Journal of Cleaner Production 425 (2023) 138937

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Monitoring the Italian transposition of the EU regulation concerning renewable energy communities and the relevant policies for battery storage

Pablo De Juan-Vela [a], Asja Alic [a], Vincenzo Trovato [a,b,*]

[a] Department of Civil, Environmental and Mechanical Engineering – University of Trento, Via Mesiano 77, 38123, Trento, Italy
[b] Department of Electrical and Electronic Engineering, Imperial College London – Exhibition Road, SW7 2BX, London, UK

ARTICLE INFO

Handling Editor: Giorgio Besagni

Keywords:
Renewable energy community
Energy storage
Renewable energy sources
European Union

ABSTRACT

This paper deals with the transposition of the European Union (EU) Directive concerning Renewable Energy Communities (RECs) into the Italian legislation. The methodology aims at identifying those national provisions which do not comply with the EU legislation. Consequently, long and onerous infringement procedures may ultimately limit the development of RECs. Moreover, the proposed methodology quantifies the economic value of national policies concerning the participation of storage assets in RECs. Three policy options are compared against the case without flexible assets. To do so, ad-hoc mixed-integer linear programming optimization problems are developed. The assessment is based on the formulation of three key performance indicators, concerning the revenues and costs of the REC. The main data sources in the work are the actual Italian Wholesale Market prices and the price incentives introduced by relevant Italian authorities to support the operation of the RECs. Results indicate an incorrect transposition of the fundamental rights of the EU law. These concern a significant alteration of the membership criteria for prospective RECs and the introduction of external third-parties, which may bypass fundamental requirements set out in the EU law. Numerical results call for a profound revision of the policy options for battery storage in RECs since the envisaged configurations introduce structural limits to the REC's revenues This work can support researchers and policy makers at both national and EU-level in developing policy options and techno-economic measures that foster the development of new RECs.

1. Introduction

Energy communities consist of frameworks fostering the common sharing of responsibilities and benefits arising from the local energy production (Ceglia et al., 2020). Overall, these initiatives are not new in the energy sector; examples of energy communities can be found, for instance, in remote areas of power systems (Lowitzsch et al., 2020), (O'Brien et al., 2018). This scenario is rapidly evolving, primarily driven by ambitious targets concerning the integration of Renewable energy Sources (RES) (IRENA, 2022). In particular, large amounts of RES have been connecting to the distribution networks (Gong et al., 2021), (Tutak and Brodny, 2022). The local feature of the distributed RES may push towards the development of several new energy communities. National and international institutions have taken fundamental steps in this direction.

As part of the Clean Energy Package (European Commission a), the European Commission (EC) approved the Directive (EU) 2001/2018 (European Commission, 2018). This directive, also known as the Renewable Energy Directive (RED)-II, sets out the legal framework for the *Renewable Energy Communities* (RECs). RECs are considered the main vector to organize and incentivize the penetration of distributed RES (Montoya-Bueno et al., 2016) whilst giving value to individual and collective actions of the citizens that decide to join them. An overview on the RED-II reveals that a REC is a legal entity based on the open and voluntary participation of its members. Specific provisions establish the criteria for the REC's members to exercise effective control and to keep the REC autonomous. Moreover, prospective members shall respect specific eligibility criteria and need to be located in the proximity of distributed RES plants. In the RED-II, the EU legislator highlights that the primary purpose of RECs is not the pursuit of financial gains but rather the achievement of environmental, economic and social benefits. Hence, while promoting the integration of distributed RES, several studies deem that these types of energy communities may be able to promote energy justice (Hanke et al., 2021), (Heldeweg and Saintier, 2020). Another type of community initiative proposed by the EU legislator in (European Commission a) concerns the so-called Citizens Energy Community (European Commission, 2019). The main differences with

* Corresponding author. Department of Civil, Environmental and Mechanical Engineering – University of Trento, Via Mesiano 77, 38123, Trento, Italy.
E-mail address: vincenzo.trovato@unitn.it (V. Trovato).

https://doi.org/10.1016/j.jclepro.2023.138937
Received 16 February 2023; Received in revised form 11 August 2023; Accepted 17 September 2023
Available online 22 September 2023

Nomenclature

Abbreviations

ARERA	Italian national regulatory authority
BC	Base case
BESS	Battery energy storage system
CapEx	Capital expenditures
CS	Case study
EC	European Commission
EU	European Union
GSE	Coordinator of the energetic services
HV	High voltage
KPI	Key performance indicator
LV	Low voltage
MISE	Ministry for the economic development
MITE	Ministry for the ecological transition
MS	Member State
MV	Medium voltage
NRA	National regulatory authority
OpEx	Operating expenses
PV	Photovoltaic
PUN	Unique national price
REC	Renewable energy community
RED	Renewable energy directive
RES	Renewable energy sources
SE	Shared energy
SME	Small medium enterprise

Parameters

h	Parameter for SE repartition in option 4
k	Share of BESS energy for SE
$\widetilde{L}_t$	Aggregate load at t
N	Number of days
n	Index of days
$\overline{P}_{M2}$	Connection capacity of PV unit
$\widetilde{P}_t$	Available aggregate PV generation at t
$\overline{S}$	Rated energy capacity of the BESS
T	Number of optimization steps in a day
t	Index of time steps in a day
Δt	Time interval t
η	Round trip efficiency
λ^i	Incentive for SE
λ^o	Price for energy from the PV to the BESS
λ^{pr}	Premium price for SE
λ_t^{pun}	PUN price at t
λ_t^{ta}	Energy tariff for end-users at t
$\overline{\Pi}$	Rated power capacity of the BESS

Decision variables and functions

P_t^g	PV power to the grid at t
S_t	BESS SoC at t
u_t	Binary variable for BESS operation at t
Π_t^{cg}	BESS charged power from grid at t
Π_t^{cpv}	BESS charged power from PV unit at t
Π_t^d	BESS discharged power at t
$\Phi_{Ox,t}$	SE at t for option x
$\mathbb{C}_{Ox}$	Consumption cost with option x
$\mathscr{R}_{Ox}^{SE}$	Revenue for SE with option x
$\mathscr{R}_{Ox}^{gen}$	Generation revenue with option x
$\Omega_{Ox}^{',\cdots,''}$	Net cost/revenue functions

respect to RECs regard the type of local energy production[1] and the eligibility criteria for prospective members. Further details are well illustrated in (Rescoop.eu, 2020). The authors wish to emphasize that this paper focuses only on RECs in accordance with the RED-II; however, part of the proposed methodology can be extended to the case of citizens energy communities.

1.1. Motivation

As envisaged for all EU directives, each Member State (MS) is tasked with transposing the RED-II into its national regulatory framework.[2] Unlike EU regulations and decisions, directives like the RED-II are not simply applicable throughout MS; they require national laws to incorporate their rules into national legislation. The implementation of this process is subject to the monitoring activity of the EC; the institution would examine the text of the national legislation to ensure that it meets the aims of the RED-II and ascertains that the envisaged deadlines are met (EUR-Lex, 2023). Delivering a correct transposition is an essential task for the MS to prevent the EC from taking a case to the EU Court of Justice and force the amendment of the national regulation if the measures taken to transpose the RED-II are deemed to be not satisfactory (European Commission b). In this case, the principle of the primacy (precedence) of EU law applies (EUR-lex).

A fundamental distinction facilitates the assessment of the transposition. Article 22 of the RED-II deals with the *rights* and the *enabling frameworks*. Although similar, these two concepts are not the same. Those provisions under the definition of rights are directly enforceable by law. Hence, the entry into force of the RED-II automatically guarantees that the relevant rights are exercised. The definition of enabling frameworks is instead looser, granting MS room for interpretation. The concept of rights is more powerful than any MS policy implemented to establish enabling frameworks. In other words, the rights of RECs established in the RED-II cannot be modified by the national legislator. An example of rights are the eligibility criteria for the members of the RECs. On the other hand, the development of policy options for the effective integration of Battery Energy Storage Systems (BESS) within RECs is one of the enabling frameworks that a MS is requested to carry out. Nonetheless, the EC may still require amendments of the national policies for BESS in RECs which do not guarantee a level playing field or do not comply with the general scope of application of the RED-II.

The considerations above motivate this paper and originate the following research questions:

- How can national legislation and policies limit or compromise the spread of RECs by failing at transposing the rights of the RED-II?
- Do existing national policy options effectively deliver the enabling framework for flexible assets in RECs?
- Up to which extent potentially shortsighted enabling frameworks can affect the development of RECs?
- Do national incentive schemes effectively combine the fundamental rights and financial purposes of RECs?

1.2. Relevant work

This subsection recalls the main works concerning RECs and discusses their relevance to the considerations presented in the previous section. Given their wide scope of application, the research effort

[1] RECs restrict the eligible sources of energy production to RES. This limitation does is not present in citizens energy communities.

[2] By 30 June 2021, in accordance with Article 36 of the RED-II.

concerning RECs may focus on different aspects and several perspectives.

The work in (Soeiro and Ferreira Dias, 2020) collects the data, using a survey, to study the main features and the motivations of individuals to participate to RECs. The analysis of the main features of the RECs considering the EU framework of the RED-II is in (Rescoop.eu, 2020) and (Caramizaru and Uihlein, 2020). The authors in (Lowitzsch et al., 2020) reviewed the characteristics of the governance model of RECs at EU-level. A comparison between RECs and similar community-level frameworks is in (Mihailova et al., 2022). A set of policy recommendations that are crucial for the transposition of RED-II is presented in (Hoicka et al., 2021). This work highlights the benefits and challenges of widespread development of RECs and provides policy recommendations for effective implementation of the RED II with respect to RECs. The study in (Inês et al., 2020) maps a cross-country comparison between the regulatory frameworks providing the legal reference of the acts transposing the RED-II in nine MS. Further analysis of the legal frameworks and operational characteristics of RECs at national level are in (Wainer et al., 2022) and (Martens, 2022). The former explores the conditions under which RECs access the electricity grid in France and Germany, focusing on the governance choices and narratives, determining the technical and economic conditions for grid access. The latter deals with the role of national policies enabling successful conditions for the development of RECs in Germany. Another focus on the German implementation of RECs is in (Rommel et al., 2018). The main factors enabling the willingness to join a REC in Flanders region are analysed in (Conradie et al., 2021). The early stages of the transposition of the RED-II in the Italian regulatory framework and the main features of the corresponding incentives to the development of RECs in that MS are addressed in (Di Silvestre et al., 2021).

The methodologies and insights in the abovementioned papers refer to the regulatory frameworks for RECs pursuant to the partial/complete transposition of the RED-II in different MS. However, the relevant literature does not analyze the degree of compliance of the national-level policy framework implementing the RECs with the RED-II. Hence, without highlighting where those provisions possibly deviate from the EU scheme is not possible to verify the potential introduction of discriminations/barriers for RECs.

