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Impact of different regulatory approaches in renewable energy communities: A quantitative comparison of european implementations

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ABSTRACT

Recently, the uptake of renewable energy has surged in distribution networks, particularly due to the cost-effectiveness and modular nature of photovoltaic systems. This has paved the way to a new era of user engagement, embodied by individual and collective self-consumption, and promoted by the EU Directive 2018/2001, which advocates for the establishment of Renewable Energy Communities. However, the transposition of this directive varies across Member States, resulting in specific rules for each country. In this work, the impact that different energy sharing models have on the same community is quantitatively assessed. The policy analysis focuses on the regulation of two countries, Italy and Portugal, chosen for the specular ways in which their models operate, respectively virtually and physically. The analysis is supported by a suite of tools which includes two optimization problems for community's operations, one for each analysed regulation, and a set of consumer protection mechanisms, to ensure no member is losing money while in community. Results demonstrate that the sharing model impacts community's optimal operations, optimal battery size and configuration, and members' benefit. As these models are sensitive to different variables, personalized interventions at national level are required.

1. Introduction

In the last decades, Renewable Energy Sources (RES) have become increasingly relevant in the European energy sector as they provide clean and affordable energy. In particular, the cost-modularity nature of Photovoltaic (PV) systems makes them particularly suitable for establishing small-medium sized plants along the distribution network. However, this characteristic presents both risks and opportunities. On one hand, the integration of PV plants into the distribution system reduces the network inertia and requires a change in DSO operations; on the other hand, it concurrently promotes the decentralization of the energy system, encouraging users' participation through individual and collective self-consumption. In this context, Renewable Energy Communities (REC) represent one of the most ambitious proposals by the European Union to support the integration of RES in the electric power system by taking advantage of the opportunity embodied by collective self-consumption. The EU Directive 2018/2001 (RED II) (European Parliament and Council, 2018), part of the *Clean Energy for All European* package, defines them as legal entities made by natural persons, small-medium size enterprises and local authorities that utilise, store, share and sell self-produced energy from RES among community members. However, significant challenges arise due to the diverse energy sharing models resulting from the transposition of this directive into national legislation. This diversity has resulted in distinct sets of rules, potentially leading to different outcomes when managing the community. In literature, just a few works address the problem of optimally managing the community within the constraints set by the regulation. The regulatory framework of a specific country is generally incorporated in the community design or operations. In (Moncecchi et al., 2020), the community investment is optimized by maximising the Net Present Value (NPV), considering REC peculiarities under the Italian regulation. Moreover (Silva et al., 2023), proposes a multi-step centralised optimization problem for community operation under the Portuguese regulation that ensures no members lose money while staying in the REC. Even if these works include the role of the regulatory framework, they are limited to the analyses of just one country. Comparisons of the RED II transposition among different Member States can also be found in literature. For example (Rocha et al., 2021), compares the REC regulation between Spain and Portugal. Similarly (Inês et al., 2020; Krug

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Nomenclature

Parameters

η_C	Battery charging efficiency
η_D	Battery discharging efficiency
$\lambda_{i,t}^{BUY}$	Retailer buying price of member *i* in period *t*
λ_t^{GRID}	Access tariff for usage of public distribution network in period *t*
λ_t^{p2p}	Price of REC internal exchanges in period *t*
$\lambda_{i,t}^{SELL}$	Retailer selling price of member *i* in period *t*
C_i	Battery nominal capacity of member *i*
$E_{i,t}^{C}$	Energy demand of member *i* in period *t*
$E_{i,t}^{G}$	Energy generated by member *i* in period *t*
N	Number of members in the REC
P_n	Nominal installed power of REC plants
P_{max}	Maximum charging or discharging power
p_z	Zonal price
SI_i	Sharing index of member *i*
SOC_{max}	Maximum state of charge
SOC_{min}	Minimum state of charge
TIP_t	Feed-in-premium on energy shared in period *t*
$TRAS_E$	Variable component of the transmission system network charges

Variables

$Bill_i^{IND}$	Energy bill sustained by member *i* in the overall period when not included in the REC
$E_{i,t}^{BC}$	Energy charged to the battery of member *i* in period *t*
$E_{i,t}^{BD}$	Energy discharged from the battery of member *i* in period *t*
$E_{i,t}^{B}$	Energy stored into the battery of member *i* in period *t*
$E_{i,t}^{INJ}$	Energy physically injected by member *i* in period *t*
$E_{i,t}^{MET}$	Energy metered of member *i* in period *t*
$E_{i,t}^{PUR}$	Energy purchased from the REC by member *i* in period *t*
$E_{i,t}^{SALE}$	Energy sold in the REC by member *i* in period *t*
$E_{i,t}^{SH}$	Energy shared in the REC by member *i* in period *t*
$E_{i,t}^{SUP}$	Energy supplied by the retailer to member *i* in period *t*
$E_{i,t}^{SUR}$	Energy surplus available in the market of member *i* in period *t*
$E_{i,t}^{WITHD}$	Energy physically withdrawal by member *i* in period *t*
$SOC_{i,t}$	Battery state of charge of member *i* in period *t*

Acronyms

RED II	EU Directive 2018/2001
AC	Allocation coefficient
EB	Equal benefit
SHAP	Shapley value
IMC	Marginal contribution
PC	Proportional contribution
MMR	Mid-market rate
SDR	Supply-demand ratio
CSDR	Corrected supply-demand ratio
POOL	Post-delivery pool market
MC	Marginal cost
EPR	Energy-to-power ratio
PCS	Power conversion system

Sets and Indexes

$i \in N$	Member of community
$t \in T$	Hour of the day
$s \in S$	Day-type

et al., 2023), carry out comparisons of REC regulatory frameworks among nine European countries. However, the analysis is limited to a qualitative comparison of the main outcomes resulting from the country-specific transposition processes. A quantitative comparison of how different regulatory frameworks impact on a community is therefore missing. To fill this gap, it is necessary to assess the goodness of diverse legislative transpositions of the REC concept by analysing the results obtained from energy management optimization tools under different regulatory frameworks on the same community. The comparison should be carried out by taking care of how diverse legislations imply different optimization techniques. Moreover, the evaluation should not look only at the economic effectiveness of the regulation, but also on the socio-economic fairness of the results. In this work, the former is addressed by looking at the regulation impact on the overall community, while the latter by analysing its impact on the economics of single members through the ability of the regulation-specific benefit redistribution methods to cover the costs sustained by the members for staying in the community. This is done to avoid discontent by guaranteeing that no member loses money while participating in the community. Therefore, in this paper we are not investigating the fairness or stability of the redistribution methods, as done in (Kulmala et al., 2021), but the influence of different regulatory frameworks on a REC to provide a quantitative evaluation of its economic impact on the community and single members. In particular, the presented research provides two main contributions, as shown in the comparative analysis of Table 1. First, it presents a quantitative assessment of how distinct REC legislations affect both the overall community and single members in economic terms. This is done by taking the case of Portugal and Italy, which adopted two specular regulatory approaches towards the implementation of the REC concept, starting from an analytical study of the RED II transposition in the two countries. Second, to carry out the comparison, a set of management tools is developed. It incorporates the national REC peculiarities of Italy and Portugal and allows the prevention of individual members' losses when state-of-the-art sharing methods and pricing algorithms are adopted. The toolset includes: (i) a two-step optimization problem, applicable to both Italy and Portugal, featuring an additional constraint to ensure no member is spending more money in the community rather than alone; and (ii) an alternative approach, based on the variation of users' energy bills, to distribute the Italian incentive among the members by avoiding sub-optimal solutions and simultaneously guaranteeing no individual member's loss.

The rest of the paper is organised as follows. Section 2 provides a review of the RED II transposition in two EU Member States, namely Italy and Portugal. Section 3 presents the proposed methodology for the policy analysis under diverse regulatory frameworks. Section 4 applies the methodology to an illustrative REC case study. The section also encompasses a comprehensive discussion of the key findings derived from the study. Finally, Section 5 summarises the most relevant policy implications coming from the obtained results.

2. Regulatory framework

The RED II gives mandatory provisions to Member States about renewable energy deployment, while leaving them free to define the specific details for the national implementation of the foreseen measures. The main difference resulting from the RED II transposition lies in the way in which the benefits of collective self-consumption are accounted for in the members' energy bills. In particular, two main REC models have been developed in the European context.

First, a virtual model, in which the energy shared by every member

Table 1
Comparative analysis highlighting research gaps and paper contributions with respect to the literature.

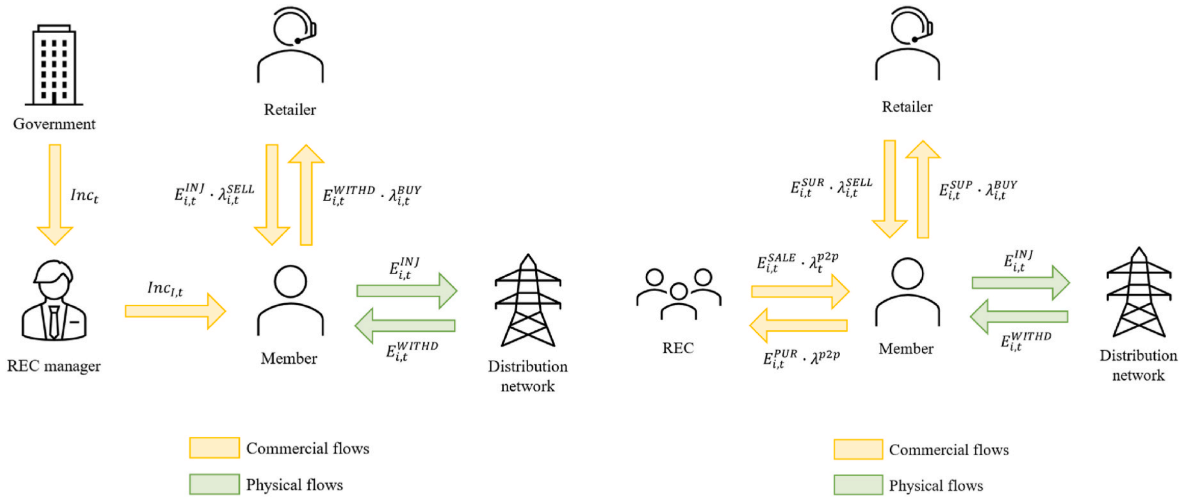
	Regulation	Technical tools	Comparison
(Brusco et al., 2023)	Europe	Energy costs minimisation in multi-step optimization problem for optimization of community operation and flexibility provision	*None*
(Moncecchi et al., 2020)	Italy	NPV maximisation in MILP problem for optimization of community design Shapley value for incentive redistribution	*None*
(Belloni et al., 2024)	Italy	NP maximisation in electro-thermal co-simulation for optimization of community design	*None*
(Silva et al., 2023)	Portugal	Energy costs minimisation in multi-step MILP problem for optimization of community operations Pricing algorithms for internal price computation	*None*
(Sousa et al., 2023)	Portugal	Investors' benefit maximisation in linear optimization problem for optimization of community design	*None*
(Lazzari et al., 2023)	Spain	Energy surplus minimisation with genetic algorithms for optimization of community design and allocation coefficients in community operations	*None*
(Rocha et al., 2021)	Portugal, Spain	*None*	Qualitative
(Inês et al., 2020)	Belgium, Croatia, France, Germany, Italy, Portugal, Spain, the Netherlands, United Kingdom	*None*	Qualitative
(Krug et al., 2023)	Belgium, Germany, Italy, Latvia, the Netherlands, Norway, Poland, Portugal, Spain	*None*	Qualitative
This paper	**Italy, Portugal**	**Energy costs minimisation in multi-step MILP problem for optimization of community operations** **Sharing methods for incentive redistribution** **Pricing algorithms for internal price computation**	**Quantitative**

