual self-consumption is over 25% lower than in December, when the members collectively exchange more energy with the public network since the low PV production meets only a small part of the electrical loads of all members. On the other hand, in May a high values of SEI show the effectiveness of the REC in simultaneously injecting and absorbing energy into/from the distribution network: in fact, in May just 7.5% of the energy that is sold is not virtually self-consumed by the members of the REC.

To analyse more in detail how the seasonal variations affect the energy performances of the REC, Table 9 shows the results of the KPIs for two additional weeks in October and in March.

These two additional scenarios are characterised by similar values of total electrical demand, energy withdrawn from the distribution network and energy shared within the REC, while the RES production and the energy injected into the external network are higher in the week of October. This results in very close values for the SSR and VSCI, while the PSCI and SEI are significantly higher in March, with just 8% of the energy injected into the distribution network not being virtually self-consumed by the REC members.

4.4. Trade-off between maximization of energy sharing and minimization of battery degradation

To provide a quantitative measure of the reduction of the shared energy when trying to preserve BESSs and EV batteries' health, Table 10 reports the results of the energy shared within the REC assuming the coefficient ϕ^{sum} in the objective function equal to 0 (i.e., not considering the minimization of the charging and discharging cycles of BESSs and EV batteries) and to 1.

As expected, both for the week of December and May, the total shared energy within the REC slightly increases if $\phi^{sum} = 0$, with respect

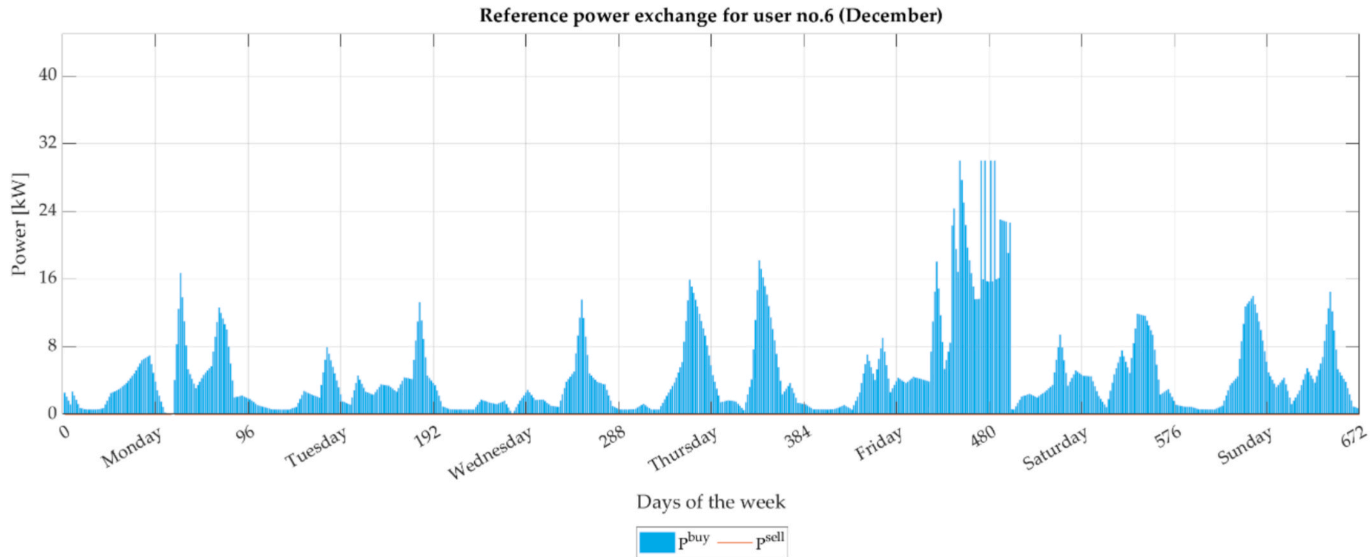

Fig. 13. Reference profile of power exchange with the distribution network for user no.6 – December scenario.

Table 6
Centralised EMS results – December scenario.