Another set of papers focuses on the economic benefits for of RECs by also considering the contribution of BESS. The review of the main business models for RECs is introduced in (Reis et al., 2021). The definition and implementation of effective investment models for RECs in Italy are studied in (Cielo et al., 2021) and (Iazzolino, 2022). Both studies acknowledge the value of integrating BESS in RECs. However, these works did not consider the approval of the technical rules for BESS in Italian RECs (Gestore dei Servizi Energetici, 2022), which came after the publication of these studies. Authors in (De Santi et al., 2022) provide an alternative investment model for RECs in Italy but neglect the presence of a BESS. The problem of establishing a fair redistribution of the revenue of a RECs among its members is investigated in (Casalicchio et al., 2022). Concerning operational perspectives for BESS, reference (Moncecchi et al., 2020) proposes to treat the REC as a coalitional game. In a similar context, authors in (Norbu et al., 2021) study the techno-economic benefits of community-owned versus individually-owned energy assets considering the network constraints. Although providing solid mathematical modeling and control of RECs, these two works do not fully contextualize the economic results with the actual enabling frameworks and current policy options for BESS. In other words, the actual possibility to implement the proposed strategies is neglected. A model for probabilistic social and private cost-benefit analyses for photovoltaic-green roof energy communities is developed and tailored to Luxembourg (Cruz Torres et al., 2023). The work in (Ghiani et al., 2022) provides an analysis of the economic and energy performance during the first year of renewable community piloting in Italy. However, the corresponding policy framework is outdated. A three-steps iterative methodology is adopted in (Rossi et al., 2021) to design new feed-in tariffs for RECs in Italy. The wider scope of application pursued in this work bypass some of the features of the Italian transposition of the RED-II. In general, none of the abovementioned papers dealing with BESS consider the impact of the actual connection schemes of these assets and the policy options for their operation in the economic assessment of the REC's revenues and costs. In other words, the lack of a detailed correspondence with existing national policies impedes a critical analysis of the actual opportunities for BESS in RECs or the identifications of policy-based barriers.

1.3. Contributions

The extensive literature review in the previous subsection confirms the wide interest of the research community in the development of RECs. However, the research questions highlighted in Section 1.1 remain unanswered. This paper aims at bridging such gap, focusing on the Italian case. The authors wish to emphasize that the proposed methodology and approach can be replicated to analyze other MS since the fundamental procedure for the transposition of the RED-II is the same in each MS. For example, all the MS are requested to fully implement at national level the rights of RECs as provided in the RED-II.

Hence, the work provides the following key novel contributions:

I. The up-to-date description of the legal references of the Italian transposition of the RED-II. To the authors' best knowledge, this is the first paper dealing with the most recent and impactful deliberations of the Italian National Regulatory Authority (NRA). All the papers considering the Italian context in the literature review deal with the outdated transient set of rules concerning RECs.

II. A novel, policy-related comparative analysis of the main legal acts and provisions concerning the transposition of RECs in Italy with respect to fundamental scopes and features of the EU RED-II. This paper expands the analysis and results by relevant previous works which focus more on the overview of the EU and national legislation. This work rather compares national and EU regulations by critically monitoring the correctness of the national transposition of the fundamental *rights* of the RECs expressed at EU level. The novel approach concerns those rights of RECs that are already exhaustively defined at EU-level and whose transposition into the national framework exhibits differences and possible contradictions with respect to the RED-II. The proposed monitoring activity produces a further contribution since it considers the development of new national requirements which go beyond the scope of application of the RED-II and affect its actual application.

III. A novel investigation of the *enabling frameworks* and possible related barriers for BESS joining RECs depending on their actual connection schemes and policy options. The recent technical connection rules for BESS may arguably prevent certain storage configurations from receiving the economic incentives envisaged for the other members of the RECs, thus affecting a level playing field. The paper critically analyzes the effectiveness of the rationale behind the current policy options and proposes alternative policy frameworks which could alleviate the identified shortcomings.

IV. The assessment of the impact of the policy options concerning BESS in RECs is supported by quantitative results obtained through Mixed Integer Linear Programming (MILP) optimization models. Each policy option is effectively translated into a set of mathematical constraints. This improves the accuracy and the neutrality of the policies' investigation.

V. The formulation of three simple yet insightful Key Performance Indicators (KPIs) concerning the cash flows of the RECs. These are evaluated for all the connection schemes and policy options considered in the paper and are also assessed with respect to the case of a REC without a BESS. The use of the three KPIs extend the analysis of the results obtained in previous works, which do not differentiate between financial gains (e.g. reduction of the energy costs of the REC) and the economic, environmental and social benefits of RECs expressed in the RED-II. The novel formulation allows to evaluate, at the same time, the respect of the fundamental rights of RECs and their financial aims.

Overall, the results of this paper contribute to the ongoing research on RECs by bringing new insights on regulatory and techno-economic challenges concerning the effective development of such communities. National and EU-level policy makers may benefit from the methodology developed for the proposed analysis in order to assess the effectiveness of certain policy options and legal provisions and their compliance with the EU law. In fact, the proposed work may anticipate the methodology, the insights and the outcomes of the actual monitoring exercise to be carried out in future by the EC concerning the RED-II.

1.4. Paper structure

The rest of the paper is structured as follows. Section 2 introduces the methodology carried out in this paper. Section 3 recalls the main features and legal references of RECs as in the RED-II and in the Italian legislation. The modeling of the connection and policy options for a BESS in a REC is in Section 4. Qualitative and quantitative results concerning the correctness of the transposition of the RED-II into the Italian legislation and concerning the economic benefits for BESS in RECs are presented in Section 5. Finally, Section 6 deals with the discussion of the outcomes of this paper and with future research perspectives.

2. Methodology

The illustrative summary of the methodology proposed in this paper in Fig. 1. As shown, it consists of four consecutive phases, i.e. *analysis*, *modeling*, *results* and *discussion*; each of them is characterized by a different color. Moreover, the methodology addresses two macro-areas. The first (left hand-side) deals with the transposition of the main *rights* of RECs established in the RED-II into the Italian regulation. The second concerns one of the *enabling frameworks* of the RED-II, i.e. the creation of a level playing field for the effective integration of BESS into the framework and incentives for RECs. The numbers in Fig. 1 indicate the order of appearance of the corresponding tasks in the reminder of the paper.

The first phase (green area) deals with the *analysis* of the fundamental *rights* of RECs. To do so, the corresponding legal references to the RED-II and to the Italian legislation are recalled. The aim it twofold: providing an up-to-date regulatory picture - especially with respect to the latest developments the Italy - and highlighting the general requirements of RECs that shall be maintained at national level after the transposition. Furthermore, concerning the enabling frameworks, the second task performs the analysis of the different policy options and consequent financial opportunities for the actual integration of BESS in RECs in accordance with the current Italian legislation.

The second phase of the proposed methodology (grey area) deals with the *modeling* of the enabling framework for the integration of BESS in RECs. The first task of this phase requires the development of possible alternatives to the current policy options (recalled in the first phase). Here, considering policy options for BESS in RECs, which are alternative to those currently binding in the Italian context, is proper since the RED-II does not exhaustively define a unique EU-level policy on this matter to be implemented by all MS. This leaves room to the MS for choosing the implementation of the relevant enabling frameworks. In other words, since Italy has the opportunity to establish its own policy options, it is worth carrying out a comparative analysis between the current options and potential alternatives. To do so, the second task of the modeling phase aims at translating the main features of existing and alternative policy options for BESS in RECs into analytical models. The resulting models would enable a quantitative techno-economic assessment of the BESS operation in RECs. In fact, the technical features of a particular connection scheme for BESS and the economic impact of the applicable policy option are both considered. The constitutive modeling features for BESS in the REC are modelled as MILP optimization problems aiming at maximizing the net revenues of the REC. The last task of this phase consists in the development of set of KPIs concerning the main revenue/cost streams of the REC. These KPIs characterize the actual contribution of the BESS.

The authors wish to emphasize that the modeling phase will not involve the main rights of the REC since these are exhaustively defined at EU-level and should be faithfully maintained at national level. This paper rather analyzes the correctness of the national transposition of the rights established in the EU law than proposing alternative provisions to an already binding EU directive.

The third phase of the proposed methodology (light blue area) deals with the assessment of the *results*. Concerning the main rights of the RECs, the assessment will qualitatively highlight those provisions and requirements that are already exhaustively defined at EU-level and whose transposition into the national framework exhibits differences and possible contradictions with respect to the EU law. Results would also point out the development new national requirements which go beyond the scope of application of the RED-II and affect its actual application. The second task of the third phase of the methodology carries out a quantitative assessment of the set of connection and policy options concerning the participation of BESS in RECs. The analysis of the results is based on the KPIs defined in the previous phase concerning the ability of a BESS to contribute to the applicable incentives.

Finally, the fourth phase (orange area) proposes a critical and detailed *discussion* concerning the insights highlighted in the previous phases. In particular, it deals with the policy implications of an incorrect transposition of the EU RED-II into the national framework. Leveraging on the numerical results, this phase discusses the effects and the potential implications of the policy options for BESS considered in this paper.

3. The legal references to the EU and the Italian legislation concerning RECs

This section deals with the first phase of the methodology illustrated in Fig. 1. Hence, its first objective is to recall the main rights and requirements of RECs, as designed by the European legislator (Section 3.1). Afterwards, Section 3.2.1-2 discuss the main steps of the transposition of the RED-II into the Italian regulatory framework. This gives the opportunity to introduce the legal acts concerning RECs recently approved by the relevant Italian entities. Finally, in accordance with the proposed methodology, Section 3.2.3 recalls the main Italian provisions concerning the framework enabling the integration of BESS in a REC.

3.1. The EU regulation on RECs

In accordance with Article 2(16) of RED-II, the main features of a REC are:

- *"a legal entity which, in accordance with the applicable national law, is based on open and voluntary participation, is autonomous, and is effectively controlled by shareholders or members that are located in the proximity of the renewable energy projects that are owned and developed by that legal entity;*

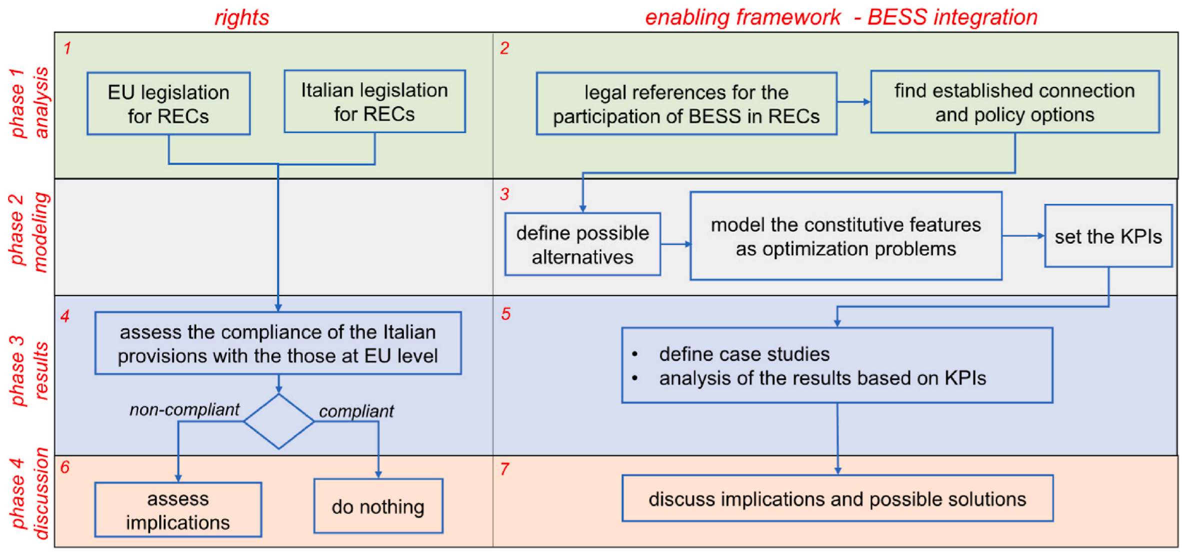

Fig. 1. Illustrative scheme of the methodology of the paper. Each of the four phases, analysis, modeling, results and discussion, is labelled with a color. The numbers indicate the order of appearance of the corresponding tasks in the reminder of the paper. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

- *the shareholders or members of which are natural persons, SMEs*[3] *or local authorities, including municipalities;*
- *the primary purpose of which is to provide environmental, economic or social community benefits for its shareholders or members or for the local areas where it operates, rather than financial profits."*

Concerning the first bullet point above, a univocal meaning of *effective control* is not present in the RED-II. The authors' interpretation is that the concept and features of effective control are rooted within the *local* framework of a REC i.e. the *geographical proximity*. The concept of proximity is pivotal; it should be generally understood as the geographical scope in which the members or shareholders that effectively control the REC should be located (e.g. reside). Since the RED-II does not provide an exhaustive definition to size the geographical proximity, MS have room to elaborate their own methodologies and criteria to quantitively and univocally set the boundaries of the geographical proximity. Furthermore, another important feature is the notion of *autonomy* which may go beyond the one of effective control. The Recital (71) of the RED-II opens up to the establishment of a framework supporting a democratic internal decision-making process which ensures adequate representation of the members.