in the configuration is not directly discounted from the members' bills. This means that members continue to be billed by their supplier for their total energy withdrawal and energy injection, whether it comes or not from other community members. In these cases, the benefit of staying in the community is represented by an incentive, granted to the REC according to country-specific rules, that can be shared among the members according to community rules privately defined. An example of a virtual model application can be seen in Italy, where the incentive is influenced by the zonal price and is recognised on the energy shared within the community, as explained in Section 2.1. Another example is set by the Netherlands, where the Cooperative Energy Generation (SCE) subsidy scheme is widely adopted to support PV plants in energy communities, as underlined by (Teladia et al., 2023) in her analysis of several Dutch support schemes. In this case, the subsidy is paid to the cooperative proportionally to the total energy produced by the community plants (Ministerie van Economische Zaken en Klimaat, 2021) and can be either distributed among the members or used to finance the community plants (Teladia et al., 2023). The subsidy is determined as the difference between a fixed term (base amount), designed to cover the investment and the operating costs, and a variable term (correction amount), following the fluctuations of the electricity market price. A price floor keeps the subsidy always above a certain threshold, even when the electricity market price drops. No upper limit is instead present. Unlike the Italian regulation, the concept of energy shared does not exist in the Netherlands since the incentive is granted on the total energy production. Users are motivated to join the community not for sharing energy, but for increasing the installed capacity of the community plant (5 kW for each new participant up to a maximum of 100 kW). This increases the production and, therefore, the revenues. However, both Italy and the Netherlands are based on a virtual model since the amount of money granted to the community needs to be redistributed and is not directly discounted from the members' bills.

Opposed to the virtual model, in the physical model the energy exchanged in the community by every member is directly discounted from the members' bills. In this case, members are billed by their supplier just for the remaining part of their energy withdrawal and injection, while the energy purchased or sold inside the community is valorised at a different internal price. This generally causes a deviation between the physical and commercial energy flows since the metered energy is paid partially to the retailer and partially to other community's members, as shown in Fig. 1 that graphically summarises the physical and commercial flows taking place in virtual and physical REC models.

An example of physical model application can be seen in Portugal or Spain, where the energy shared in the community is allocated to every member employing allocation coefficients (ACs) that follow country-specific rules. These two countries share several similarities because they are both based on the application of ACs. However, as illustrated in Section 2.2, Portuguese regulation allows the application of dynamic ACs, which consents the energy partitioning according to users' actual needs and not to predefined rules. On the other hand, Spanish regulation allows ACs either fixed, throughout the year, or variable, according to users' contractual power or other predefined rules (Ministerio para la Transición Ecológica, 2019), therefore not allowing dynamic ACs yet. This is the reason why scientific research dealing with the Spanish regulation, such as (Lazzari et al., 2023), focuses on the optimization of these coefficients, that can be changed only every four months, rather than the optimization of peer-to-peer transaction in real-time, as in (Silva et al., 2023), in which dynamic ACs are instead adopted. Another example of physical model application, even if not based on ACs, is represented by the Tenant Electricity Model (TEM) in Germany, on which is also based the work of (Braeuer et al., 2022) about the development of an optimization instrument for community design and operation under the German regulation. In this case, the eligible members are those living in the same building whose private network, owned by the tenants, is adopted for the exchanges (Bundesrepublik Deutschland, 2023). The community plants, property of the landlord, are used by the residents for physical self-consumption. The remaining energy consumption is billed to the users by the landlord who subsequently settles the payments with the retailer. However, members see a direct discount on their bills as the energy supplied is billed at a reduced price. Therefore, even if no direct transactions among the peers occurs, the physical nature of the model allows community members to see a direct benefit in their energy bills due to the discount required by the law.

The REC concept varies a lot among Member States due to the different ways in which the RED II directive has been transposed.



(a) Virtual model

(b) Physical model

Fig. 1. – Graphical representation of commercial and physical energy flows in REC virtual (a) and physical (b) models.

Table 2
Summary of main differences between virtual and physical energy sharing models.

	Virtual model	Physical model
Direct benefits on members' bills	**No,** all metered energy is billed by the retailer at the retailer's prices	**Yes,** metered energy is partially billed by other parties at a different price
Connection grid	Public	Public or private
Incentivization scheme	A posteriori reimbursement	Internal price
Member States	Italy, the Netherlands	Portugal, Spain, Germany

Despite the different ways in which the either virtual or physical model work in each Member State, the main difference does not rely in their specific operating rules, but in the presence or absence of a direct link between the sharing benefits and the members' bills, as shown in Table 2. Indeed, in physical models, not all metered energy is billed at the retailer's prices, but part of it can be valorised at a different price; thus, the sharing benefit is directly accounted in each member's bill. On the other hand, in virtual models, the sharing benefit comes as a posteriori reimbursement that can be redistributed among the members; thus, no accounting link between the members' bills and the sharing benefits is present. Therefore, the way in which benefits are accounted for in members' bills represents the determinant characteristic defining the virtual or physical nature of the energy sharing model. Hence, it is possible to build the policy discussion by taking two examples of regulations, one for each model, while generalizing the results obtained. In the rest of this section, the legislative background of two illustrative countries, Italy and Portugal, is presented in more detail. The reason behind the selection of these two countries is tied to the specular way in which they have transposed the RED II directive, with Italy adopting a virtual model and Portugal adopting a physical one.

2.1. Italy

The Italian regulation relies on an energy sharing model that can be defined as virtual. Under this model, the energy shared within the community is virtually exchanged, meaning that it is not directly discounted from the members' energy bills. Members continue to be billed for their total energy withdrawal and injection, measured at their corresponding meters, regardless of whether the energy comes from the grid or the community. A posteriori, the GSE (Gestore dei Servizi Energetici, an Italian public entity) monthly computes the energy shared by community members, using the members' validated measurements of energy withdrawal and injection. The energy shared is computed as the hourly minimum between the energy withdrawal and injection of the whole community (Repubblica Italiana, 2020), as shown in (2.2) in Section 3.2.1. This computation is essential since the Italian government recognises to the community a reimbursement for the collective self-consumption that is proportional to the energy shared. The money is given to the community manager, and not directly to the single members, who has the responsibility to manage it as previously chosen by the REC. The money can be either distributed among the members or reinvested in the community. Since the energy exchange in the community is always kept virtual, the community members need to be connected to the public distribution grid (Repubblica Italiana, 2021), in particular under the same primary substation and the same market zone (note that Italy has several bidding zones corresponding to different market zones) (ARERA Autorità di Regolazione per Energia Reti e Ambiente, 2022).

The incentive recognised to the REC includes two components. The first is a reimbursement of the variable component of the transmission network charges, in a cost-reflective usage of the network (ARERA Autorità di Regolazione per Energia Reti e Ambiente, 2020). The second is a feed-in-premium, called TIP, initially set at 110 €/MWh for 20 years (Ministero dello Sviluppo Economico, 2020). Since 2023, the incentive scheme has changed by introducing a novel method for setting the TIP level, as shown in Tables 3 and 4 (Ministro dell'Ambiente e della Sicurezza Energetica, 2023). The incentive level is tied to the current value of the zonal market price p_Z and it varies according to the installed capacity P_n of the REC plants. Additionally, the incentive scheme includes the possibility to correct the TIP according to the community's geographical location. This is done to valorise the energy sharing, that generally comes from PV plants, in the regions of Northern Italy, where the irradiation is generally lower than in the South.

Table 3
Base incentive according to REC size and zonal price.

P_n	Unit	TIP	CAP	Unit
≤ 200	kW	$80 + \max(0, 180 - p_Z)$	120	€/MWh
200–600	kW	$70 + \max(0, 180 - p_Z)$	110	€/MWh
≥ 600	kW	$60 + \max(0, 180 - p_Z)$	100	€/MWh

Table 4
Correctional coefficient according to REC geographical location.

Location	Premium	Unit
North of Italy	+10	€/MWh
Centre of Italy	+4	€/MWh
South of Italy and islands	+0	€/MWh

2.2. *Portugal*

The Portuguese regulation relies on an energy sharing model that can be defined as physical. In this model, the energy shared within the community is exchanged among members through direct commercial transactions. Therefore, the members see a direct discount on their energy bills due to collective self-consumption. In particular, the available generation within the community is allocated among members according to ACs that can be either fixed for a specific period (ERSE Entidade Reguladora dos Serviços Energéticos, 2021), proportional to the members' energy consumption (ERSE Entidade Reguladora dos Serviços Energéticos, 2021) or dynamic, computed after knowing the metered values of members' consumption and generation, according to rules agreed upon by the community members (Presidência do Conselho de Ministros, 2022). Members are therefore billed by their supplier just for their energy withdrawal reduced by their energy allocation. The surplus is instead aggregated and managed by the EGAC (Entidade Gestora do Autoconsumo Coletivo, the community manager). To share energy, members can use a distribution grid that can be either private or public. In case the public distribution grid is adopted, members that buy community energy must pay the grid access tariff on the energy purchased inside the community. However, this tariff is reduced with respect to the one applied by the retailer on the energy supplied, in a cost-reflective usage of the network. In particular, it is defined as the access fee of the voltage level to which the members are connected, discounted by the higher voltage level access fees (ERSE Entidade Reguladora dos Serviços Energéticos, 2020). Finally, to belong to the same energy community, members need to comply with the proximity rules shown in Table 5 (Presidência do Conselho de Ministros, 2022).

3. Methodology

In this section, the modelling framework adopted for the policy analysis is introduced. In particular, the proposed methodology is based on the flowchart shown in Fig. 2 and it is applied to the regulations analysed in Section 2, namely Italy and Portugal. As anticipated, the reason behind the choice of these two countries relies on the specular way (virtual vs physical) in which they have transposed the RED II directive into their national legislations. The very initial step consists in the optimization of users' individual behaviours when they act alone. This step computes the maximum energy bill that can be imputed to every user to define a baseline for their energy costs in the following steps. After that, a further optimization is carried out when members are gathered in a community. The community benefit is distributed among the members starting from this solution and according to the methods required by the corresponding energy sharing model. In Italy, sharing methods are adopted to redistribute the incentive. In Portugal, the internal transactions are settled at an internal price computed through *ad-hoc* pricing algorithms. In case any member experiences a negative benefit concerning its individual energy bill, therefore incurring uncovered additional costs, consumer protection mechanisms are adopted to avoid these losses. The influence of the regulation on the optimization of battery size and configuration is also investigated in addition to the findings derived from community optimization.

Table 5
Proximity requirements for community members and community power plants.