User	$E^{grid,b,tot}$ [kWh]	$E^{grid,s,tot}$ [kWh]	$E^{BESS,ch,tot}$ [kWh]	$E^{BESS,dch,tot}$ [kWh]	$E^{EV,ch,tot}$ [kWh]	$E^{EV,dch,tot}$ [kWh]
1	10,406	7.11	242.11	199.25	2,626.80	701.69
2	0	10,645	–	–	–	–
3	58.11	0	–	–	–	–
4	4,935.3	0	–	–	–	–
5	67.89	1.41	–	–	–	–
6	799.04	0.035	0	0	127.1	0
7	171.26	2.45	–	–	66.18	0
8	2,043.40	0	–	–	–	–
REC	18,481	10,656	242.11	199.25	2,820.08	701.69

Table 7
REC overall energy results – December scenario.

	$E^{PV,tot}$ [kWh]	$E^{WIND,tot}$ [kWh]	$E^{D^{el},tot}$ [kWh]	$E^{sh,tot}$ [kWh]
REC	1,134.3	10,645	17,443	8,371

to the scenarios with $\phi^{sum} = 1$. Indeed, the BESSs and EVs can be charged and discharged without any constraints on the maximum number of cycles during the considered time horizon, enabling the REC members to virtually self-consume more energy.

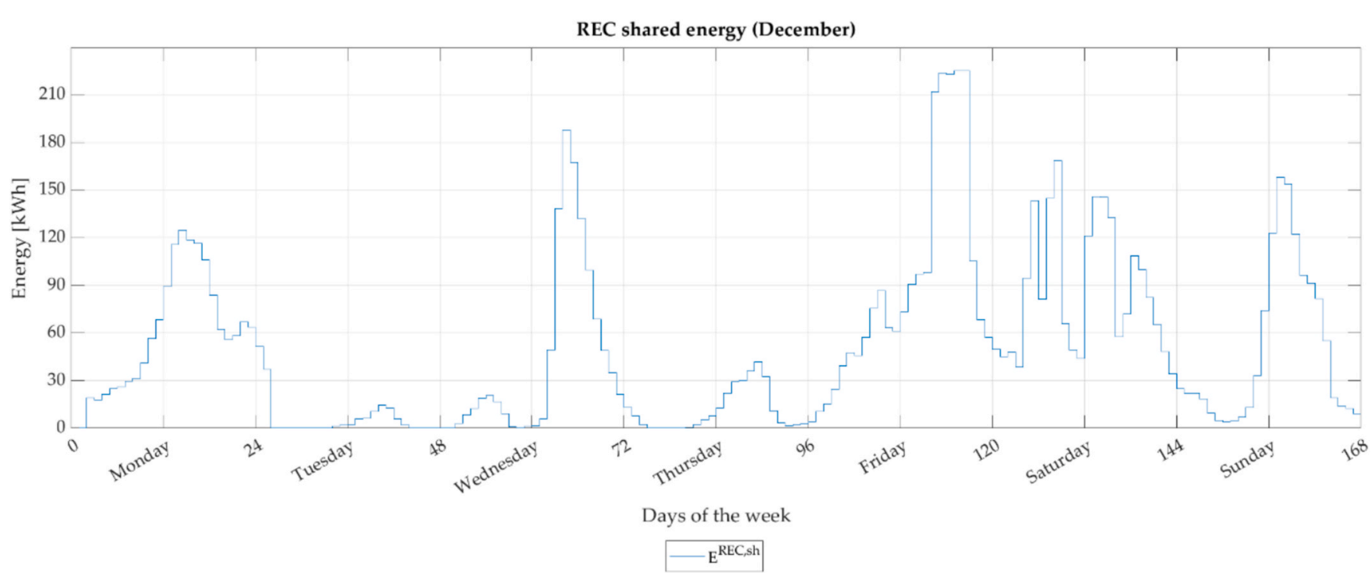

Fig. 14. Energy shared within the REC – December scenario.

Table 8
KPIs of the REC for the two considered scenarios.

Scenario	SSR [%]	PSCI [%]	VSCI [%]	SEI [%]
December	9.87	15.96	66.02	78.56
May	39.13	55.81	40.84	92.42

Table 9
KPIs of the REC for two additional scenarios.

Scenario	SSR [%]	PSCI [%]	VSCI [%]	SEI [%]
October	36.97	57.31	26.88	62.98
March	35.82	69.13	28.34	91.81

Table 10
REC shared energy results considering and not considering minimization of battery degradation.