With respect to the second bullet point above, the EU legislator establishes eligibility criteria to become member of a REC. The RED-II mandates private undertakings joining a REC to be Small Medium Enterprises (SMEs). Besides the respect of size-related limitations, a private undertaking joining a REC shall comply with further requirements. Article 22(1) of the RED-II mandates that:

"Member States shall ensure that final customers […] are entitled to participate in a renewable energy community […] provided that for private undertakings, their participation does not constitute their primary commercial or professional activity."

Hence, those private undertakings, whose participation to the REC represents the primary commercial or professional activity shall not be able to join the REC. Note that Article 22(1) does not refer to a particular sector of the activities of a private undertaking (e.g. energy, finance etc.) whereas it rather targets those undertakings that might be created with the sole purpose of becoming members of a REC. The RED-II paves the way to the application of *combined provisions* - Article 2(16) and Article 22(1) - which require that private undertakings willing to become members/shareholders of a REC shall be registered as SMEs and, *at the same time*, shall ensure that their participation to the REC does not constitute the primary commercial or professional activity.

The third bullet point above sets out the purpose of RECs. It is worth noting that this purpose does not aim at impeding the realization of a return on the investments sustained by the RECs. However, the realization of returns and other financial profits for members shall not be the central effort. For example, RECs may still realize profit as long as the latter is reinvested into the community's activities (e.g. renewables generation projects), or are used to pursue general public interest aims such as local development etc. The definition of economic, environmental or social benefits is not exhaustive, leaving MS with room for specifications.

3.2. The Italian regulation on RECs

Italy, as all the other MS, has been tasked (European Commission c) to implement the necessary legislative procedures to formally transpose the RED-II by June 30, 2021. The Italian transposition of the RED-II has been carried into two phases, a trial one followed by the more definite phase. A graphical summary of the timeline of the main events and approvals of the legal acts and technical documents concerning the RECs in Italy is offered in Fig. 2.

3.2.1. The trial phase

The trial phase started with the approval of the *Legge n.8/2020* which entered into force in 2020 (Gazzetta Ufficiale, 2020). Although still legally binding at present, the framework established through *Legge n.8/2020* is characterized by intrinsic transience since it does not constitute the outlook of the formal implementation of the RED-II. Nonetheless, it created a solid context to start with initial establishments of first RECs. The scope of the Italian legislator was to gain experience and assess potential critical elements before formally transposing the RED-II.

The RECs under the scope of application of *Legge n.8/2020* are characterized by the following features:

[3] SMEs means micro, small and medium enterprises as defined in Article 2 of the Annex to Commission Recommendation 2003/361/EC (European Commission d).

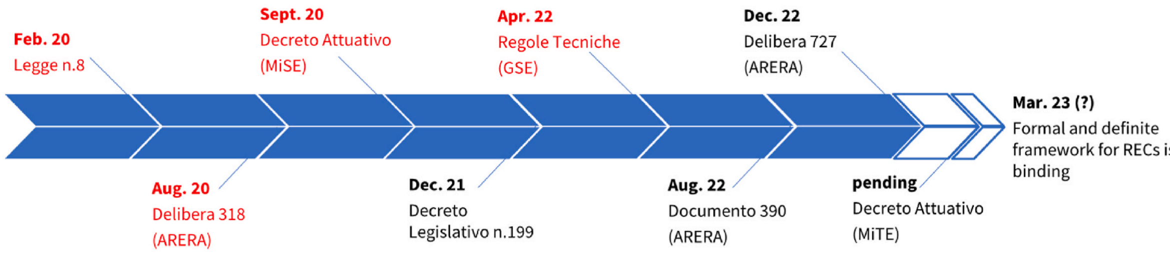

Fig. 2. Timeline of approval of the main legal documents concerning the RECs in the Italian regulatory framework. The red font refers to events related to the trial phase whereas the black font indicates events concerning the formal transposition of the RED-II. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

- The energy is produced by RES and the power ratings of the generating assets is below 200 kW.
- All the assets of the REC must be connected to the same Medium Voltage (MV) – Low Voltage (LV) transformation station (i.e. substations or secondary stations). This, in a way, rests on the concept of geographical proximity discussed in Section 3.1.
- The *Shared Energy* (SE) is equal to the minimum, at each hourly period, between the electrical energy produced and fed into the grid by RES and the electrical energy absorbed from all the customers.
- The economic incentives for RECs are guaranteed for 20 years. Afterwards, annual tacit renewals apply.

Three main legal and technical acts followed. The first is the *Delibera 318/2020* of the ARERA, the Italian energy NRA (ARERAa). ARERA established the incentive λ^i for each kWh of SE in the form of network cost avoidance. For the year 2022, the ARERA[4] set $\lambda^i = 0.00778 + 0.00059$ €/kWh. The second act is the *Decreto attuativo* of the MiSE (the Italian Ministry for the Economic Development) (Ministero dello Sviluppo Economico, 2020), which has established the feed-in premium $\lambda^{pr} = 0.11$ €/kWh for the SE of the REC. The third act is the *Regole Tecniche* of the Italian coordinator of the energetic services (*Gestore dei Servizi Energetici* - GSE). This is a set of technical provisions setting up and managing the rewards of the incentives for the SE (Gestore dei Servizi Energetici, 2022).

3.2.2. The formal transposition

Italy has formally transposed the RED-II by approving the *Decreto Legislativo n.199* in December 2021 (Presidenza della Repubblica italiana, 2021). Two main technical changes are introduced by the *Decreto Legislativo n.199* with respect to the *Legge n.8/2020*. The maximum rated capacity for RES moves from 200 kW to 1 MW and the perimeter relevant to the assessment of the SE moved from MV-LV sub-stations to those High-Voltage (HV) - MV primary stations. These changes allow to build plants of a larger size, which can effectively meet the energy needs of a community and not just those of a few families as it was the case with the setup of *Legge n.8/2020*.

Nonetheless, it is worth noting that the implementation process did not conclude with the approval of the *Decreto Legislativo n.199*. The ARERA and the Italian Ministry for the Ecological Transition (MiTE)[5] are tasked to complete the regulatory framework, implementing some of the provisions in Articles 8 and 32 of the *Decreto Legislativo n.199*. In particular, Article 32(3)(a) requires the ARERA to define the network-related incentives i.e. λ^i for the SE. Article 8 of the same legal act requires the MiTE, in collaboration with the GSE, to assess the premium tariff applicable to the SE i.e. λ^{pr}.

Pursuant to its obligations, the ARERA published in August 2022 the *Documento per la consultazione 390/2022* (ARERA, 2022) which presented the orientations of the ARERA concerning an integrated set of provisions regarding the implementation of the *Decreto Legislativo n.199*. Relevant stakeholders had the opportunity to publicly consult providing the ARERA with their feedback until September 23, 2022. Recently, the ARERA completed its tasks by publishing in December 2022 the *Delibera 727/2022* and its *Annex A*. These legal acts recall the main orientations of the stakeholders and implement the remaining provisions in Article 32 of the *Decreto Legislativo n.199*. One of the outcomes of the *Annex A* of the *Delibera 727/2022* is the definition in Article 6 of λ^i as the variable part of transmission network tariff for LV connections (so-called TRASe).

The actions from the MiTE concerning Article 8 of the *Decreto Legislativo n.199* are still pending. The provisions in *Legge n.8/2020* and associated acts from the ARERA, the MiSE and the GSE, forming the trial regulatory framework for the RECs, will remain binding until[6] the implementation of the remaining tasks of the MiTE in collaboration with the GSE.

3.2.3. The current regulation for BESS in a REC

A possible configuration of a REC is illustrated in Fig. 3. It consists of an aggregation of loads connected together with a Photovoltaic (PV) plant at the LV-side of the same transformer. For the sake of simplicity and without lack of generality, it is assumed that the loads are inflexible residential customers. Also, the PV plant could actually be any RES plant. The diamonds indicate the energy meters which must exhibit

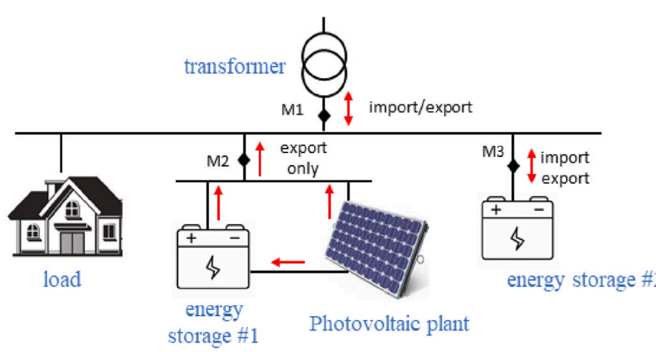

Fig. 3. A prospective configuration of a REC.

[4] the first component corresponds to the variable part of transmission network tariff for LV connections (so-called TRASe). The second component is the highest value of the variable distribution tariff defined for LV users for other uses (so-called BTAU).

[5] which is referred as to as the Italian Ministry for the Environment and the Energy Security.

[6] the *Delibera 727/2022* of the ARERA provided that the new regulatory framework in the *Decreto Legislativo n.199* and associated acts will become binding after 1 March 2023 whereas the MiTE publishes, by that date, the decree envisaged in Article 8 of the *Decreto Legislativo n.199*. Alternatively, the new regulatory framework will become binding only after the publication the MiTE.

certain capabilities. Meter M1 measures the energy flows from the REC to the grid and vice versa. Meter M2 is the export-only meter of the PV system. Two different connection schemes for BESS are represented. In the first case, the BESS is connected *behind-the-meter* of the PV system; the battery can only charge from the renewable generator; the energy injected to the grid through Meter M2 is the aggregation of the PV energy and the one resulting from a discharging operation of the BESS. In the second case, the BESS is connected in a *standalone* configuration via the Meter M3. Here, the BESS absorbs/injects energy directly from/to the grid and these flows are measured by the bidirectional import/export Meter M3.

From a technical point of view, both connection schemes do not exhibit particular challenges and have been widely adopted to interface BESS with transmission and distribution networks. However, their differences have been exploited by the Italian legislator to define and motivate ad-hoc policy options enabling, upon certain limitations, the contribution of BESS to the SE of the REC. In fact, the flexibility offered by BESS may be exploited by the RECs' members in accordance with Article 31(2)(f) of the *Decreto Legislativo n.199*. However, the regulation only acknowledges the legal space for these assets without providing specific details concerning their contribution to the SE. The first set of impactful provisions concerning BESS in RECs are in Section 2.1.4 of the *Regole Tecniche* of the GSE. The energy that charges BESS in a behind-the-meter connection and then is re-injected, at a later moment, into the grid via Meter M2 contributes, as local generation, to the SE and its reward. As opposite, the *Regole Tecniche* of the GSE prohibits the energy absorbed/generated from/to the grid by the BESS (via Meter M3) from contributing to the SE.