Voltage level	Proximity
LV	Distance <2 km or same secondary substation
MV	Distance <4 km and same primary substation
HV	Distance <10 km and same substation
VHV	Distance <20 km and same substation

3.1. *Individual optimization*

The first step consists of the individual optimization of each member's operation to define the energy assets management when members are not acting together. Each member is characterized by its own energy demand $E^{C}_{i,t}$ and energy production $E^{G}_{i,t}$ due to behind-the-meter plants. Members can instantaneously self-consume the energy produced by their own plant. However, in case the production is not enough to cover the users' demand, members can withdraw energy $E^{WITHD}_{i,t}$ from the grid, being supplied by their retailer, or they can discharge energy $E^{BD}_{i,t}$ from their own behind-the-meter battery. On the other hand, in case of an exceed of production, the additional energy $E^{BC}_{i,t}$ can be charged into the battery for later use or the energy $E^{INJ}_{i,t}$ can be injected and sold to the distribution network. The energy withdrawal $E^{WITHD}_{i,t}$ and injected $E^{INJ}_{i,t}$ are valorised at the retailer's buying $\lambda^{BUY}_{i,t}$ and selling $\lambda^{SELL}_{i,t}$ prices, respectively. These include all the network and general charges applicable by the retailer to end-users. In this first step, each member i considers its own objective function, as shown in eq. (1.1), and its constraints. In each time period, the selling revenues of injected energy $E^{INJ}_{i,t}$ are discounted from the costs of withdrawal electricity $E^{WITHD}_{i,t}$, then the sum of all net values (i.e. the total energy costs of member i in the overall time horizon) is minimised. The adopted formulation is a revisitation of the first-step optimization problem mathematically formulated in (Rocha et al., 2023). The key departure from the original work involves the omission of self-consumption that is not behind-the-meter. This modification ensures that the proposed optimization model remains adaptable to any regulatory framework, as it does not account for country-specific rules regarding self-consumption along the distribution network.

$$\min\sum_{t\in T}E^{WITHD}_{i,t}\cdot\lambda^{BUY}_{i,t}-E^{INJ}_{i,t}\cdot\lambda^{SELL}_{i,t},\quad\forall i\in\{1,\dots,N\}\tag{1.1}$$

The objective function is subjected to several constraints. In particular, constraint (1.2) represents the user's energy balance, while constraint (1.3) computes the member's net energy metered $E^{MET}_{i,t}$. Constraints (1.4)–(1.7) refer to the battery operation. Constraint (1.4) defines the energy stored in the battery $E^{B}_{i,t}$ as a function of the energy previously stored that can be incremented or decremented by charging or discharging. Constraint (1.5) defines the state of charge of the battery $SOC_{i,t}$, while constraint (1.6) limits the state of charge reachable by the storage during its normal operation. Lastly, constraint (1.7) limits the charging and discharging power.

$$\mathrm{E}^{\mathrm{WITHD}}_{\mathrm{i,t}}=\mathrm{E}^{\mathrm{MET}}_{\mathrm{i,t}}+\mathrm{E}^{\mathrm{INJ}}_{\mathrm{i,t}},\quad\forall i\in\{1,\dots,N\},\forall t\in\{1,\dots,T\}\tag{1.2}$$

$$E^{MET}_{i,t}=E^{C}_{i,t}+E^{BC}_{i,t}-E^{G}_{i,t}-E^{BD}_{i,t}\quad\forall i\in\{1,\dots,N\},\forall t\in\{1,\dots,T\}\tag{1.3}$$

$$E^{B}_{i,t}=E^{B}_{i,t-1}+E^{BC}_{i,t}\cdot\eta_C-\frac{E^{BD}_{i,t}}{\eta_D}\quad\forall i\in\{1,\dots,N\},\forall t\in\{1,\dots,T\}\tag{1.4}$$

$$SOC_{i,t}=\frac{E^{B}_{i,t}}{C_i}\quad\forall i\in\{1,\dots,N\},\forall t\in\{1,\dots,T\}\tag{1.5}$$

$$SOC_{min}<SOC_{i,t}<SOC_{max}\quad\forall i\in\{1,\dots,N\},\forall t\in\{1,\dots,T\}\tag{1.6}$$

$$\frac{E^{BC}_{i,t}}{\Delta t},\frac{E^{BD}_{i,t}}{\Delta t}\le P_{max}\quad\forall i\in\{1,\dots,N\},\forall t\in\{1,\dots,T\}\tag{1.7}$$

The decision variables are the energy charged $E^{BC}_{i,t}$ and discharged $E^{BD}_{i,t}$

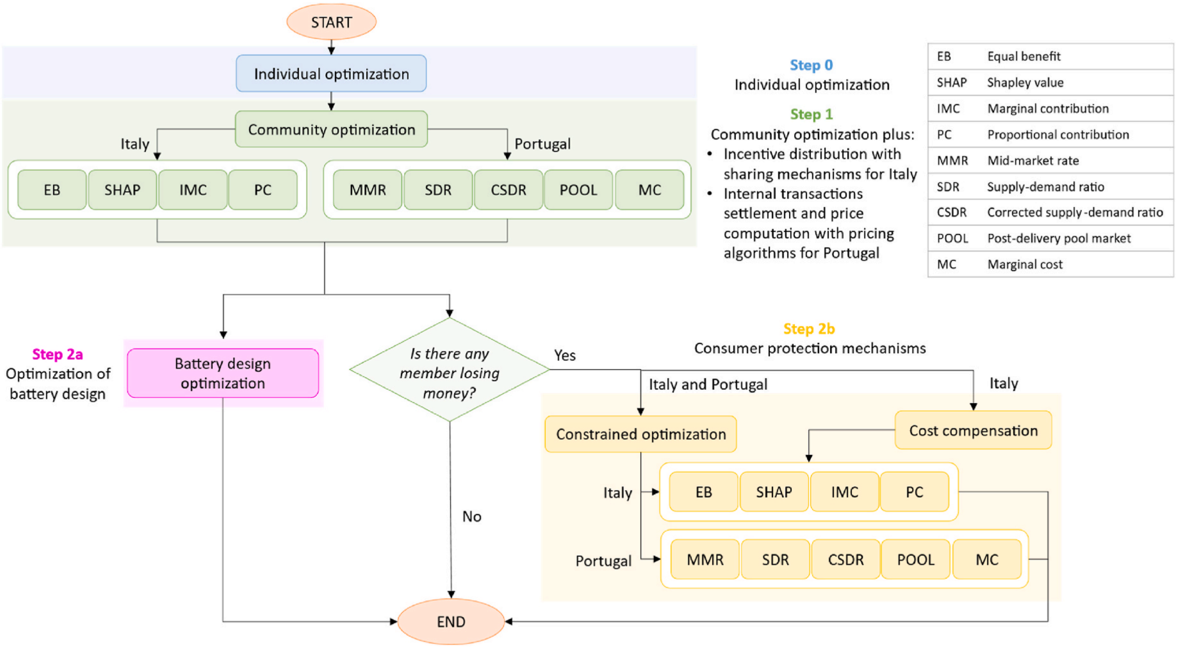


Fig. 2. – Proposed multi-step methodology, for the assessment of the Italian and Portuguese regulatory frameworks. It includes individual optimization (step 0), community optimization and benefit redistribution (step 1), battery design optimization (step 2a) and consumer protection mechanisms in case of members' losses (step 2b).

by members' batteries. The outcome of the problem is the energy costs $Bill_i^{IND}$, sustained by each member in the overall period, represented by the result of eq. (1.1).

3.2. *Community optimization*

The second step is represented by the community optimization. By assuming that users are now gathered in a community, this stage aims at defining the optimal asset management when energy exchanges among community members is included. Clearly, this stage must consider the peculiarities of the country's regulatory framework. Therefore, different regulatory frameworks require distinct community optimization models, which are described in Sections 3.2.1 and 3.2.2, for Italy and Portugal, respectively.

3.2.1. *Italy*

Within the Italian context, the objective function minimises the community energy costs within the overall time horizon and including all members, as shown in eq. (2.1). In each time period, the sum of all members' net energy costs, computed as in the individual optimization, is discounted of the corresponding incentive, as requested by the virtual model which does not allow a direct benefit in the members' bills. Therefore, users continue to be billed by the retailer for the total energy withdrawn $E_{i,t}^{WITHD}$ and injection $E_{i,t}^{INJ}$, while the incentive $(TIP_t + TRAS_E)$ is applied to the overall energy shared E_t^{SH}.

$$\min\sum_{t\in T}\sum_{i\in N}\left(E_{i,t}^{WITHD}\cdot\lambda_{i,t}^{BUY}-E_{i,t}^{INJ}\cdot\lambda_{i,t}^{SELL}\right)-E_t^{SH}\cdot(TIP_t+TRAS_E) \tag{2.1}$$

The objective function is subjected to several constraints. Constraints (1.2)–(1.7) still hold true, but the community constraint (2.2) is added to calculate the hourly volume of energy shared E_t^{SH} within the community.

$$E_t^{SH}=\min\left(\sum_{i\in N}E_{i,t}^{WITHD},\sum_{i\in N}E_{i,t}^{INJ}\right)\quad\forall t\in\{1,\dots,T\} \tag{2.2}$$

Besides the energy withdrawal $E_{i,t}^{WITHD}$ and injection $E_{i,t}^{INJ}$ of each member, which affects the energy shared E_t^{SH} among all members, the decision variables of this stage include the energy charged $E_{i,t}^{BC}$ and discharged $E_{i,t}^{BD}$ by members' batteries. Finally, starting from these results, it is possible to determine the members' benefit for staying in the community with respect to acting alone. The computation, as shown in eq. (2.3) and eq. (2.4), requires distributing the community incentive among the members by means of sharing indexes (SI). Those indexes are calculated by means of dedicated sharing mechanisms as shown in Table 6.

$$Bill_i^{COM}=\sum_{t\in T}E_{i,t}^{WITHD}\cdot\lambda_{i,t}^{BUY}-E_{i,t}^{INJ}\cdot\lambda_{i,t}^{SELL}\quad\forall i\in\{1,\dots,N\} \tag{2.3}$$

$$Benefit_i=Bill_i^{IND}-\left(Bill_i^{COM}-SI_i\cdot\sum_{t\in T}Incentive_t\right)\quad\forall i\in\{1,\dots,N\} \tag{2.4}$$

3.2.2. *Portugal*

Within the Portuguese context, the objective function still minimises the community energy costs within the overall period and including all members, as shown in eq. (2.5). However, unlike the Italian case, the physical model allows discounting the energy exchanged directly from the members' bills. This leads to a divergence between users' physical and commercial flows that was not present in the individual and Italian models. In fact, the physical flows are represented by the users' energy withdrawal $E_{i,t}^{WITHD}$ and injection $E_{i,t}^{INJ}$. In the individual and Italian models, those two variables coincide with the energy accounted by the retailer for the users' bills computation. Instead, in the Portuguese model, part of this energy, the energy $E_{i,t}^{PUR}$ purchased from the community and the energy $E_{i,t}^{SALE}$ sold in the community, is settled by means of internal transactions at the community price. The remaining part, the energy supplied $E_{i,t}^{SUP}$ and the energy surplus $E_{i,t}^{SUR}$, are accounted by the retailer for the bill computation. Since the internal transactions compensate each other at community level, just the retailer's commercial flows $E_{i,t}^{SUP}$ and $E_{i,t}^{SUR}$ appear in the objective function. Therefore, in each time period and for each member, the net energy costs are computed by discounting the selling revenues of surplus energy $E_{i,t}^{SUR}$ from the energy costs of supplied electricity $E_{i,t}^{SUP}$. Buyers should also pay

Table 6
Analysed sharing mechanisms for the Italian regulatory framework.