$E^{sh,tot}$ [kWh]	$\phi^{sum} = 0$	$\phi^{sum} = 1$
December	8,600.1	8,371
May	5,755.5	5,708.6

4.5. *Impact of users' behaviour on energy sharing*

Given the bilevel structure of the proposed REC EMS, it is important to assess whether the knowledge of the REC users' intention to be cooperative or non-cooperative is relevant for the centralised EMS to deliver an effective action for maximizing the energy shared within the REC. To this purpose, a comprehensive analysis has been carried out, analysing how the shared energy varies in accordance with the possible set of non-cooperative users and to the possible knowledge of those users' behaviour by the centralised EMS. The scenarios are summarized in Table 11.

Scenario 1 is the one that was analysed in the previous subsections: here, the centralised EMS is run considering all the 8 members of the REC, disregarding their approach (cooperative/non-cooperative). This represents the ideal scenario, since the only objective is to maximize the energy shared within the REC without considering economic aspects.

In Scenario 2a the centralised EMS is run considering that it has not knowledge of the REC users' behaviour. Nevertheless, it is assumed that User 1 (the industrial microgrid) has actually a non-cooperative behaviour (i.e., it tries just to minimize its operating costs). In this configuration, the centralised EMS is run over 8 REC users, but the calculation of the shared energy is carried out by considering the injection/absorption profiles deriving from the centralised EMS only for the seven cooperative members, while the injection/absorption profiles of the industrial microgrid user, that is non-cooperative, are obtained from the local EMS, that minimizes its net operating costs.

Scenario 2b has the same configuration of Scenario 2 in terms of cooperative/non-cooperative users, but the centralised EMS is aware of the non-cooperativeness of User 1: thus, the centralised EMS is run just considering the 7 cooperative users. As post-processing, the calculation of the shared energy is made considering the injection/absorption profiles deriving from the centralised EMS for the 7 cooperative members, while the injection/absorption profiles of the industrial microgrid user, that is non-cooperative, are obtained from its local EMS.

Scenario 3 is a benchmark scenario: indeed, all the REC users are supposed to be non-cooperative, thus operating just to minimize their own operating costs. The corresponding shared energy is the benchmark to evaluate the effectiveness of the centralised EMS action. Indeed, the centralised EMS has no impact on this scenario.

The Scenarios from 4a to 7b represent sensitivities with respect to Scenario 2a and Scenario 2b: indeed, Scenarios labelled with letter *a* are related to Scenario 2a in which the centralised EMS has no knowledge about the behaviour of the users, while in Scenarios labelled with letter *b,* the centralised EMS is aware of the non-cooperativeness of some users. The differences among the scenarios are given by the number of users that are non-cooperative, as highlighted in Table 11.

The results for the first four Scenarios are provided in Table 12. The fact that a user is non-cooperative of course leads to a reduction in the energy shared within the REC, evident both in Scenario 2a and 2b: in these cases, the decrease in shared energy is considerable since the chosen non-cooperative member is User 1, the biggest one in terms of size of RES and BESSs plants, capacity of the EV charging system and committed power. This trend is evident in both months. Comparing Scenario 2a with Scenario 2b, a much smaller difference: in December, basically the awareness by the centralised EMS of the intention of User 1 to be non-cooperative leads to a basically negligible variation (around 0.01 %), while in May the difference is around 1 %. This is due to the fact that, despite being non-cooperative, the industrial user is anyway a member of the REC and participates in energy sharing mechanism.

Table 12
Centralised EMS awareness analysis – Shared energy comparison – Main scenarios.

$E^{sh,tot}$ [kWh]	December	May
Scenario 1 (S_1)	8,371	5,708.6
Scenario 2a (S_{2a})	6,997.7	3,785.2
Scenario 2b (S_{2b})	6,996.5	3,825.2
Scenario 3 (S_3)	6,859.2	3,700.1

Table 11
Impact of users' behaviour on energy sharing – Description of the scenarios. C = cooperative, NC = non-cooperative, √=centralised EMS has knowledge of the users' behaviour, ×=centralised EMS has not knowledge of the users' behaviour, N/A = not applicable (i.e., the knowledge/unknowledge of user behaviour is not in the scope of the scenario).