Recently, the *Delibera 727/2022* of ARERA commented on the policy implications introduced by the GSE and it proposed a new policy option to enable the contribution of BESS in standalone configuration. In practice, only the energy absorbed by the BESS, multiplied by the "average" cycling efficiency of the asset, contributes to the amount of SE that receives the incentives. The energy injected at a later moment by the BESS would not be accounted for.

4. Modeling of connection and policy options for BESS in RECs

4.1. Introduction to alternative policy options

The policy option concerning the contribution of BESS to the SE approved by the GSE in its *Regole Tecniche* is currently the only binding set of provision for BESS in Italian RECs. So far, the proposal in the *Delibera 727/2022* of ARERA has not been formally received by the GSE, which in turn has not published an updated version of the *Regole Tecniche*. At a first glance, the policy options of the GSE and the ARERA exhibit fundamental limitations. For example, the first prevents a BESS in a standalone connection from contributing to the SE, although it easily guarantees that the energy injected by the BESS comes from renewable sources. The second procedure of the ARERA would allow to consider only *a priori* the shifting actions of the BESS. Besides the limitations above, the development of effective policy options for BESS in RECs are part of the enabling frameworks of the RED-II, which do not have to strictly transpose a set of EU requirements.

These considerations pave the way to the development of new policy options which may treat the contribution of BESS to the SE via frameworks alternative to the ones of the GSE and the ARERA. Considering a standalone connection scheme, in order to prevent energy from non-renewable sources to be part of the SE, the operation of the BESS and its contribution to the SE may be guided and limited by a de-rating factor.[7] This allows to effectively consider only the amount of energy absorbed and later injected which comes from RES. Furthermore, it is worth exploring so-called hybrid configurations i.e. where a standalone BESS is also able to directly charge from a RES unit and discharge behind the meter of the renewable generator.

In accordance with the proposed methodology in Fig. 1, the next subsections translate the fundamental characteristics of each of these options as MILP optimization problems. The scope is to assess the role and benefits of a BESS integrated in a REC together with an aggregation of end-user customers and a PV energy unit. It is assumed that all the assets operate under a *cooperative* approach, contributing to the achievement of a common objective, which is the maximization of the net revenue of the REC.

4.2. Mathematical formulation

4.2.1. Option 1 (O1) – No BESS

In a comparative assessment it is important to first determine a Base Case (BC) condition. The REC in Fig. 4(a), operating without a BESS and named Option 1, represents the BC. As required in (Gestore dei Servizi Energetici, 2022), the energy Meter M1 measures the energy flows from the REC to the grid and vice versa; Meter M2 is an export-only meter accounting for the PV energy. Assuming that the energy consumption of the loads is inflexible, the operation of this configuration of REC does not require the formulation and solution of an optimization problem.

In accordance with its definition in the *Decreto Legislativo 199*, the amount of SE, $\Phi_{O1,t}$ in (1a), is computed as the minimum, at each step t, between the PV production $\widetilde{P}_t$ and the consumption $\widetilde{L}_t$. Two revenue streams are defined. The first, $\mathscr{R}^{SE}_{O1}$ in (1b), refers to the SE $\Phi_{O1,t}$ rewarded with the incentives λ^{pr} and λ^{i} (see Section 3.2.1). Besides the SE and its revenue, the PV unit would still sell energy at the wholesale energy market. The corresponding revenue streams consider the relevant market price λ^{pun}_t (1c). The end-users of the REC must sustain the cost for purchasing energy given the corresponding tariff[8] λ^{ta}_t (1d). The quantities in (1) are computed for each $t = \{1 \dots T\}$ and for each day of the year indexed by $n = \{1 \dots N\}$.

$$\Phi_{O1,t} = \min\{\widetilde{P}_t, \widetilde{L}_t\} \bullet \Delta t \tag{1a}$$

$$\mathscr{R}^{SE}_{O1} = \sum_{n=1}^{N} \left[\sum_{t=1}^{T/2} \Phi_{O1,t} \bullet \left(\lambda^{pr} + \lambda^{i}\right) \right]_n \tag{1b}$$

$$\mathscr{R}^{gen}_{O1} = \sum_{n=1}^{N} \left[\sum_{t=1}^{T/2} \widetilde{P}_t \bullet \lambda^{pun}_t \bullet \Delta t \right]_n \tag{1c}$$

$$\mathbb{C}_{O1} = \sum_{n=1}^{N} \left[\sum_{t=1}^{T/2} \widetilde{L}_t \bullet \lambda^{ta}_t \bullet \Delta t \right]_n \tag{1d}$$

4.2.2. Option 2 (O2) – BESS behind the generation meter

The BESS in Option 2 is connected behind the export-only Meter M2 of the PV generator – Fig. 4(b). Since the BESS can only charge from a renewable generator, this connection scheme fully implements the

[7] Note that the adoption of de-rating factors is not new in the electricity sector to differentiate the performance and capabilities of different technologies. A practical example is the capacity market (Department of Energy and Climate Change, 2015).

[8] The tariff λ^{ta}_t for residential customers or small industries/offices connected to the LV system is likely to correspond to the so-called "*regime a maggior tutela*" (ARERAe). The contractual conditions are defined by the ARERA and target those users that have not opted for the wholesale energy prices. The value of λ^{ta}_t is updated every three months bases on ARERA's projections on future wholesale electricity prices.

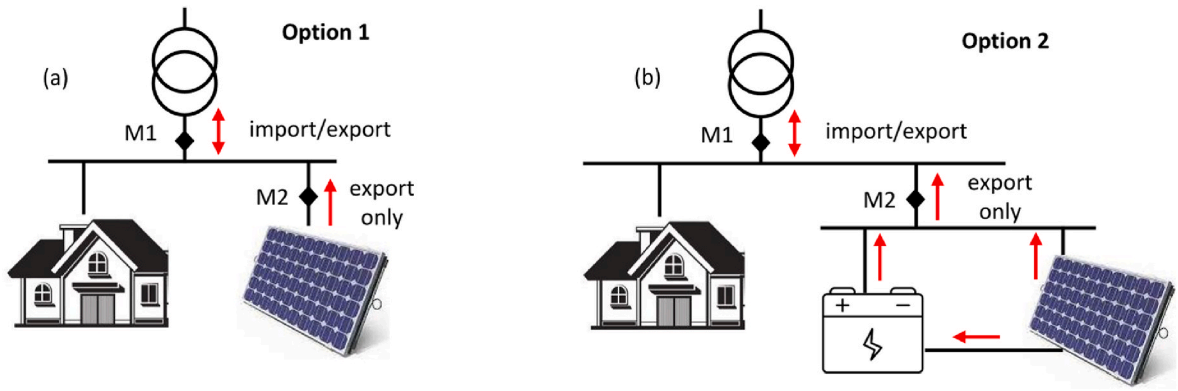

Fig. 4. Connection schemes for RECs under the features of Option 1 (a) and Option 2 (b).

connection and policy option in the *Regole Tecniche* of the GSE. The presence of a BESS, whose operation is flexible, requires the resolution of the MILP optimization problem (2) to maximize the net revenue of the REC. The problem is presented in a deterministic formulation, although a stochastic formulation to account for the PV uncertainty is not impeded. The PV availability is assumed to be perfectly known $\forall t = \{1 \dots T\}$.

$N = 365$ individual simulations indexed by n are carried out solving problem (2) since the horizon of the analysis is one year. The time window of each simulation $n = \{1 \dots N\}$ is 48-h with hourly time steps t of length $\Delta t = 1$ h so that $T = 48$. Only the solution of the first 24-h is kept, discarding all the decisions beyond this limit. This is done to avoid trivial solutions e.g. a nil energy level of the BESS at the end of the day. When moving from day n to $n+1$, the inter-temporal constraint relevant to the BESS energy level is adjusted. Note that, for compactness of the notation, the dependency on n is no longer shown beyond the objective function (2a). The dependency on n is reintroduced in (2g) as necessary.

$$\max\left\{\Delta t \bullet \sum_{n=1}^{N}\left[\sum_{t=1}^{T}\left(\Pi_t^d + P_t^g\right) \bullet \lambda_t^{pun} - \Pi_t^{cpv} \bullet \lambda^o + \Phi_{O2,t} \bullet \left(\lambda^{pr} + \lambda^i\right)\right]_n\right\} \quad (2a)$$

s.t.$\forall t = 1 \dots T$

$$0 \le \Pi_t^{cpv} \le (1 - u_t) \bullet \overline{\Pi} \quad (2b)$$

$$0 \le \Pi_t^d \le u_t \bullet \overline{\Pi} \quad (2c)$$

$$0 \le S_t \le \overline{S} \quad (2d)$$

$$S_{t+1} = S_t + \eta \bullet \Delta t \bullet \Pi_t^{cpv} - \frac{\Delta t \bullet \Pi_t^d}{\eta} \quad (2e)$$

$$S_1 = S_T \quad (2f)$$

$$S_{1_{|n+1}} = S_{T/2_{|n}} \quad (2g)$$

$$\Phi_{O2,t} \le \Pi_t^d + P_t^g \quad (2h)$$

$$\Phi_{O2,t} \le \widetilde{L}_t \quad (2i)$$

$$\Pi_t^d + P_t^g \le \overline{P}_{M2} \quad (2j)$$

$$P_t^g + \Pi_t^{cpv} \le \widetilde{P}_t \quad (2k)$$

It is worth pointing out that Π_t^d and P_t^g are the BESS discharge power and the share of the available PV power directed to the grid, respectively. These powers flow through Meter M2. The BESS can increase its state of charge S_t only by absorbing Π_t^{cpv} i.e. the share of PV generation directed to the BESS and not injected into the grid. The REC may decide that the price λ^o to charge the BESS is nil. Constraints (2b)-(2c) account for the BESS maximum generated/absorbed power, respectively. The use of binary variable u_t impedes double operating conditions at the same t. Energy boundaries are set by (2d); the energy conservation is expressed by (2e), where η is the round-trip efficiency. Equations (2f)-(2g) manage the initial and final energy levels maintaining the continuity between days.

Besides the benefits of arbitraging between λ_t^{pun} and λ^o, the value of introducing a BESS in the REC are highlighted by (2h) since the asset can contribute to the SE $\Phi_{O2,t}$. Clearly, (2i) completes the definition of the SE as minimum between the local generation and consumption. The power exported to the grid is limited in (2j) by the connection capacity $\overline{P}_{M2}$ of the Meter M2. The PV output is kept below the available level by (2k).

The revenue/cost streams associated to Option 2 are expressed in (3).

$$\mathscr{R}_{O2}^{SE} = \sum_{n=1}^{N}\left[\sum_{t=1}^{T/2}\Phi_{O2,t} \bullet \left(\lambda^{pr} + \lambda^i\right) \bullet \Delta t\right]_n \quad (3a)$$

$$\mathscr{R}_{O2}^{gen} = \sum_{n=1}^{N}\left[\sum_{t=1}^{T/2}\left(\Pi_t^d + P_t^g\right)\lambda_t^{pun}\Delta t\right]_n \quad (3b)$$

$$\mathbb{C}_{O2} = \sum_{n=1}^{N}\left[\sum_{t=1}^{T/2}\left(\widetilde{L}_t \bullet \lambda_t^{ta} + \Pi_t^{cpv} \bullet \lambda^o\right) \bullet \Delta t\right]_n \quad (3c)$$

4.2.3. Option 3 (O3) – standalone BESS

The standalone connection scheme is modelled with Option 3 in Fig. 5(a). The BESS is able to export/import energy to/from the grid respectively via Meter M3. The PV generation does not directly recharge the BESS. This option does not comply with the indications of the *Regole Tecniche* of the GSE concerning the contribution of BESS to the SE. Nonetheless the overall scheme of a standalone BESS is common to two of the policy options considered in this paper. The first is the proposal of the ARERA (see Section 3.2.3), while the second is the proposal envisaging de-rating factors to modulate the BESS contribution to the SE (see Section 4.1).