Name		Sharing index	Ref
Equal benefit	EB	The benefit is shared equally among all the members. $SI_i = \frac{1}{N}$	Li et al. (2021)
Marginal contribution	IMC	The benefit is shared according to the marginal contribution of each member. This is computed as the difference between the community benefit of community S when member *i* participates and the community benefit when the same member is not part of the configuration. $MC_i = Benefit^{COM}_{S\cup i} - Benefit^{COM}_{S}$ $Benefit^{COM}_{S} = \sum_{i\in S} Bill^{IND}_i - \left(\sum_{i\in S} Bill^{COM}_i - \sum_{t\in T} Incentive_t\right)$ $SI_i = \frac{MC_i}{\sum_{i\in N} MC_i}$	Casalicchio et al. (2022)
Shapley value	SHAP	The benefit is shared according to the Shapley value of each member. It is computed by considering their marginal contribution in all possible coalitions multiplied by a weight that indicates the probability of the members to join the coalition in that order. The marginal contribution is computed in relation to the community benefit as in the IMC. $SV_i = \sum \frac{S!(N-S-1)!}{N!} \cdot MC_i$ $SI_i = \frac{SV_i}{Benefit^{COM}}$	Moncecchi et al. (2020)
Proportional contribution	PC	The benefit is firstly allocated equally among the groups of buyers and sellers, then it is shared proportionally to the member's energy injection or withdrawal. $SI_i = 0,5 \cdot \frac{\sum_{t\in T} E^{INJ}_{i,t}}{\sum_{i\in N}\sum_{t\in T} E^{INJ}_{i,t}} + 0,5 \cdot \frac{\sum_{t\in T} E^{WITHD}_{i,t}}{\sum_{i\in N}\sum_{t\in T} E^{WITHD}_{i,t}}$	Fioriti et al. (2023)

an access tariff λ^{GRID}_t on the shared energy $E^{SH}_{i,t}$ that flows across the public grid, according to the specific voltage level exploited. Then, the sum of all net values (i.e. total energy cost in the overall time horizon) is minimised.

$$\min \sum_{t\in T}\sum_{i\in N} E^{SUP}_{i,t} \cdot \lambda^{BUY}_{i,t} - E^{SUR}_{i,t} \cdot \lambda^{SELL}_{i,t} + E^{SH}_{i,t} \cdot \lambda^{GRID}_t \tag{2.5}$$

The objective function is subjected to several constraints. Constraints (1.3)–(1.7) still hold true, while constraint (1.2) is modified to include the internal exchanges, as shown in (2.6). Constraint (2.7) defines the energy $E^{SH}_{i,t}$ shared by each member through the public grid, while constraint (2.8) ensures the energy balance within the community. Lastly, constraint (2.9) prevents the presence of negative ACs which are not allowed by the regulation yet.

$$E^{SUP}_{i,t} + \left(E^{PUR}_{i,t} - E^{SALE}_{i,t}\right) = E^{MET}_{i,t} + E^{SUR}_{i,t} \quad \forall i \in \{1,\dots,N\}, \forall t \in \{1,\dots,T\} \tag{2.6}$$

$$E^{SH}_{i,t} = \min\left[\max\left(E^{MET}_{i,t}, 0\right), \max\left(E^{PUR}_{i,t} - E^{SALE}_{i,t}, 0\right)\right] \quad \forall i \in \{1,\dots,N\}, \forall t \in \{1,\dots,T\} \tag{2.7}$$

Table 7
Analysed pricing algorithms for the Portuguese regulatory framework.

Name		Internal price	Ref
Mid-market rate	MMR	The internal price is computed as the average between the retailer's buying and selling prices. $\lambda^{p2p}_t = \frac{\lambda^{BUY}_t + \lambda^{SELL}_t}{2}$	Mello et al. (2023)
Supply-demand ratio	SDR	The internal price depends on the amount of available generation, which is indicated by the SDR index. If the index is between 0 and 1, less generation than demand is present in the community, therefore the internal price is placed between the retailer's buying and selling price. On the other hand, if the index is higher than 1, more generation than demand is available, therefore the internal price is set at the retailer's selling price. $SDR_t = \frac{\sum_{i=1}^{N_i} E^{INJ}_{i,t}}{\sum_{i=1}^{N_i} E^{WIDTH}_{i,t}}$ $\lambda^{p2p}_t = \frac{\lambda^{BUY}_t \cdot \lambda^{SELL}_t}{\left(\lambda^{BUY}_t - \lambda^{SELL}_t\right) \cdot SDR_t + \lambda^{SELL}_t}$	Mello et al. (2023)
Corrected supply demand ratio	CSDR	The internal price is defined as in the SDR but, when the SDR index is higher than 1, the internal price is not set at the retailer's selling price, but to a higher price. This is done to favour the internal transaction also under these conditions. In this case, the internal price depends on a compensation factor λ. $0 < \lambda < \lambda^{BUY}_t - \lambda^{SELL}_t$ $\lambda^{p2p}_t = \frac{\lambda^{BUY}_t \cdot \left(\lambda^{SELL}_t + \lambda\right)}{\left(\lambda^{BUY}_t - \lambda^{SELL}_t - \lambda\right) \cdot SDR_t + \lambda^{SELL}_t + \lambda}$	Mello et al. (2023)
Post-delivery pool market	POOL	The internal price is computed with a market-based approach and it represents the clearing price. This market works like a pool market, but the energy traded has already been consumed or produced. Buyers and sellers should bid at their opportunity cost, which is their retailer price λ^{BUY}_t and λ^{SELL}_t.	Mello et al. (2023)
Shadow price	MC	The internal price is defined as the marginal costs of the system.	

$$\sum_{i\in N} E^{PUR}_{i,t} = \sum_{i\in N} E^{SALE}_{i,t} \quad \forall i \in \{1,\dots,N\}, \forall t \in \{1,\dots,T\} \tag{2.8}$$

$$E^{SALE}_{i,t} - E^{PUR}_{i,t} \le \max\left(-E^{MET}_{i,t}, 0\right) \quad \forall i \in \{1,\dots,N\}, \forall t \in \{1,\dots,T\} \tag{2.9}$$

The decision variables are still the energy charged $E^{BC}_{i,t}$ and discharged $E^{BD}_{i,t}$ by members' batteries. The outcomes consist of the energy supplied $E^{SUP}_{i,t}$ and surplus $E^{SUR}_{i,t}$ of each member when participating in the community, and their energy shared $E^{SH}_{i,t}$. Finally, starting from these results, it is possible to determine the members' benefit for staying in the community with respect to acting alone. The computation, as shown in eq. (2.10) and eq. (2.11), requires the definition of an internal price λ^{p2p}_t by means of dedicated pricing algorithms as shown in Table 7.

$$Bill_i^{COM} = \sum_{t\in T} E_{i,t}^{SUP}\cdot\lambda_{i,t}^{BUY} - E_{i,t}^{SUR}\cdot\lambda_{i,t}^{SELL} + E_{i,t}^{SH}\cdot\lambda_t^{GRID} + \left(E_{i,t}^{PUR} - E_{i,t}^{SALE}\right)\cdot\lambda_t^{p2p} \quad \forall i \in \{1,\dots,N\} \tag{2.10}$$

$$Benefit_i = Bill_i^{IND} - Bill_i^{COM} \quad \forall i \in \{1,\dots,N\} \tag{2.11}$$

3.3. Consumer protection mechanisms

The last step guarantees that no member loses money by participating in the community, therefore the user's energy costs resulting from the community optimization must be lower or at least equal to its individual costs. Indeed, when the community is optimized, some members may experience additional costs concerning their individual behaviour. This may happen because the request of a different assets operation to some members may lower the community costs while increasing those of these users. However, if this effort is not adequately compensated, a consumer protection mechanism should be introduced.

The capacity to safeguard members' economic interests strongly depends on the inherent regulatory framework. In particular, in a virtual model based on an ex-post reimbursement (the Italian one), it is necessary to implement fair strategies to share the community incentive among its members. On the other hand, in a regulatory framework based on dynamic ACs (the Portuguese one), the attention is focused on defining a fair price for internal transactions. In this analysis, two distinct approaches are considered to ensure a positive benefit for all members, as described below.

3.3.1. Constrained community optimization

The consumer protection mechanism described in this section can be applied to both Italy and Portugal by making small changes. For the Portuguese case, the constrained optimization problem is based on the formulation published in (Rocha et al., 2023). It includes a further constraint, shown in (3.1), with respect to the community problem described in Section 3.2.2, to ensure that no member's bill is higher than its individual cost $Bill_i^{IND}$ when participating in the community. The internal price λ_t^{p2p} needs to be calculated by using one of the aforementioned pricing algorithms (see Table 7) before running the constrained optimization problem.

$$\sum_{t\in T} E_{i,t}^{SUP}\cdot\lambda_{i,t}^{BUY} - E_{i,t}^{SUR}\cdot\lambda_{i,t}^{SELL} + E_{i,t}^{SH}\cdot\lambda_t^{GRID} + \left(E_{i,t}^{PUR} - E_{i,t}^{SALE}\right)\cdot\lambda_t^{p2p} \le Bill_i^{IND} \quad \forall i \in \{1,\dots,N\} \tag{3.1}$$

A similar logic can be applied to the Italian case by considering its regulatory specificities. The constraint shown in (3.2) is added to the community problem described in Section 3.2.1. To do so, the sharing indexes (see Table 6) must be computed before running the constrained optimization problem, based on the results of the community solution.

$$\sum_{t\in T}\left(E_{i,t}^{WITHD}\cdot\lambda_{i,t}^{BUY} - E_{i,t}^{INJ}\cdot\lambda_{i,t}^{SELL}\right) - SI_i\cdot\sum_{t\in T} E_t^{SH}\cdot\left(TIP_t + TRAS_E\right) \le Bill_i^{IND} \quad \forall i \in \{1,\dots,N\} \tag{3.2}$$

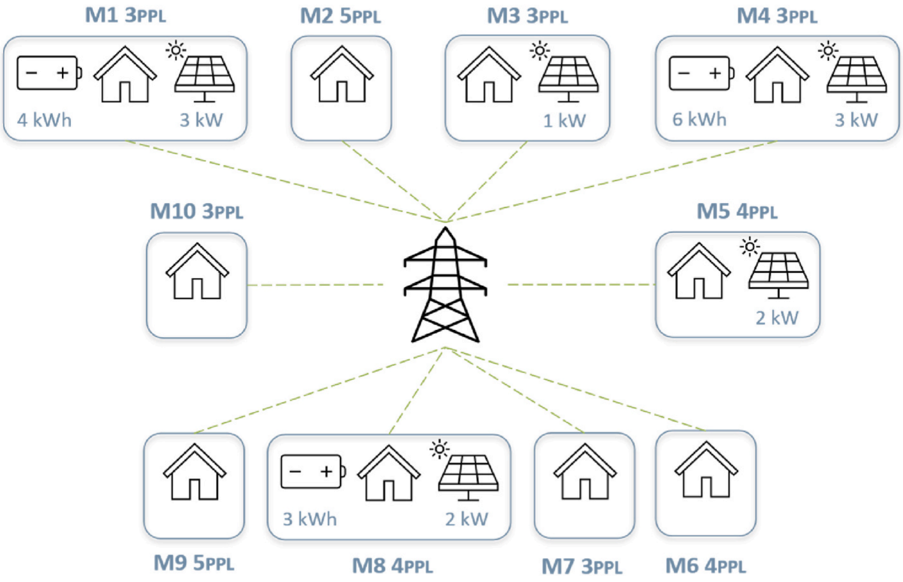


Fig. 3. – Structure of the 10-member REC considered for the case study.