		Scenarios											
		S_1	S_{2a}	S_{2b}	S_3	S_{4a}	S_{4b}	S_{5a}	S_{5b}	S_{6a}	S_{6b}	S_{7a}	S_{7b}
REC users	1	C	NC	NC	NC	NC	NC	NC	NC	C	C	NC	NC
	2	C	C	C	NC	C	C	C	C	C	C	C	C
	3	C	C	C	NC	C	C	C	C	C	C	C	C
	4	C	C	C	NC	C	C	C	C	C	C	C	C
	5	C	C	C	NC	C	C	C	C	C	C	C	C
	6	C	C	C	NC	NC	NC	NC	NC	NC	NC	C	C
	7	C	C	C	NC	C	C	NC	NC	NC	NC	NC	NC
	8	C	C	C	NC	C	C	C	C	C	C	C	C
	9	C	C	C	NC	C	C	C	C	C	C	C	C
	10	C	C	C	NC	C	C	C	C	C	C	C	C
Centralised EMS aware of users' behaviour?		N/A	×	✓	N/A	×	✓	×	✓	×	✓	×	✓

Table 13
Centralised EMS awareness analysis – Shared energy comparison – Further scenarios.

$E^{sh,tot}$ [kWh]	December	May
Scenario 4a (S_{4a})	6,896.0	3,705.0
Scenario 4b (S_{4b})	6,896.0	3,713.4
Scenario 5a (S_{5a})	6,859.2	3,700.1
Scenario 5b (S_{5b})	6,859.2	3,700.1
Scenario 6a (S_{6a})	8,224.2	5,534.6
Scenario 6b (S_{6b})	8,115. 2	5,575.2
Scenario 7a (S_{7a})	6,960.9	3,779.0
Scenario 7b (S_{7b})	6,952.7	3,818.2

With respect to the benchmark scenario (S_3), it is evident that the centralised EMS action is effective in boosting energy sharing within the REC. Indeed, if all the REC users are "cooperative" (S_1), the shared energy increases of 22 % in December and of 54 % in May with respect to Scenario 3, where all the REC users behave as "non-cooperative". Scenario 2a and Scenario 2b show results that are similar, both in December and in May, to the ones of Scenario 3 since the behaviour of the industrial microgrid user, acting as "non-cooperative" also in Scenario 2a and Scenario 2b, impacts significantly on the total energy shared within the REC, more than possible "non-cooperative" residential users.

The results for the further analysed scenarios are reported in Table 13. All the proposed scenarios are characterized by a shared energy that is greater than the one obtained in Scenario 3, where all the users are non-cooperative. This demonstrates the effectiveness of the action of the centralised EMS. Moving from Scenarios 2a-2b to 4a-4b and 5a-5b, it is evident a progressive reduction of the shared energy, due to the increase of the set of non-cooperative members (as detailed in Table 11). Passing from Scenario 2a to 4a, a reduction in shared energy of 1.4 % is evident in December, with a reduction of 2.1 % in May. This is due to the non-cooperativeness of User 6. Analysing the impact of centralised EMS awareness between Scenarios 4a and 4b, in December no difference is evident, while in May the difference stands at 2.1 %. In Scenarios 5a and 5b, no differences are evident when considering an "aware" centralised EMS with respect to an "unaware" one.

In Scenarios 6a and 6b the shared energy is larger than in 4a/4b and 5a/5b since the industrial microgrid (User 1) is considered as cooperative. In this case, the awareness by the EMS of the non-cooperative behaviour of users 6 and 7 (residential ones) has a dual effect: in December, the awareness leads to a reduction in the shared energy (−1.3 %), while in May the awareness leads to an increase in the shared energy (+0.7 %).

The same trend is evident in Scenario 6a and 6b.

The analysis proves that the knowledge of the cooperative/non-cooperative behaviour by the centralised EMS has an impact on the energy that is globally shared within the REC, even if limited in percentage. In addition, the impact is not monotonic: indeed, in some scenarios the awareness of users' behaviour by the centralised EMS leads to an increase of the shared energy, while in other cases it leads to a decrease.

5. Conclusions

The purpose of this paper was to develop and implement an EMS serving the aggregator of a whole REC, assumed to be located in the North of Italy, consisting of eight different members: seven who have installed PV plants, BESSs and EV charging stations at their facilities, as well as a stand-alone wind turbine, which is a REC member itself. Among them, an industrial MG is comprised, having also EV trucks charging facilities.