The optimization problem (4a)-(4g) mathematically translates the modeling features which are common to both these policy options under the same standalone connection scheme.

$$\max\left\{\Delta t \bullet \sum_{n=1}^{N}\left[\sum_{t=1}^{T}\lambda_t^{pun} \bullet \left(\Pi_t^d - \Pi_t^{cg}\right) + \Phi_{O3,t} \bullet \left(\lambda^{pr} + \lambda^i\right)\right]_n\right\} \quad (4a)$$

s.t.$\forall t = 1 \dots T$

$$0 \le \Pi_t^{cg} \le (1 - u_t) \bullet \overline{\Pi} \quad (4b)$$

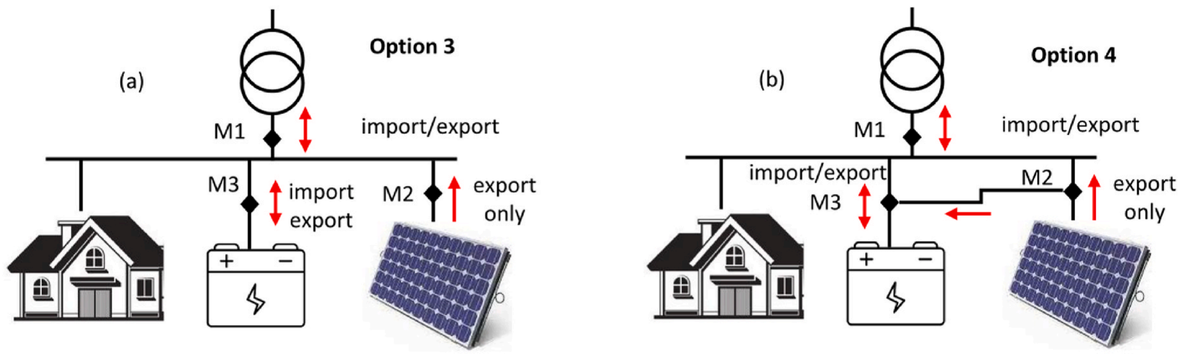

Fig. 5. Connection schemes for RECs under the features of Option 3 (a) and Option 4 (b).

$$0 \le \Pi_t^d \le u_t \bullet \overline{\Pi} \tag{4c}$$

$$0 \le S_t \le \overline{S} \tag{4d}$$

$$S_{t+1} = S_t + \eta \bullet \Delta t \bullet \Pi_t^{cg} - \frac{\Delta t \bullet \Pi_t^d}{\eta} \tag{4e}$$

$$S_1 = S_T \tag{4f}$$

$$S_{1_{|n+1}} = S_{T/2_{|n}} \tag{4g}$$

The amount of PV energy is no longer a decision variable since the generator can only export it through Meter M2 and cannot directly spare part of it to charge the BESS. Hence the BESS contributes alone to the maximization of the revenue by arbitraging against market prices (first term of the sum in (4a)) and contributing to the SE (second term of the sum in (4a)). Constraints (4b)-(4e) extend the scopes of (2b)-(2g) to the standalone connection. Differently from (2b), the storage unit can charge from the grid with Π_t^{cg}. The way the BESS contributes to the formation of the SE characterizes the differences between the proposal adopting de-rating factors and proposal of the ARERA.

On the one hand, the first of these two policy options is modelled with (4h)-(4i). The BESS effectively contributes to the SE while discharging (4h) and charging (4i). These are parametrized by the parameter $k = [0, 1]$, which represents the de-rating factor to account the share of energy purchased by BESS from those providers of 100% green energy contracts. It is worth noting that the particular case $k = 0$ would implement the approach of the GSE in its *Regole Tecniche* for standalone BESS, whereas $k = 1$ grants the BESS full contribution to the SE. Note that k is an input parameter and it is not a decision variable of the problem (4a)-(4i).

$$\Phi_{O3,t} \le k \bullet \Pi_t^d + \widetilde{P}_t \tag{4h}$$

$$\Phi_{O3,t} \le k \bullet \Pi_t^{cg} + \widetilde{L}_t \tag{4i}$$

On the other hand, the BESS contribution to the SE in accordance with the policy option of the ARERA is modelled by means of (4j)-(4k). Only the energy absorbed by the BESS, multiplied by the "average" cycling efficiency, is used in the calculation of the amount of SE. The energy injected to the grid by the BESS would not be accounted for. The proposal of the ARERA is fully modelled with the optimization problem (4a)-(4g),(4j),(4k).

$$\Phi_{O3,t} \le \widetilde{P}_t \tag{4j}$$

$$\Phi_{O3,t} \le \eta \bullet \Pi_t^{cg} + \widetilde{L}_t \tag{4k}$$

The revenue/cost streams relevant Option 3 are expressed in (5). These fit with the features of both the policy options recalled in this subsection.

$$\mathscr{R}_{O3}^{SE} = \sum_{n=1}^{N} \left[\sum_{t=1}^{T/2} \Phi_{O3,t} \bullet \left(\lambda^{pr} + \lambda^{i}\right) \bullet \Delta t \right]_n \tag{5a}$$

$$\mathscr{R}_{O3}^{gen} = \sum_{n=1}^{N} \left[\sum_{t=1}^{T/2} (\Pi_t^d + \widetilde{P}_t) \lambda_t^{pun} \Delta t \right]_n \tag{5b}$$

$$\mathbb{C}_{O3} = \sum_{n=1}^{N} \left[\sum_{t=1}^{T/2} \left(\widetilde{L}_t \bullet \lambda_t^{ta} + \Pi_t^{cg} \bullet \lambda_t^{pun}\right) \bullet \Delta t \right]_n \tag{5c}$$

4.2.4. Option 4 (O4) – hybrid BESS connection

The schematics of the last policy option discussed in Section 4.1 is presented in Fig. 5(b). The BESS can absorb/inject power from/to the grid via its own Meter M3 (as in Option 3) and charge directly from the PV generator (as in Option 2). It is assumed that all the energy flows through Meter M3 contribute to the SE (i.e. implicitly $k = 1$). The net revenue maximization problem is expressed by (6).

$$\max \left\{ \Delta t \bullet \sum_{n=1}^{N} \left[\sum_{t=1}^{T} \lambda_t^{pun} \bullet \left(\Pi_t^d + P_t^g - \Pi_t^{cg}\right) - \Pi_t^{cpv} \bullet \lambda^o + \Phi_{O4,t} \bullet \left(\lambda^{pr} + \lambda^i\right) \right]_n \right\} \tag{6a}$$

$$\text{s.t.} \forall t = 1 \dots T$$

$$0 \le \Pi_t^{cg} \le (1 - u_t) \bullet \overline{\Pi} \tag{6b}$$

$$0 \le \Pi_t^d \le u_t \bullet \overline{\Pi} \tag{6c}$$

$$0 \le \Pi_t^{cpv} \le (1 - u_t) \bullet \overline{\Pi} \tag{6d}$$

$$\Pi_t^{cg} + \Pi_t^{cpv} \le u_t \bullet \overline{\Pi} \tag{6e}$$

$$0 \le S_t \le \overline{S} \tag{6f}$$

$$S_{t+1} = S_t + \eta \bullet \left(\Pi_t^{cg} + \Pi_t^{cpv}\right) \bullet \Delta t - \frac{\Delta t \bullet \Pi_t^d}{\eta} \tag{6g}$$

$$S_1 = S_T \tag{6h}$$

$$S_{1_{|n+1}} = S_{T/2_{|n}} \tag{6i}$$

$$\Phi_{O4,t} \le \Pi_t^d + P_t^g + h \bullet \Pi_t^{cpv} \tag{6j}$$

$$\Phi_{O4,t} \le \Pi_t^{cg} + (1 - h) \bullet \Pi_t^{cpv} + \widetilde{L}_t \tag{6k}$$

$$P_t^g + \Pi_t^{cpv} \le \widetilde{P}_t \tag{6l}$$

Considering Fig. 5(b), Π_t^{cpv} may contribute to the SE in a twofold manner. Whether it is treated as part of "generation" power measured by M2, it contributes to the SE by means of (6j). In this case, the unitless parameter h should be set to 1. Alternatively, Meter M3 would account for Π_t^{cpv} if the latter is treated as power consumption of the BESS ($h = 0$ in (6k)). Note that h is an input parameter and not a binary decision variable.

The revenue/cost streams relevant to the REC under the features of Option 4 are expressed in (7).

$$\mathscr{R}_{O4}^{SE} = \sum_{n=1}^{N}\left[\sum_{t=1}^{T/2}\Phi_{O4,t} \bullet \left(\lambda^{pr} + \lambda^{i}\right) \bullet \Delta t\right]_n \tag{7a}$$

$$\mathscr{R}_{O4}^{gen} = \sum_{n=1}^{N}\left[\sum_{t=1}^{T/2}\left(\Pi_t^{d} + P_t^{g}\right)\lambda_t^{pun}\Delta t\right]_n \tag{7b}$$

$$\mathbb{C}_{O4} = \sum_{n=1}^{N}\left[\sum_{t=1}^{T/2}\left(\widetilde{L}_t \bullet \lambda_t^{ta} + \Pi_t^{cg} \bullet \lambda_t^{pun} + \Pi_t^{cpv} \bullet \lambda^{o}\right) \bullet \Delta t\right]_n \tag{7c}$$

4.3. Definition of the KPIs

The final task of the modeling phase of the methodology in Fig. 1, is the definition of the KPIs for the quantitative assessment of role and benefits of integrating BESS in RECs considering current and alternative connection and policy options.

The three KPIs formulated in this paper are expressed below for a generic option $x \in \{O1, O2, O3, O4\}$:

$$\Omega_{Ox}^{'} = \mathscr{R}_{Ox}^{SE} + \mathscr{R}_{Ox}^{gen} - \mathbb{C}_{Ox} \tag{8}$$

$$\Omega_{Ox}^{''} = \mathscr{R}_{Ox}^{gen} - \mathbb{C}_{Ox} \tag{9}$$

$$\Omega_{Ox}^{'''} = \mathscr{R}_{Ox}^{gen} + \sum_{n=1}^{N}\left(\sum_{t=1}^{T/2}\Phi_{Ox,t} \bullet \lambda^{i}\right) - \mathbb{C}_{Ox} \tag{10}$$

The first KPI $\Omega_{Ox}^{'}$ in (8) indicates the algebraic sum of the three cash flows defined for each of the options in Section 4.2; the second KPI $\Omega_{Ox}^{''}$ in (9) computes the net cash flow while neglecting the whole contribution relevant to the SE. The last one, $\Omega_{Ox}^{'''}$ in (10) adds up to $\Omega_{Ox}^{''}$ only the portion of SE revenue which refer to the incentive λ^{i} established by the ARERA for the avoidance of network charges.

The first KPI does not differentiate between the actual use and purpose of the relevant cash flows. In fact, it is the only one considering all the actual cash flows of the REC. Note that the formulation of $\Omega_{Ox}^{'}$ in (8) implicitly assumes that the members of the REC can use the entire amount of the SE revenue to net-off their energy costs. In other words, this would imply that the SE revenues can be entirely used for financial purposes. However, the authors wish to emphasize that the primary purpose of a REC is to provide environmental, economic or social community benefits rather than financial profits.[9] Hence, the second KPI $\Omega_{Ox}^{''}$ in (9) imposes that the whole revenue stream from the SE cannot be used to reduce the total electricity costs of the REC. A compromise formula is modelled by means of the third KPI $\Omega_{Ox}^{'''}$ (10), enabling the achievement of a partial financial gain. The REC is correctly refunded of the payment of the use-of-network charge λ^{i} with respect to SE, which, by definition, has not flowed through the main distribution grid.