Table 8
Information on consumption, electrification level and equipment of REC members.

Id	Number of residents	Annual load [kWh]	Electrified consumption	PV [kW]	Battery [kWh]
M10	3	1713	Traditional	0	0
M7	3	2011	Traditional	0	0
M1	3	2127	Traditional plus cooling	3	4
M3	3	2714	Traditional plus cooling and induction cooker	1	0
M4	3	3743	Traditional plus cooling, induction cooker and electric heating	3	6
M6	4	2489	Traditional	0	0
M5	4	3617	Traditional plus cooling and induction cooker	2	0
M8	4	4126	Traditional plus cooling, induction cooker and electric heating	2	3
M9	5	2749	Traditional	0	0
M2	5	5828	Traditional plus cooling, induction cooker and electric heating	0	0

3.3.2. *Sharing methods with cost compensation*

An alternative consumer protection mechanism to distribute the incentive granted in the Italian context is proposed here. Firstly, the additional costs sustained by the members due to their participation in the community, defined as shown in eq. (3.3), are compensated with an integration revenue given just to the members that incur additional costs, compared to their individual behaviour. Then, the remaining incentive (if any) is distributed among the members according to their sharing indexes, as shown in eq. (3.4). This approach is based on the redistribution strategy developed in (Stentati et al., 2023), but generalises it by including the possibility to share the remaining part of the incentive with different sharing methods, and not only proportionally to the members' energy injection and withdrawal.

$$Cos\,t_i^{ADD} = Bill_i^{COM} - Bill_i^{IND} \quad \forall i \in \{1, \dots, N\} \tag{3.3}$$

$$Benefit_i = Cos\,t_i^{ADD} + SI_i \cdot \left(\sum_{t \in T} Incentive_t - \sum_{i \in N} Cos\,t_i^{ADD} \right) \quad \forall i \in \{1, \dots, N\} \tag{3.4}$$

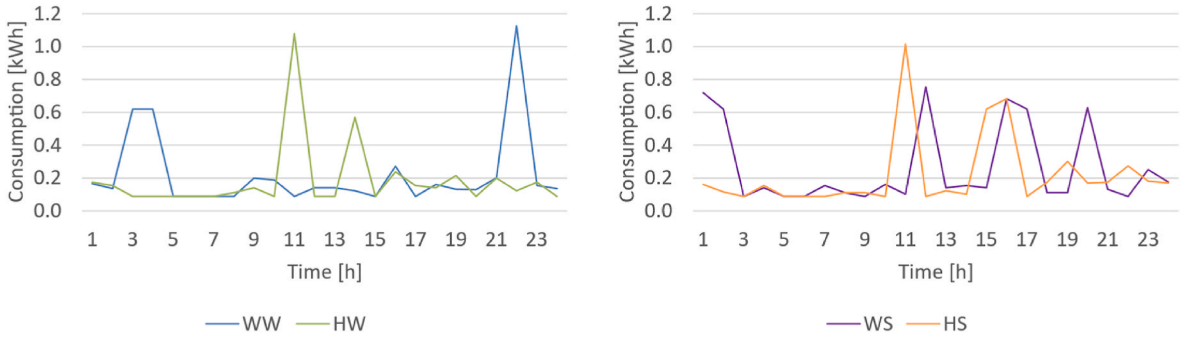
4. Case study, simulation and results

An illustrative case study, described in Section 4.1, is adopted to assess the impact of the analysed regulations from a policy perspective through the proposed methodology. Results are presented in sections 4.2, 4.3 and 4.4. All simulations were carried out on a daily horizon with hourly resolution. Algorithms were implemented in Python, using the modelling language Pyomo (Pyomo Development Team, 2023) and the open-source COIN-OR Branch-and-Cut as a MILP solver (COIN-OR Foundation, 2020) on an Intel® Core™ i7-7500U CPU@2.70GHz processor with 8 GB RAM.

4.1. *Case study description*

The reference case study consists of a 10-members REC connected through the public LV distribution grid, as shown in Fig. 3. It includes three types of consumers: those equipped with both behind-the-meter PV panels and storage, those equipped with a behind-the-meter PV plant, and those that only consume. Users are classified by the number of residents in the house and their annual load consumption, as shown in Table 8. The different levels of consumption are seen as an indicator of the electrification level in the corresponding homes. The traditional electrification level, taken as a reference, refers to a situation in which the heating and cooking consumptions are not electrified and no cooling system is installed (Caldera et al., 2018). More advanced electrification levels include the installation of electric heating (through heat pumps) or induction cookers.

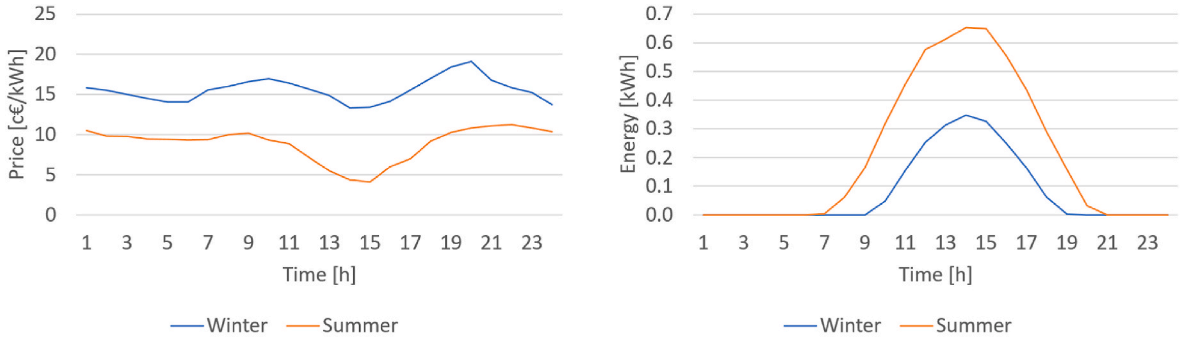
The community is analysed through an entire year by performing the aforementioned algorithms on four day-types: working-winter (WW), holiday-winter (HW), working-summer (WS) and holiday-summer (HS). This distinction has been included to consider the effects of the relation between the users' load curve and their home occupancy (working vs holiday) and the one between the PV production, zonal price and irradiation (winter vs summer) (Trotta, 2020). Consumption curves of users are defined starting from profiles that come from an elaboration of Politecnico di Milano on real meters' data. The data is not publicly available, but results from several DSOs' past analysis on residential clients' consumptions. The original dataset included the yearly consumption with hourly resolution of 100 users. Among them, ten users were picked, trying to differentiate as much as possible between the number of residents in the house and the total yearly consumption. Each daily profile has been then classified in one of the four mentioned categories by means of labels. The labelling is performed by considering



(a) Winter days.

(b) Summer days.

Fig. 4. – Consumption profiles resulting from clustering of user M1 during winter (a) and summer (b) days.



(a) Zonal price. (b) Output power of 1 kW PV plant.

Fig. 5. – Profiles of zonal price (a) and PV production (b) considered for the analysis during winter and summer periods.

Table 9
Information on the retailer buying price of REC members.

Energy component		Network charges	System charges	Unit	User
F1	F23				
27.64	26.64	0.943	2.9658	c€/kWh	M4
22.20					M1, M6
19.00					M7
18.00					M3, M9, M10
p_Z					M2, M5, M8

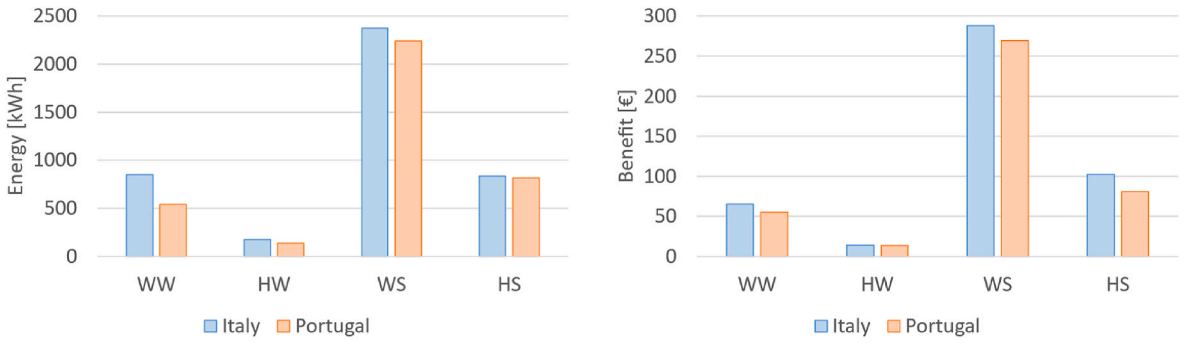
months from October to March as winter and months from April to September as summer. Moreover, bank holidays are included in the holiday category, despite their actual day. Then, one consumption profile for each user and each day-type is picked. This profile is the one minimising the distance from all the others in the same day-type for the same user and it has been selected by applying the k-medoids technique, which is commonly adopted to perform clustering (McLoughlin et al., 2015). Fig. 4 represents an illustrative sample of consumption profiles in the considered day-types. The relationship between day-type and occupancy is more evident during winter, in which the consumption is mostly concentrated in the morning and in the evening during working days and in the middle of the day during holidays. During summer, two more consumption spikes occur in the middle of working days, probably manifesting the additional cooling system consumption.