The centralised EMS was designed with a multi-objective approach, aiming at the maximization of the shared energy within the REC and the minimization of the charging and discharging cycles of BESSs and EVs' batteries over the week to avoid degradation. Taking into account the latest developments and state-of-the-art in the technological and regulatory fields, this study provided an overview of the energy performance of the examined REC, by formulating a MILP model for the EMS used by the aggregator who daily manages the REC and by developing some KPIs for the performance analyses.

The results were analysed by identifying two different scenarios, namely a week in May and a week in December. The KPIs implemented in this paper were used to assess the performance of the REC in the management of energy locally produced and to evaluate the impact of self-consumed and shared energy on the REC efficiency. With values higher than 75 % in both scenarios, the SEI shows a significant percentage of shared energy over the energy injected into the distribution grid by the whole REC, meaning that this kind of REC configuration is optimal to maximise the energy sharing mechanism, which can also lead to maximise the economic incentives among REC users, but not discussed here. With respect to the energy produced by RES plants installed locally and BESSs and EVs discharging, the REC has a greater tendency to the virtual self-consumption than physical self-consumption when the energy injected into the distribution grid, mainly coming from the wind turbine production, is significant, as shown from the results of VSCI and PSCI, respectively 66.02% and 15.96%, in December. In terms of REC self-sufficiency to meet the electrical demand of its users exclusively through local production, the SSR shows a good result only in the period of May, reaching a 39.13%, when the energy withdrawn from the external network is significantly lower than in December thanks to the higher PV production. Regarding the mid-season weeks in March and October, increased PSCI (+12%) and SEI (+8%) appear in March with respect to October, due to a larger drop in the sold energy if compared to the RES production decrease.

It was proved that the centralised EMS action was effective in boosting energy sharing within RECs, with respect to a condition in which each user aims just at minimising its own operating costs (+22% in December and +54% in May). The paper investigated also the impact that the awareness by the centralised EMS of users' cooperative or non-cooperative behaviour has on the energy sharing. The analyses considered a total of 12 scenarios, each one characterised by different configuration in terms of non-cooperative users and in terms of awareness/unawareness of their behaviour by the centralised EMS. The analyses showed that awareness of users' behaviour has an impact on the energy that is globally shared within the REC, even if limited to some percentage points. Moreover, this impact is not monotonic but, depending on the considered month and configuration, shared energy may increase or decrease when having knowledge of the non-cooperative behaviour of the users. To cope with this, REC statute may include a clause prescribing that the non-cooperative members should provide an expected power exchange profile with the external network to the centralised EMS, that can furtherly refine the optimal active power exchange profiles of the cooperative users.

The flexibility assumes a relevant role in improving the match between consumption and production and thus reducing the total energy costs. BESSs and EVs can increase the virtual self-consumption of REC users by allowing for absorbing the energy withdrawn from the local distribution network that was produced from other users' RES plants and thus counted as shared energy. Further contribution might be provided by BESSs and V2G-enabled EVs when the Italian regulating authority will better clarify their role in shared energy computation.

The next steps of this study will focus on local EMSs that optimise the daily operation of the single users, trying to minimise a multi-objective function. On the one hand, if the REC users follow a cooperative approach, the local EMSs will aim to adhere to the desired active power exchange profiles with the external network provided by the centralised EMS described in the present paper (thus aiming at maximising the shared energy), while also minimising the net operating costs of the users; on the other hand, if the REC users follow a non-cooperative approach the local EMSs will aim at minimising only the net operating costs.

Further developments of the present study may involve the integration of real-time dynamic pricing strategies to better reflect market fluctuations and encourage efficient energy consumption of the REC users. Another development of the proposed EMS may concern the involvement of multiple interconnected RECs in the national electricity markets as ancillary and flexible service providers, for example with an exchange of reference signals between a central aggregator, managing multiple coordinated RECs, and the Ancillary Service Market..

Finally, the proposed EMS architecture can be improved by developing a scenario-based stochastic optimisation, taking into account variability of EV arrival and departure times (depending on the behaviour of the different users), RES production and load profiles. This could lead to an enhanced dispatchment of the users' BESSs, furtherly improving both physical and virtual self-consumption within the REC and thus increasing the energy and economic performance.

CRediT authorship contribution statement

Tommaso Robbiano: Writing – original draft, Software, Methodology, Data curation, Conceptualization. **Matteo Fresia:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Data curation. **Martina Caliano:** Visualization, Supervision, Project administration. **Stefano Bracco:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

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.

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Data availability

The data that has been used is confidential.

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