[9] in accordance with Article 2(16) of the RED-II and Article 31(1)(a) of the *Decreto Legislativo 199*.

5. Results

5.1. Assessment of the Italian transposition of the RED-II

In accordance with the methodology illustrated in Fig. 1, the first part of the results of this paper assesses the correctness of the Italian transposition of specific rights of the RECs established in the RED-II and the presence of other provisions potentially conflicting with the EU design added by the Italian legislator. The implementation of three fundamental aspects appears to deviate from the scopes and objectives envisaged by the EU legislator.

5.1.1. Becoming a member and exercising effective control

The first aspect deals with the transposition of the provisions concerning the status of members or shareholders and the notion of effective control from the RED-II into the *Decreto Legislativo n.199*. As recalled in Section 3.1, The RED-II introduced the *combined provisions* for prospective private undertakings. These shall:

- be listed as SMEs (Article 2(16) of the RED-II) and, *at the same time*,
- ensure that their participation to the REC does not constitute the primary commercial or professional activity (Article 22(1) of the RED-II).

The definition of RECs in Article 31(1)(c) of the *Decreto Legislativo n.199* appears to enforce only the second bullet point for prospective private undertakings in RECs. In other words, the *Decreto Legislativo n.199* may fail to prevent large private undertakings (i.e. beyond SMEs) from joining the REC as a member.

The need for private undertakings to be listed as SMEs would only affect those entities willing to exercise effective control over the REC. For the sake of clarity, an extract of the point (b) of Article 31(1) of the *Decreto Legislativo n.199* is recalled. The authors wish to emphasize that they are not aware of an official English translation of the *Decreto Legislativo n.199*. Hence, the authors' translation is:

"[…] the community is an autonomous legal character and control power shall be exercised only by natural persons, SMEs, territorial entities and local authorities […]"

The setup above is confirmed in the *Regole Tecniche* of the GSE and in the *Delibera 727/2022* of the ARERA.

5.1.2. The primary commercial or professional activity of private undertakings

Concerning the limitations on the commercial or professional activity of private undertakings in RECs, the *Decreto Legislativo n.199* exhibits a faithful transposition of the corresponding provisions in the RED-II. In fact, the participation to the REC by a private undertaking shall not constitute the main commercial and/or industrial activity. However, Section 2.3.1 of the *Regole Tecniche* of the GSE add that private undertakings in RECs may also demonstrate that their prevalent ATECO code[10] is not 35.11.00 (Codicea) nor 31.14.00 (Codiceb). Note that:

- The ATECO code 35.11.00 refers to the management of generating plants producing electrical energy from any source with the exception of waste incineration.
- The ATECO code 35.14.00 refers to the pursuit of activities such as the sale of electrical energy to end-users, the acting as intermediaries or agents organizing the sale of electrical energy via distribution systems managed by third-parties, and the trade of electrical energy and transmission capacity.

This setup appears to be unjustified and not in accordance with the

[10] The ATECO is the Italian version of the NACE, the European classification of the economic activities.

RED-II. First, Article 22(1) of the RED-II does not assign any discretional power to MS concerning the applicable requirements for members of the REC. In fact, the provisions of Article 22(1)–(2) are part of the *rights* for members of the REC. These are automatically guaranteed by the EU regulation and do not require any further interpretation or provision from the MS during the transposition process. Second, none of the RED-II articles which are relevant to the RECs ever mention belonging to the commercial or industrial sector of private undertaking to a specific sector as a discerning factor among the eligibility criteria.

The only ground for appeal to support the restrictions introduced in the Italian legislation concerning the primary commercial or professional activity of private undertakings is the Recital (71) of the RED-II. A recital is a piece of text at the beginning of EU acts that explain the underlying reasons for the following articles. However, recitals are not in themselves legally binding in the same way that the articles are (European Union). A MS implementing EU legislation into national law does not have to transpose the recitals.

An extract of Recital (71) of the RED-II is reported below:

"To avoid abuse and to ensure broad participation, renewable energy communities should be capable of remaining autonomous from individual members and other traditional market actors that participate in the community as members or shareholders […]."

Regardless of the fact that the Recital (71) discusses the concept of autonomy of a REC and not its membership criteria, this extract of the RED-II reflects on the intrinsic advantages concerning the operation of a REC that energy/market-related enterprises might hold compared to any other type of member/shareholder e.g. natural persons or local authorities. However, it is worth noting that Recital (71) does still not open up to the restrictions of the Regole Tecniche of the GSE. In fact, the recital clearly envisages the possibility of having traditional market actors, i.e. private undertakings active in the energy field, as members of the REC. Hence, Recital (1) cannot be used, in any way, to justify the discriminative provisions introduced by the GSE.

5.1.3. The role of "third-parties"

The *Regole Tecniche* of the GSE introduces further provisions concerning the private undertakings in the electricity sector. Section 2.3.2 of this document grants producers of electrical energy from RES (i.e. some of the private undertakings with ATECO code 30.11.00) the opportunity to join a REC as third-parties. The provision does not specify the size of the private undertaking; it is therefore licit to assume that the opportunity is not limited to SMEs only. RES producers that are located in the portion of the network forming the REC may let the energy produced from their assets to be included in the computation of the SE, although these producers may not be members of the REC due to their primary commercial or professional activity.

However, it is worth noting that the role of the third-parties is not present in the RED-II nor in the *Decreto Legislativo n.199*. The above-mentioned provisions in the *Regole Tecniche* of the GSE introducing the third-parties do not transpose or implement any specific article from the two regulations. For this reason, third-parties might not have any legal ground.

Moreover, the introduction of third-parties contradicts another clear objective of the EU and Italian legislation. The private undertakings active in the electricity sector that use the third-parties definition as a back-door entry into the REC may be entities whose main objective is indeed the participation to the REC. However, this is exactly what the RED-II (Article 22(1)) and the *Decreto Legislativo n.199* (Article 31(1)(c)) aim to impede.

As for the issues discussed in Section 5.2.2, the additional requirements introduced by the GSE have been recalled by the Italian NRA. The *Documento 390/2022* of the ARERA may confirm the possibility for certain producers to contribute to the community's SE as third-parties, without being members. The *Documento 390/2022* simply affirms that the generating assets of these third-parties shall be fully controlled and made available to the community. Finally, Article 3(2)(c) of the *Annex A* of the *Delibera 727/2022* of the ARERA requires that the electrical energy produced by third-parties can be rewarded with the applicable incentives (i.e. contributing to the assessment of the SE) provided that these third-parties are subject to the instructions of one or more members of the community.

5.2. Assessing the connection and policy options for BESS in a REC

The second part of the results deals with the quantitative assessment of the role for BESS joining RECs in order to contribute to the SE and the associated revenue stream. Besides the proposals brought forward by the GSE and the ARERA, two other policy options are considered and compared to the BC without any BESS (Section 4.2). Results mainly consist in the assessment of the three KPIs formulated in Section 4.3.

5.2.1. Case studies and input data

Before evaluating the numerical results, Table 1 lists the main features of the corresponding optimization problems and cost/revenue calculations for the simulated case studies. The BC implements the connection option 1 (Section 4.2.1); due to the lack of BESS, the compliance with the GSE or the ARERA rules is not applicable; for the same reason, the computation of the KPIs does not require the resolution of an optimization problem. CS1 refers to connection option 2 (the behind the meter - Section 4.2.2), which complies with the GSE provisions concerning the contribution of the BESS to the SE. CS2_an up to CS2_d envisage a standalone connection for the BESS (Section 4.2.3). The operation of the BESS and the consequent contribution to the SE would depend on different numerical values for the de-rating factor k in (4h)-(4i). CS3 implements again a standalone connection for the BESS (Section 4.2.3) and it applies with (4j)-(4k) the policy option of the ARERA. Finally, the hybrid connection is studied with CS4. Note that, CS2_an up to CS2_d and CS4 carry out policy options with do not comply with the GSE provisions nor with proposal of the ARERA.

Input data for the aggregate load consumption and PV generation are from the dataset in (Goncalves et al., 2022). Details are in Appendix. The connection capacity $\overline{P}_{M2}$ has been chosen to be 80 kW, slightly above the maximum recorded PV output (76.8 kW). Reference values for the BESS are $\overline{\Pi} = 80$ kW, $\overline{S} = 80$ kWh and $\eta = 0.92$ (Trovato and Kantharaj, 2020). For simplicity, the effect of the degradation of the state-of-health of the BESS is neglected. Without loss of generality, λ^o, the price for the BESS to absorb energy from the PV generation, is set to zero. Moreover, $\lambda^{pr} = 0.11$ EUR/kWh (ARERAb) and $\lambda^i = 0.00837$ EUR/kWh (ARERAc). Reference simulations (results in Section 5.2.2) are carried out using the actual 2021 Italian wholesale market prices i.e. the Unique National Price (PUN) prices λ_t^{pun} (Gestore dei Mercati Elttrici (GME)). Sensitivity

Table 1
Description of the case studies.

Case studies	Connection option	BESS compliance with		Optimization problem	Revenue/cost calculation
		GSE rules (Gestore dei Servizi Energetici, 2022)	ARERA solution (ARERA, 2022)		
BC	1	n.a.	n.a.	n.a.	(1)
CS1	2	✓	×	(2)	(3)
CS2_a	3	✓	×	(4a)-(4i), $k = 0$	(5)
CS2_b	3	×	×	(4a)-(4i), $k = 0.33$	(5)
CS2_c	3	×	×	(4a)-(4i), $k = 0.66$	(5)
CS2_d	3	×	×	(4a)-(4i), $k = 1$	(5)
CS3	3	×	✓	(4a)-(4g), (4j)-(4k)	(5)
CS4	4	×	×	(6)	(7)

studies (results in Section 5.2.3) adopt the PUN prices of 2020 and 2022. The same structure is applied to the tariff λ_t^{ta} set by the ARERA for end-user customers within the so-called "*regime di maggior tutela*" (ARERAd). In general, λ_t^{pun} and λ_t^{ta} have both increased significantly moving from 2020 to 2022 (as illustrated in the Appendix closing the paper).

It is worth noting that the relationship between the incentive λ^{pr} for the SE and both the λ_t^{pun} and λ_t^{ta} has significantly changed over the considered period. Whether λ_t^{pun} and λ_t^{ta} have largely increased from 2020 to 2022, the incentive λ^{pr} was set in 2020 and it has been kept constant since then. The analysis in Table 2 exhibits that the magnitude of the incentive λ^{pr} in 2020 has been 99.95% of the times above the maximum wholesale market price λ_t^{pun}. The same condition was respected in 2021 only 60.47% of the times due to the initial rise of λ_t^{pun}. An opposite condition is registered in 2022, letting the λ^{pr} be above λ_t^{pun} rarely. Similar trends characterize the comparison between λ^{pr} and λ_t^{ta}.

5.2.2. Analysis of the cost/revenue streams

Fig. 6 presents the annual cost/revenue streams obtained by the considered REC for the case studies in Table 1. For a generic connection option x and then the corresponding case study, the red bars correspond to $\mathscr{R}_{Ox}^{SE}$ the annual revenue arising from the contribution to the SE; the blue bars indicate the generation revenue $\mathscr{R}_{Ox}^{gen}$, accounting for the discharged energy from the BESS and the energy generated by the PV unit. The bars in grey refer to $\mathbb{C}_{Ox}$ the consumption cost (negative value) sustained by end-users and the BESS while in charging operation. The numbers indicate the percent variation of the SE revenue with respect to the one in BC.