PV production is instead differentiated according to the season and computed as shown in eqs. (4.1) and (4.2). Temperature T_{amb} and solar radiation J_g, coming from ARPA measurements in the city of Milan (Italy) during 2023 (ARPA Agenzia Regionale per la Protezione dell'Ambiente, 2023), refer to two specific days. The chosen days, one in February and one in August, were arbitrarily taken to be representative of the overall winter and summer periods, respectively. The PV production curve is computed taking 1 kW installed power as reference, starting from data of a representative PV module of the manufacturer FuturaSun (2022). Finally, to maintain the relationship between the PV penetration and the market price, the Northern Italy zonal price of the same days has been considered for this analysis (GME Gestore Mercati Energetici, 2023). Fig. 5 shows the relation between the zonal price p_Z and the PV penetration. During winter, when the PV penetration is lower, the zonal price results to be flatter through the day. On the other hand, it drops in summer during the middle of the day due to the presence of high PV penetration.

$$T_{cell} = T_{amb} + (NOCT - 20)\cdot J_g/800 \tag{4.1}$$

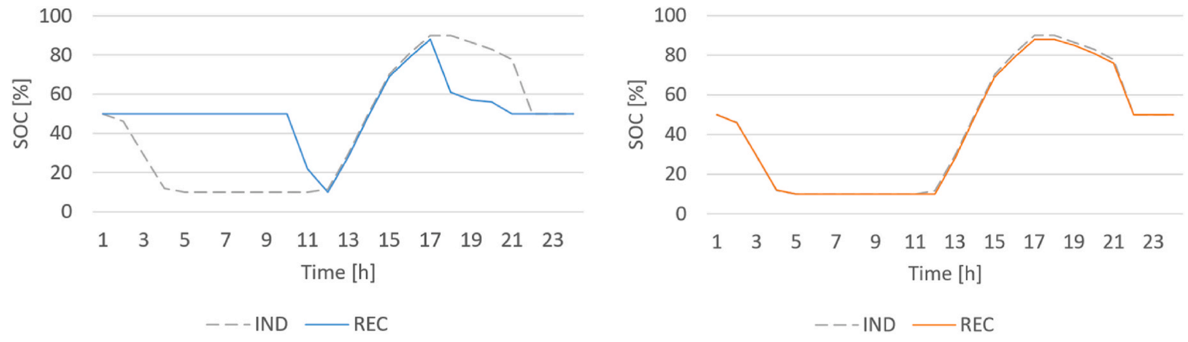
$$P_{out} = J_g \cdot A_{1kW} \cdot \eta_{PV}\cdot\left[1 - \left(1000 - J_g\right)\cdot \rho_{irr} - \left(T_{cell} - T_{STC}\right)\cdot \rho_T\right] \tag{4.2}$$

Finally, in every scenario, every member sells energy to the grid at the same price, that corresponds to the zonal price, but they are characterised by different buying prices, as shown in Table 9. The energy component corresponds to real-life electricity retailer's contracts for domestic users (ENEL Energia per il Mercato Libero, 2023), which may vary from flat tariffs to time-of-use tariffs (F1 and F23), or to real-time tariffs based on the zonal price p_Z. Network and system charges for domestic users are defined by the Italian regulator (ARERA Autorità di Regolazione per Energia Reti e Ambiente, 2023). The same data are applied to the Portuguese simulation to ensure comparability of the results. The Italian network charges' reimbursement $TRAS_E$ is assumed



(a) Energy shared. (b) Community benefit.

Fig. 6. – Amount of energy shared (a) and community benefit (b) in community optimization under the Italian and Portuguese regulations for period-type.



(a) Italian virtual model.

(b) Portuguese physical model.

Fig. 7. – Battery behaviour of user M1 in the WW scenario under the Italian (a) and Portuguese (b) regulations.

equal to 0.848 c€/kWh (ARERA Autorità di Regolazione per Energia Reti e Ambiente, 2021), while the access tariff to be paid on the energy shared in the Portuguese case is computed as the difference between the Italian network charges and the $TRAS_E$ component, to ensure again uniformity and comparability. Other assumptions include the charging/discharging battery power, limited to 1 kW with equal charging and discharging efficiencies of 90% for all storage systems, as also assumed by (Rocha et al., 2023). Lastly, the SOC of the batteries is limited between 10% and 90% during normal operations, while a SOC equal to 50% is assumed as the initial and final point in the simulation period.

4.2. Community optimization

This section illustrates the effects of the regulation on the results obtained from the community optimization in both Italy and Portugal. Fig. 6 represents the different levels of energy shared and community benefit in both countries. The comparatively lower level of community benefit in Portugal, as opposed to Italy, may be attributed to two key factors: (i) the users' tariffs and (ii) the level of the Italian TIP incentive. The amount of energy shared within the community is linked to how the objective function is formulated, which directly depends on the country's regulation. In general, the energy shared is maximised if the additional costs coming from the different assets management are completely covered by the community revenues. In the Italian regulation, this ability is tied to the incentive level that should be sufficiently high to cover those costs. In the Portuguese model, the advantage of sharing energy is instead a combination of the buyers' and sellers' welfare that trade energy at an intermediated price. Since at community level all internal transactions compensate each other, the advantage is therefore linked to the difference between the buyers' retailer buying price and sellers' retailer selling price. However, if those tariffs are very close to each other, as in the considered case study, revenues are not able to cover the potential additional costs. This leads to an assets management that causes a significant reduction in the energy potentially shared which is translated, in turn, into a reduction of the community benefit.

Thisa behaviour can be easily seen in Fig. 7, in which the battery behaviour of user M1 is shown in the WW days. User M1's battery changes completely its behaviour under the Italian regulation. In fact, the usage for individual self-consumption is limited to the individual case as the battery favours the community by increasing the energy sharing. This is done mostly by discharging the battery to cover the community load. On the other hand, the behaviour of M1's battery does not significantly change under the Portuguese regulation with respect to the individual case. As explained, this happens because the potential costs that would be incurred for a change in the battery behaviour would not be covered by an adequate amount of revenues coming from energy sharing. Therefore, M1 does not change its battery behaviour and this causes a reduction in the energy shared, as depicted in Fig. 6. From the illustrated results, it is possible to observe that the regulatory framework has a strong impact on the community management, particularly on three main variables: (i) the energy shared within the community, (ii) the overall community benefit and (iii) the flexibility.

4.3. Battery design optimization

Since it was observed that the regulatory framework influences the flexibility provided by the batteries in the overall community, one can analyse if the optimization of the battery design may be affected too. This is done as a direct consequence of the results obtained in the previous section. To do so, the optimization problems discussed in Section 3.2 are modified. In particular, two modifications are introduced. Firstly, the battery capacity of each member is not anymore given as an input, but it is defined as a new variable that needs to be optimized and given as a result at the end of the algorithm. Since the battery capacity is now a new variable of the problem, constraint (1.5) is removed and constraint (1.6) is modified as shown in (4.3) to avoid non-linearity.

$$SOC_{min}\cdot C_i \le E^B_{i,t} \le SOC_{max}\cdot C_i \quad \forall i \in \{1,\dots,N\} \tag{4.3}$$

The second modification concerns the objective function of the problem. The optimization is carried out in an integrated way that includes the minimisation of the community energy cost for all day-types, multiplied by their cardinality c_s. This is done to ensure that the resulting battery capacity is optimized throughout the year. Moreover, the annualised investment costs and the operational expenditure are also minimised in the objective function, as shown in eq. (4.4) for Italy and in eq. (4.5) for Portugal. With the exception of the aforementioned modifications, all the other elements of the previously introduced optimization models have not been modified in this analysis, including the input data discussed in section 4.1.

$$\begin{aligned}\min \sum_{i\in N}\left(\frac{Capex_i}{t_{life}} + Opex_i\right) \\ + \sum_{s\in S} c_s \cdot \sum_{t\in T}\sum_{i\in N}\left(E^{WITHD}_{i,t}\cdot\lambda^{BUY}_{i,t} - E^{INJ}_{i,t}\cdot\lambda^{SELL}_{i,t}\right) - E^{SH}_{t}\cdot\left(TIP_t + TRAS_E\right)\end{aligned} \tag{4.4}$$

$$\begin{aligned}\min \sum_{i\in N}\left(\frac{Capex_i}{t_{life}} + Opex_i\right) \\ + \sum_{s\in S} c_s \cdot \sum_{t\in T}\sum_{i\in N}\left(E^{SUP}_{i,t}\cdot\lambda^{BUY}_{i,t} - E^{SUR}_{i,t}\cdot\lambda^{SELL}_{i,t} + E^{SH}_{i,t}\cdot\lambda^{GRID}_{t}\right)\end{aligned} \tag{4.5}$$

The capital expenditure is computed as shown in eq. (4.6) (Rancilio et al., 2022), in which k_E and k_P are assumed respectively as 300 €/kWh

Table 10
Optimal battery size and configuration for REC under Italian and Portuguese regulations.

Country	Total	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	Unit
Italy	13	0	3	0	5	2	0	0	3	0	0	kWh
Portugal	9	3	0	0	4	0	0	0	2	0	0	kWh

Table 11
Investment cost and community benefit of optimal REC configuration under Italian and Portuguese regulation.

Country	Investment cost	Total community benefit	Unit
Italy	2550	989 (+111%)	€
Portugal	1800	678 (+62%)	€

(NREL National Renewable Energy Laboratory, 2021) and 150 €/kW (Pacific Northwest National Laboratory, 2019), while the operational expenditures are assumed as 5 €/kWh per year (NREL National Renewable Energy Laboratory, 2021). The coefficient k_E represents the capex associated with a battery with an Energy-to-Power Ratio (EPR) equal to 1 h. However, the investment cost of the storage can vary according to the cost associated with the size of the Power Conversion System (PCS), represented by the coefficient k_P. The size of the PCS determines the maximum power that can be charged or discharged every hour. Therefore, the investment cost per unit of battery's capacity is reduced in case the EPR is higher than 1 h as the power P_{max} is lower than the capacity C_i and the battery takes more time to completely charge or discharge. On the other hand, it increases in case of faster batteries with EPR lower than 1 h, with a PCS power higher than the battery capacity. Another assumption is made about the lifetime of the battery t_{life}. In real life, the battery degradation is influenced not only by the calendar ageing, but also by the cycles operated. However, in this analysis, it is assumed that the storage will last for at least 10 years, as typical of batteries for stationary applications (Rancilio et al., 2019).

$$Capex_i = k_E \cdot C_i + k_P \cdot (P_{max} - C_i) \quad \forall i \in \{1, \dots, N\} \tag{4.6}$$

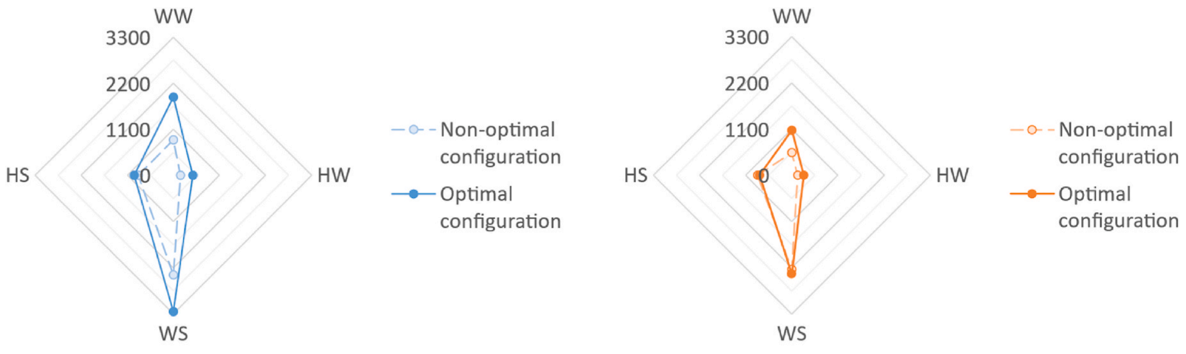
The results of the battery design optimization are shown in Table 10. Users equipped with a battery in the optimal configuration are not always the same in the two countries and, even when they are, their battery sizes are still diverse. Therefore, it is possible to state that the regulatory framework in place also affects the optimal battery size and configuration.