It is worth noting that the SE revenue increases with respect to the BC for all the case studies but the CS2_a; in that case, the flexibility of the BESS does not contribute to the SE since $k = 0$ in (4h)-(4i). The limitations to the BESS flexibility under the CS1 allow for the lowest increment 15% (besides the CS2_a). The remaining connection options refer to a BESS in a standalone configuration and produce remarkable increments in the SE revenue. The only exception is for CS3, the one implementing the policy option of the ARERA, with only a 23% increase.

Moreover, with CS2_c, CS2_d and CS4, the generation revenue is significantly more relevant than with CS1, CS2_a and CS3. This result indicates a strong interplay between the SE revenue and the generation revenue. Even a minor contribution $k = 0.33$ in CS2_b leads to twice larger generation revenue compared to the CS2_a, which implements by $k = 0$. On the other hand, a more active operation[11] of the BESS necessitates higher consumption costs $\mathbb{C}_{Ox}$. As expected, these remain constant under the CS1 and register a minor (negative) increment under the CS2_a, where the BESS can only arbitrage against market prices. A similar increment in consumption cost occurs with CS3.

Note that the results of the CS2_c and the CS4 cases are identical (both with $h = 1$ or $h = 0$). The operation of the BESS and the PV generator remain decoupled in order to exploit the incentives to the SE λ^{pr} and λ^{i}.

Table 2
Comparing premium and market prices and end-user tariff.

condition	annual frequency of occurrence [%]		
	2020	2021	2022
$\lambda^{pr} \geq \lambda_t^{pun}$	99.95%	60.47%	2.33%
$\lambda^{pr} \geq \lambda_t^{ta}$	49.86%	0.00%	0.00%

[11] it is worth emphasizing that a more participating operation of the BESS entails a higher number of charging/discharging cycles, which in turn may accelerate the degradation of the state of health of the battery, eventually affecting the performance (Trovato and Kantharaj, 2020).

Furthermore, the numerical assessment of the three KPIs (8)–(10) formulated in Section 4.3 is in Fig. 7. For a generic connection option x and then the corresponding case study, the red stars indicate the value of Ω'_{Ox} (8); grey dots compute Ω''_{Ox} (9), while black stars evaluate Ω'''_{Ox} (10). The numbers in red indicate the percent variation of the computed Ω'_{Ox} with respect to the one with the BC. Similarly, the numbers in black refer to the percent variation of Ω'''_{Ox} with respect to the one with the BC.

The limited BESS participation to the SE under the CS1 produces a −3.4% reduction in the net cash flow. Considering the red stars, the nil contribution of the BESS to the SE under CS2_a lets only a minor reduction (−2.9%). Remarkable reductions are obtained with the CS2_b, CS2_c, CS2_d and CS4 due to the active BESS participation to the SE. The increment in consumption cost in Fig. 6 is effectively compensated by the increments in the generation and SE revenue. While sharing the same standalone connection option with the CS2_b, CS2_c, CS2_d and CS4, the limitations featuring the policy option of the ARERA (CS3) produce limited cost reduction, e.g. −6.7% reduction compared to the BC. Note that the CS3 still outranks the CS1.

The trends remarkably change when considering the black stars and grey dots. The largest cost savings (−3.5%) are now obtained with the CS2_a, where the benefits stemming from the BESS flexible operation is irrelevant to the definition of the SE. A very similar result if achieved with CS3. This is expected since the only difference between CS2_a and CS3 is the BESS contribution to the SE while in charging mode. Once the relevant SE revenue is partially or totally neglected, as in Ω''_{Ox} and Ω'''_{Ox} respectively, the added value of CS3 compared to a standalone BESS (CS2_a) reduces.

Moreover, if the SE revenue are totally/partially excluded due to the abovementioned reasons, the net cost of the REC would actually increase with respect to the BC with the CS2_b, CS2_c, CS2_d and CS4. In other words, the resulting REC's electricity cost may increase by totally/partially excluding the large revenue for the SE, since the latter has to be used for purposes alternative to the mere cost reduction.

Finally, it should be emphasized that the portion of the SE revenue which could be used to directly reduce the electricity costs is overall small, as explicated by the limited difference between the grey dots and black stars. Note that for those case studies that reduce the BESS contribution to the SE, the grey dots and the black stars are almost overlapped.

5.2.3. Sensitivity to market prices and end-user tariffs

While keeping λ^{pr} and λ^{i} constant (realistic assumption), Fig. 8 illustrates the percent variation of the annual cost/revenue realized by the REC considering the λ_t^{pun} and λ_t^{ta} relevant to 2020 and 2022. The comparison is made with respect to the reference results in Fig. 7 for 2021 and it is carried out considering the most relevant case studies. As expected, both the generation revenue and consumption cost in Fig. 8(a) would drop driven by the overall lower prices in 2020 (see Appendix), exhibiting an opposite trend with the 2022 prices. On the other hand, the revenue stemming from the contribution to the SE exhibit only marginal variations - Fig. 8(b).

It can be noted that in 2020 the generation revenue would drop more than the consumption costs in relative terms; an opposite trend is for 2022 since the generation revenue increases more than consumption costs in relative terms. These trends are therefore responsible for decrements - for 2020 - and increments - for 2022 - of the annual net cash flows of the REC, with respect to the 2021. Fig. 8(b) indicates only a minor decrement of the SE revenue in 2022 due to a reduced amount of SE. The largest drop is for the CS2_d, the most intended one to the SE. For the sake of example, at a generic time-step t characterized by $\lambda_t^{pun} \gg \lambda^{pr}$ and by a low consumption $\widetilde{L}_t$, the BESS may prefer to discharge the entire energy reservoir, even if this energy no longer contributes to the SE (the minimum condition would be set by $\widetilde{L}_t$) rather than store part of

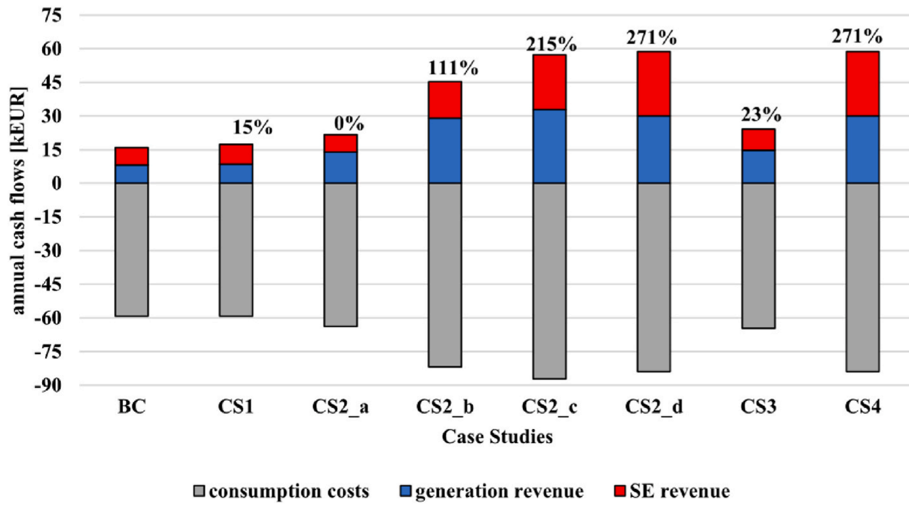

Fig. 6. Annual cash flows $\mathscr{R}_{Ox}^{SE}$ (red), $\mathscr{R}_{Ox}^{gen}$ (blue) and $\mathbb{C}_{Ox}$ (grey) of the REC. Results are computed with the 2021 numerical assumptions. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

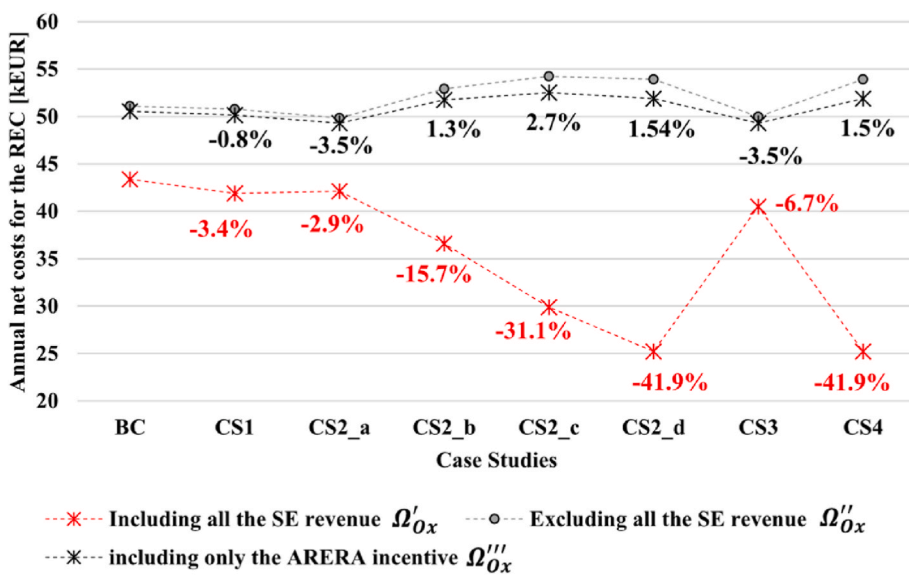

Fig. 7. Numerical value of the KPIs Ω'_{Ox} (8) red stars, Ω''_{Ox} (9) grey dots, and Ω'''_{Ox} (10) black stars. The numbers at the top are the percent variations in Ω'''_{Ox} with respect to the corresponding BC results. The numbers at the bottom are the percent variations in the Ω'_{Ox} with respect to the corresponding BC results. All the results are computed with the numerical assumptions of the year 2021. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

this energy and use it at later time to contribute to the SE. Similarly, with the 2020 market prices, the REC is able to slightly increase the SE revenue as result of a higher amount of SE, further incentivized by $\lambda^{pr} \gg \lambda_t^{pun}$. As expected, the variation in the amount and corresponding revenue of SE is nil for the BC.

6. Discussion and conclusive remarks

This paper offers an up to date overview of the transposition of the provisions of the RED-II concerning RECs into the Italian regulatory framework. First, it identifies those national requirements that do not fully comply with the *rights* of RECs as established in the RED-II. Second, it evaluates the effectiveness of current and alternative policy options enabling the contribution of BESS to the SE and its impact on the economic performance of the RECs. The participation of a BESS in a REC is an example of *enabling framework* that MS may establish to foster the development of RECs.

A critical discussion on the results and their implications is provided in the next subsections. In particular, Section 6.1 addresses the first research question raised in Section 1.1. The argumentations concerning the other research questions are in Section 6.2.