Table 11 represents the total investment costs for the batteries in the optimal design and the overall community benefit in the new configuration. The increasing benefit, in both countries but particularly in Italy, can be motivated by the higher level of energy shared within the community, as shown in Fig. 8. However, the Portuguese physical model is still affected by the close difference between the retailer buying and selling prices, as in the non-optimal configuration, which limits the community benefit and energy sharing also in the optimal configuration. Therefore, it would not be convenient to install more batteries since the potential costs of their operation would be covered neither at community level. This is an additional confirmation of the higher sensibility to the users' tariffs of the Portuguese physical model.

Moreover, the behaviour of users equipped with a battery is also affected. Fig. 9 represents the battery behaviour of a sample of users in the optimal and the non-optimal REC configuration under the Italian and Portuguese regulations. Under the optimal configuration, it is possible also for members without any PV plants to hold a battery and to use it for individual self-consumption, as it happens for M2 in Italy. When in the community, the battery can take advantage of the energy sharing by anticipating its charging. User M1 represents another member affected by the new configuration. In the Italian scenario, M1 is not equipped with a battery in the optimal configuration, even if it was in the non-optimal one. On the other hand, its battery plays an important role in the Portuguese optimal configuration. The user is called to reduce its self-consumption to increase the energy shared within the community by avoiding the charging of the battery. Finally, user M8 is equipped with a battery in both Italy and Portugal, as in the non-optimal configuration, but their sizes are different and this causes different behaviours not only during the community operation, but also in the individual one.

4.3.1. *Consumer protection mechanisms*

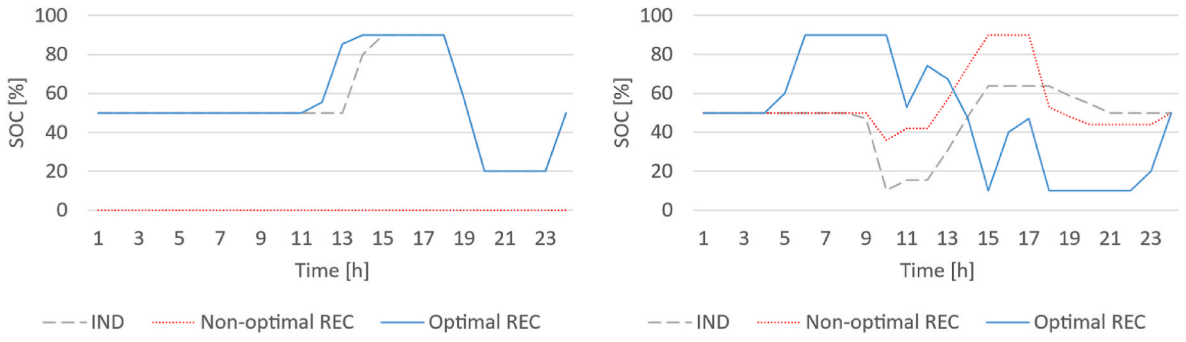
After assessing the impact of the regulation on the community optimization and battery design, its effect on the economics of single members is investigated as well. In this section the introduction of consumer protection mechanisms to safeguard the interests of individual members is assessed and discussed. To evaluate the need to introduce these measures, it is firstly necessary to compute the benefit of each member without any kind of user protection. This is done to check if members incurring uncovered additional costs are present. Therefore, starting from the solution of the community optimization in the non-optimal configuration, the incentive redistribution in the Italian regulation and the internal price in the Portuguese one are computed through the algorithms shown previously in Sections 3.2.1 and 3.2.2. A sample of members' benefits resulting from the computation is shown in Tables 12 and 13. The presence of members losing money in each



(a) Italy.

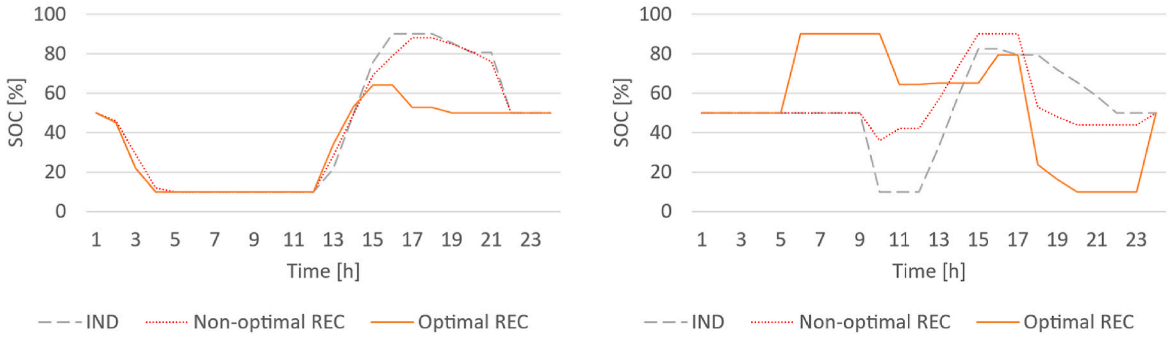
(b) Portugal.

Fig. 8. – Energy shared [kWh] within the community in optimal and non-optimal configuration under the Italian (a) and Portuguese (b) regulations.



(a) User M2 in HW days in Italy.

(b) User M8 in WW days in Italy.



(c) User M1 in WW days in Portugal.

(d) User M8 in WW days in Portugal.

Fig. 9. – Battery behaviour of users in optimal and non-optimal configuration.

scenario is graphically represented by a table cell highlighted in red. These cells also report the percentage of cost increment in the members' energy bill with respect to their individual behaviour.

The critical members, i.e. those incurring uncovered additional costs, are not always the same in the two countries. This demonstrates that the regulatory framework also affects the economic indicators of single members since it requires distinct approaches for benefit redistribution due to country-specific models. This happens even though the sharing mechanisms or the pricing algorithms adopted for the analysis are not explicitly required by the regulation. Regarding the level of those losses, they vary in the range of some euros per year and they are concentrated particularly during winter due to the lower PV penetration. However, they significantly impact in percentage terms on the overall members' bills. Therefore, consumer protection mechanisms discussed in Section 3.3 are introduced in any case of negative benefits to avoid losses that may be seen as unfair for some users. In the rest of this section, the effects of the chosen protection mechanisms on the members' benefit are presented and discussed.

The first protection mechanism implemented is represented by the constrained optimization problem presented in section 3.3.1, applied in both Italy and Portugal. Figs. 10 and 11 show the effects that adding one more constraint to the community optimization has on the battery behaviour. The constrained optimization model works similarly in both the Italian and Portuguese regulations by limiting the flexibility provided by the users' batteries to the community in presence of costs that are not covered at user level. The higher the costs, the more the battery behaviour differs from the optimal solution and tends to the individual one. This is what happens in Italy for user M1 during WW and HW days when the EB, SHAP and PC sharing methods are adopted. The different sharing methods lead to different battery behaviours because not all of them cause the same amount of uncovered additional costs. For instance, the PC method performs much better than the EB, therefore the battery behaviour under the PC scenario deviates only a little from the optimal one, while the deviation increases under the EB scenario. The same happens for user M8 during WW days and user M1 during HW days in Portugal. Member M8 incurs a signification deviation in its battery behaviour only when the MMR pricing algorithm is adopted. In any case, the new behaviours resulting from the constrained optimization represent a sub-optimal solution, in which the energy shared is reduced and consequently also the community benefit.

To avoid sub-optimal solutions, sharing mechanisms and pricing algorithms that allow users to completely recover from their additional costs should be preferred. However, in the Italian regulation, it is not necessary to strictly cut out sharing mechanisms that do not always perform well. It is still possible to implement them with a positive outcome for all members if a cost compensation logic is carried out before the incentive distribution, as explained in section 3.3.2. The logic behind this methodology is not applied to the Portuguese simulation since its regulation requires the computation of an internal price. In this case, the only way to avoid sub-optimal solutions remains the definition of an internal price that remunerates fairly all the community members. Fig. 12 shows the yearly incentive allocated to every member in the WW days with respect to their benefit when different sharing methods are adopted in the cost compensation logic. A user benefits from community participation if its associated benefit value is positive; a dashed red column represents a situation where an incentive is recognised to a user, and the latter exploits it to cover the additional costs it incurs when participating in the REC. Members incurring additional costs see a higher allocated incentive with respect to their benefit since part of their allocated incentive is eroded by their costs. On the other hand, the allocated incentive and the member's benefit coincide for users who do not incur additional costs. Therefore, this procedure is successful in

Table 12
Sample of members' benefit [€] for period-type under different sharing mechanisms in Italian community solution.

(a) WW.

	EB	SHAP	IMC	PC
M1	−20 (+111%)	−7 (+39%)	0	−1 (+7%)
M2	10	3	0	9
M4	10	3	1	5
M5	10	35	42	17
M8	5	8	8	9

(b) HW.

EB	SHAP	IMC	PC
−5 (+156%)	−1 (+42%)	0	0
2	1	0	2
2	1	1	1
2	7	9	4
2	0	0	1

(c) WS.

	EB	SHAP	IMC	PC
M1	30	74	74	57
M2	30	31	35	43
M4	30	30	25	26
M5	30	27	20	45
M8	14	26	30	27

(d) HS.

EB	SHAP	IMC	PC
10	15	14	15
11	24	32	15
10	15	13	13
11	10	7	17
7	9	8	12

Table 13
Sample of members' benefit [€] for period-type under different pricing algorithms in Portuguese community solution.

(a) WW.

	MMR	SDR	CSDR	POOL	MC
M1	2	3	3	9	11
M2	0	0	0	0	0
M4	28	26	25	7	6
M5	4	6	6	19	23
M8	−3 (+1%)	0	0	13	6

(b) HW.

MMR	SDR	CSDR	POOL	MC
−2 (+48%)	−1 (+38%)	−1 (+33%)	3	4
0	0	0	0	0
11	10	10	4	2
1	1	1	4	5
0	0	0	0	0

(c) WS.

	MMR	SDR	CSDR	POOL	MC
M1	16	7	12	49	42
M2	7	15	12	10	10
M4	22	15	17	28	27
M5	9	2	5	7	3
M8	3	5	5	20	17

(d) HS.

MMR	SDR	CSDR	POOL	MC
4	0	1	10	8
6	12	10	5	8
4	1	2	9	11
3	0	1	1	1
1	0	1	6	4

avoiding negative benefits while maintaining the optimal solution. To conclude, it has been demonstrated that consumer protection mechanisms are affecting in avoiding individual losses for critical users, and that the regulatory framework in place influences both the applicable compensation mechanisms and their results.

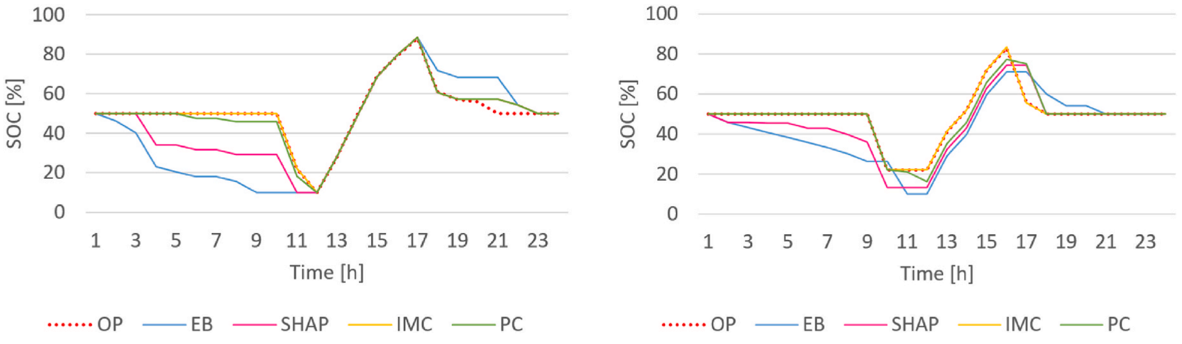
5. Conclusions and policy implications

This work aims to quantitatively evaluate the impact that different energy sharing models, resulting from the RED II transposition into national legislations, have on a REC. In particular, the analysis focuses on the regulation of two EU countries, Italy and Portugal, as they have deployed two specular models. A virtual model, in Italy, in which the members do not see a direct discount on their bills for their participation in the community, and a physical model, in Portugal, in which the community participation is directly reflected on the members' energy bills. The policy analysis is supported by a set of tools that optimize the community operation under the two regulations and ensure no negative benefits for all members. The algorithms are carried out on an illustrative 10-member REC case study, with a daily horizon in four representative day types.

The country's regulatory framework was found to impact three main community aspects. Firstly, it was observed that the specific regulation impacts the community optimal operation, particularly the amount of energy shared within the community, the community benefit and the flexibility provided by the users. This happens due to the way the objective function is formulated as a direct consequence of the country regulation, which causes the dependency of different energy sharing models to different input variables. In particular, the virtual model was found to be mostly affected by the level of the incentive, while the physical model to the level of the retailer's prices. If these elements in the corresponding regulation are not sufficiently high to cover the potential additional costs due to the flexibility provisions, the energy shared and the community benefit are limited. Moreover, the regulation was found to also impact the optimal battery size and configuration. The capacity that can be beneficially installed has an upper limit, which is given again by the ability of the incentivization scheme to cover the potential additional costs coming from the assets use. Finally, it was observed that the regulatory framework influences also the economics of single members. Different regulatory frameworks lead to different members' benefits due to the distinct ways in which, even if not explicitly required by the law, the community benefit is distributed among the members. In case of members incurring uncovered additional costs, the proposed user protection mechanisms were proved to be successful in ensuring no negative benefit for all members.

Although these results were obtained in a generic community, and their numerical values are expected to vary according to input data, they are likely to remain valid even with changes in community size and composition. This is because collective self-consumption generates positive benefits only when significant complementarities among consuming and generating members exist. Nonetheless, this general effect on community benefits is expected to influence both models in a similar way, thus not affecting the validity of the obtained results. However, future research is encouraged to focus on improving the robustness of these considerations, for example by assessing the validity of the obtained results across diverse community conditions. Moreover, sensitivity analysis on key parameters, for instance on retailer's prices or incentive levels, would additionally strengthen the results by further highlighting how these variables influence the outcomes. Finally, future research can also broaden the reached perspective by including additional quantitative comparisons on the wider socio-economic implications of the regulations, for example by enriching the analysis with considerations on the role of owners' share of assets and members' social position.

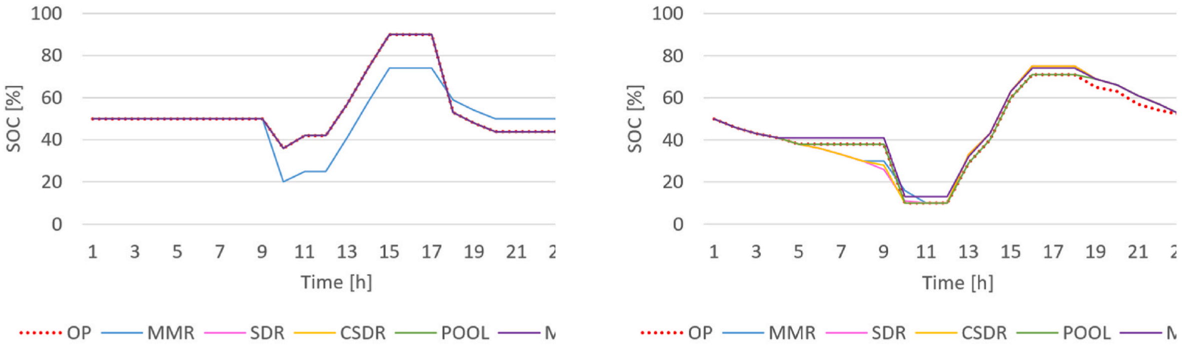
From a policy perspective, it is possible to highlight two main areas of discussion and intervention (European and national) and different



(a) User M1 in scenario WW.

(b) User M1 in scenario HW.

Fig. 10. – Behaviour of M1 battery in WW days (a) and HW days (b) under the Italian virtual model.



(a) User M8 in scenario WW.

(b) User M1 in scenario HW.

Fig. 11. – Behaviour of M8 battery in WW days (a) and M1 battery in HW days (b) under the Portuguese physical model.

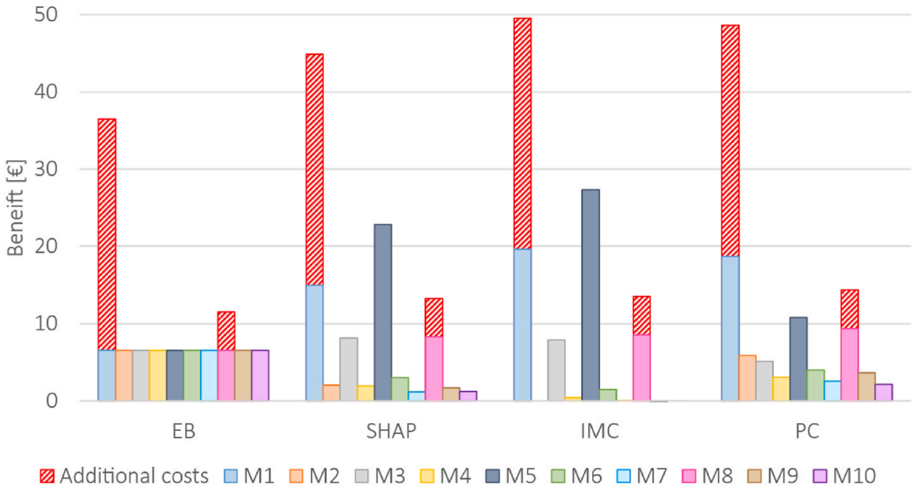


Fig. 12. – Amount of incentive allocated to every member with the compensation logic during WW days with respect to their member's benefit under the Italian regulation.

levels of priority of the proposed measure, according to their effort-benefit evaluation, as shown in Fig. 13.

- **Avoid harmonisation** From a European perspective, the harmonisation of regulations seems hard to implement due to the ongoing transposition process and the natural flexibility of each country to adapt the RED II directive according to their preferences and pre-existing regulations. In fact, this operation would require an excessive effort that may not be beneficial as it would not likely consider the specific socio-economic situation of each country. Therefore, acknowledging the national differences on RECs represents the most prudent course of action. However, it should be noted that lack of harmonisation may make transnational energy communities unfeasible or may require specific bilateral rules to implement them.

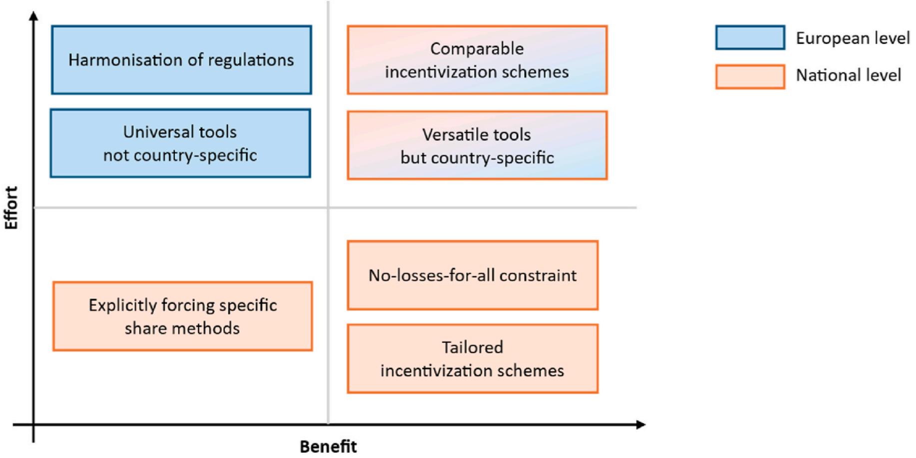


Fig. 13. Effort-benefit evaluation of every proposed intervention for priority definition.

- **No one-size-fits-all** This European fragmentation also represents a challenge for the development of technical tools applicable to more than one country, although this may not represent a significant obstacle for ICT developers. Indeed, as outlined by this research, the development of a single instrument for all models would not be beneficial, as they operate under distinct rules, making unsuitable and inadequate a single approach for all countries. On the other hand, versatile instruments, able to switch from one country to another by adapting algorithms and rules to specific regulations, as done in this analysis, may require integration and collaboration efforts at European and national levels while providing a systematic solution to this problem.
- **Tailored or comparable incentivization schemes** From a national perspective, this research underlines the importance of the legislator's awareness about the variables that affect the sharing model of its country. In this sense, it has been proved that the virtual model is significantly influenced by the level of the incentive, while the physical model depends mainly on the retailers' prices. This means that national legislators should tailor incentivization schemes to their specific energy sharing models, focusing on those actions with larger impact to incentivize the deployment of energy communities. By aligning with country-specific community needs, more effective operations can be achieved, leading to a broader adoption of these communities across the country. It is also important to note that incentivization schemes should be designed according to countries specificities but avoiding the provision of unfair competition among the involved actors, even if energy communities are not for-profit organizations. Moreover, comparable incentivization schemes at European level may be preferred for a sense of coherence among Member States, but they would require additional and complex considerations by both European and national legislators on the socio-economic situation of each country. In fact, they should not simply provide the same level of economic benefit in absolute terms, but relatively to the specific economic situation of each country.
- **No-losses-for-all constraint** Given that regulation may have an impact on single members, national policymakers should explicitly guarantee positive benefits for all involved. Indeed, as this research shows, when not explicitly addressed, individual member losses may occur, which may be perceived as unfair and disincentive to community participation. However, explicitly forcing a specific share method may be too restrictive and strongly limit the development of flexible and innovative business models. For this reason, the inclusion of a no-losses-for-all constraint in the regulation, as done in the consumer protection mechanisms developed in this research, may avoid members' discontent but leave every community free to define its specific implementation.

In conclusion, the REC concept varies significantly among the EU Member States due to the presence of distinct energy sharing models. Since their performances are not influenced by the same variables, the operation of the same community under diverse regulations may differ significantly. This highlights the importance of recognizing that there is no one-size-fits-all approach, emphasizing the need for customized strategies aligned with the specific countries' regulatory frameworks.

CRediT authorship contribution statement

Giulia Taromboli: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Conceptualization. **Tiago Soares:** Writing – review & editing, Supervision, Methodology, Conceptualization. **José Villar:** Supervision, Methodology, Conceptualization. **Matteo Zatti:** Conceptualization. **Filippo Bovera:** Writing – review & editing, Supervision, 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

Data will be made available on request.

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