6.1. Discussion on the Italian transposition of the RED-II

The results concerning the national transposition of the RED-II have indicated non-negligible criticalities. Although the *Decreto Legislativo n.199* completed the overall process, Italy has not established yet a definite scheme of the incentives related to the RECs and the SE. This task was supposed to be ended, already with significant delay, by March 2023 (see Fig. 2). As a consequence, the lack of regulatory clarity forces prospective members of RECs and investors to delay the implementation of their projects while waiting, for example, for the definition of new premium prices λ^{pr} or for a revision of the policy options for BESS. In fact, these features largely contribute to the financial feasibility of

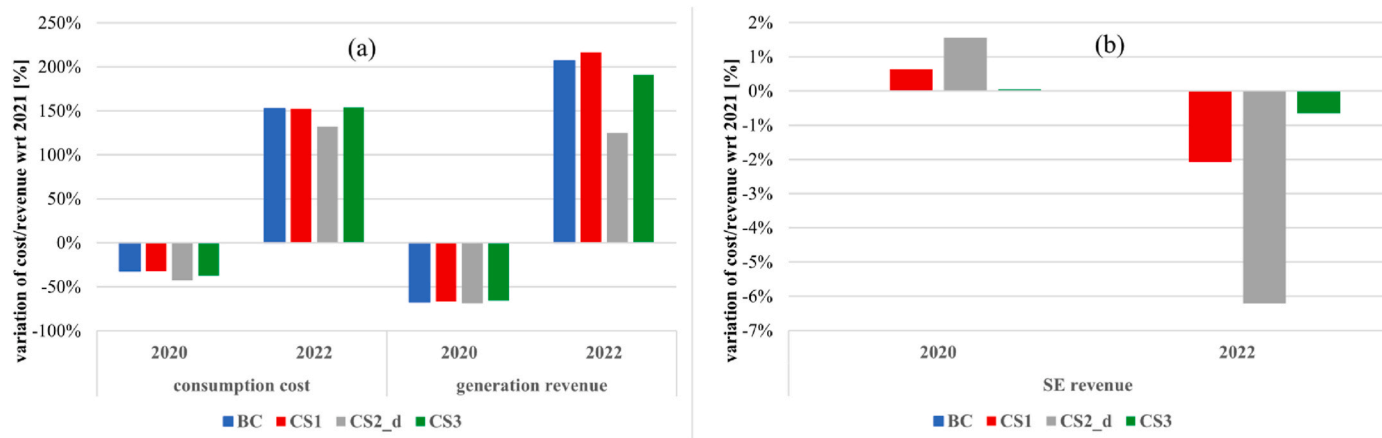

Fig. 8. Percent variation of consumption costs and generation revenue (a) and SE revenue (b) using the input prices relevant to 2020 and 2022. The numerical values are with respect to the results obtained for 2021.

investments in new RECs.

Furthermore, the results in Section 5.1 demonstrate the presence of important national provisions which do not correctly transpose with the *rights* established at the EU level or which are even in conflict with them. Once an EU directive has entered into force, the correct transposition of its provisions is a mandatory task and objective for a MS. It is worth noting, that the amendments to the national legislation, pursuant to the monitoring activities of the EC, may be enforced and implemented months/years after the approval of the national legislation. As a consequence, some/all members of the RECs could be excluded from the communities themselves or face extra-costs to ensure *post-date* compliance with the amended provisions. Last but not least, the MS and the relevant NRA could have to face single- or class-lawsuits from RECs representatives. In order to avoid the scenario above, the authors call for a rapid amendment of the non-compliant provisions detected in Section 5.1 concerning the eligibility criteria for memberships and effective control, the role of third-parties and the discriminatory provisions against certain private undertakings. The authors do not propose new alternative solutions in this case; this would be a worthless exercise since a MS cannot implement amended versions of fundamental rights of EU Directives. In fact, only a recast (EUR-Lex) of the RED-II carried out at EU level may give the opportunity to amend the RECs' rights. However, to the best of the authors' knowledge, the EC is not planning to carry out such activity in the immediate future. Nonetheless, the recast of an EU Directive is a complex exercise which could require years before its entry into force.

Besides the overall risks highlighted above, results in Section 5.1.1-3 require critical discussions on the implications of certain policies adopted in the Italian regulation. For example, letting large private undertakings (i.e. beyond SMEs) joining RECs would presumably accelerate their spread on the national territory due to large CapEx injections (Section 5.1.1); however, the role of citizens and small commercial/industrial entities in each REC could become impoverished. Moreover, if large private undertakings populate and invest in a multitude of RECs, it will be more difficult to keep the financial profits before the pursuit of environmental economic and social community benefits. Results in Section 5.1.2 deal with requirements added in the *Regole Tecniche* of the GSE preventing most, if not all, the private undertakings that are active in the electricity sector from joining a REC, regardless their size. This addition is unjustified since it lacks of any reference to a corresponding provision in the RED-II. In addition, the GSE provisions introduce a discriminatory treatment which may affect the creation of a level playing field. The envisaged setup might slow down the development of RECs since those SMEs active in the electricity sector are indeed promising candidates to guide the initial rollout of RECs; they respect the eligibility criteria due to their limited size and can bring useful experience which other types of members (e.g. natural persons) may not have at this initial stage. The authors' critical assessment is supported by several stakeholders. In fact, the *Delibera 727/2022* of the ARERA reports the stakeholders' request to the GSE to remove the ATECO code from the eligibility criteria for prospective private undertakings, preventing a discriminating treatment. The ARERA does not further elaborate on this issue. It is desirable that either the GSE or the ARERA bring clarity on this in future publications.

Furthermore, as discussed in Section 5.2.3, the GSE and the ARERA have endorsed the role of third-parties in RECs. These figures do not have any correspondent figure in the RED-II; moreover, their role and positioning in the Italian regulation concerning RECs remain vague. It is not clear whether third-parties can cash in a share or the full revenue stream applicable to their contribution to the SE of the REC or rather leave this revenue with the REC. Moreover, the interactions between the members of the REC and the third-parties are not explicated. Provided that the units owned by the third-parties shall comply with the technical requirements applicable to the assets owned by the members to the REC, the *Regole Tecniche* of the GSE do not mention the extent to which third-parties must comply with the rules forming the statute of the REC. For example, this vague setup may allow third-parties to benefit from financial incentives (λ^{i} and λ^{pr}) and set the profit realization as main objective out of the collected revenue, putting aside the pursuit of environmental, economic and social benefits. This would be an important violation of a key regulatory objective of the EU and the Italian legislator. The realization of this scenario or similar ones should be avoided. Third-parties acting outside the regulatory perimeter of a REC may *de facto* take advantage of RECs members such as small local authorities and citizens, which in turn might be incentivized to leave the REC. The authors solicit the ARERA as the competent authority on the matter to provide clarifications on the role of third-parties. However, the authors believe that the lack of a direct definition of third-parties in the RED-II and in the *Decreto Legislativo n.199* is sufficient to conclude that these figures should not operate with RECs or directly join them.

6.2. Discussion on the connection and policy options for BESS in RECs

This paper also analyzes the impact of the policy options concerning the operation of a BESS in order to contribute to the SE of a REC. The first part of the critical discussion deals with the fundamental reasoning and implications of the policy options of the GSE and of the ARERA. The second part discusses the implications of the numerical results in Section 5.2.

At the moment, the only binding policy option in Italy is the one introduced by the GSE, the entity also responsible of the SE revenues accounting. On the one hand, this option allows BESS connected *behind-*

the-meter of the renewable generators of the REC to contribute to the SE. On the other hand, the contribution from a BESS in a *standalone* connection is completely impeded; in other words, the GSE policy option implies that a BESS in a standalone configuration is worthless concerning its potential contribution to the SE revenues of the REC. This intent acts as a strong barrier to the spread of BESS in RECs. The reasoning of the GSE appears to be insufficient. This entity deems that only the behind-the-meter configuration guarantees, without further measurements, that the energy discharged by the BESS comes from RES and thus can actually contribute to the SE. However, the authors point out that, under a standalone connection, the BESS may still charge and discharge renewable energy. Several energy providers can indeed guarantee the source of the energy delivered to their customers. The Guarantee of Origin (GSE), established and monitored by the GSE itself, is an electronic certification that ensures the renewable origin of the electricity produced by renewable plants.

Although the GSE has not formally presented a new proposal, the authors advise to review the current scope of application of the *Regole Tecniche* of the GSE to include standalone BESS under the scope of application of the *Regole Tecniche.* On the one hand, the attempt of the ARERA to mitigate the limitations in the *Regole Tecniche* of the GSE should be waved positively. On the other hand, the practical implementation of the policy option of the ARERA distorts the bi-directional and flexible nature of a BESS, forcing these assets to be considered only as flexible loads. If RECs have been imagined as a framework to foster the local sharing of renewable energy, the BESS should have the right to contribute to this scope not only while charging but also while discharging. In fact, the ability of BESS to store energy and shift in time should be used and rewarded in a twofold manner i.e. increase the REC's load at times with large RES availability and, vice versa, to increase the REC's generation at times with low RES availability.

The critical discussion concerning the policy options proposed by the GSE and the ARERA paved the way to two alternative solutions for a BESS in a REC. The first one envisages the contribution to the SE of a standalone battery to be adjusted by de-rating factors. Note that this policy option can be actually implemented without major technical complexities; in fact, it can rely on the use of Contract of Origin (GSE) to account the share of RES energy absorbed/injected by the BESS and thus set the value of the de-rating factors accordingly. The second policy deals with a BESS connected in hybrid configuration (i.e. the assets may charge from behind-the-meter of the RES generator and from the grid).

Detailed results concerning the values of the KPIs for all the policy options are in Section 5 and require to a critical discussion. All the KPIs referring to the proposal of ARERA (CS3) outrank those with the CS1, implementing the GSE proposal. This is expected due to the overall higher flexibility of a BESS in standalone configuration compared to a behind-the-meter connection. However, this result does not prove the actual effectiveness of the ARERA proposal. In fact, the first KPI (8), computed for all the other policy options in standalone connection and contributing to the SE (CS2_b up to CS2_d) or for the hybrid option CS4, outrank the on evaluated with ARERA proposal (CS3). There is another way to prove the ineffectiveness of the ARERA proposal. If the economic assessment does not (or only partially) consider the SE revenue ($\Omega^{''}_{Ox}$, $\Omega^{'''}_{Ox}$, (9) and (10) respectively), the net electricity cost of a REC following the ARERA proposal does not differ from the one in CS2_a. In practice, there is no difference in terms of net electricity cost between having a BESS completely neutral to the SE (CS2_a) and operating the BESS to contribute to the SE under the scheme set by the ARERA ((4j)-(4k)).

Overall, the numerical results are consistent with those reported in similar studies (e.g. (Cielo et al., 2021), (Ghiani et al., 2022)) and highlight potential value for BESS in RECs. Note that this statement applies only some of the policy options considered in this work. To the best of the authors' knowledge, there is no information on the application of the ARERA proposal nor the policy option adopting de-rating factors in other works. Moreover, other works typically assess numerical metrics like the KPI (8) without computing (9) or (10).

Another important result of this paper may inform on the upcoming revision of the incentive premium λ^{pr} for the SE. Results in Table 2 highlight a clear intent pursued in 2020 when setting the value λ^{pr} i.e. having the premium price λ^{pr} always above the wholesale market price λ^{pun}_t. This situation drastically changed in 2021, reaching the opposite condition in 2022. Pursuant to these increments in the wholesale prices, it was not straightforward to assess the actual ability of λ^{pr} to effectively incentivize the members the REC to contribute to the SE. Looking at Fig. 8(b) and recalling the insights in Table 2, it is possible to conclude that the value of λ^{pr} has been able to effectively incentivize the achievement of SE even during 2022, when λ^{pun}_t and λ^{ta}_t have been both (almost) always above the λ^{pr}. This empirical result lets a more structural consideration. Setting a high incentive λ^{pr} (in absolute terms) or at least higher than market prices $\lambda^{pr} \gg \lambda^{pun}_t$ is not necessary since it may only marginally increase the realization of SE. the acknowledgment of this feature could allow for significant savings of the public funding to sustain λ^{pr}. The savings could be directed to other objectives e.g. to increase the value of λ^{i} and thus letting members of RECs to perform higher actual energy cost savings. The reasoning above, based on the quantitative results in Fig. 8(b) and Table 2, allows to criticize the proposal of the Italian Ministry for the Environment and Energic Security in (Ministero dell, 2022) to increase the value of λ^{pr} by 4–10 EUR/kWh in addition to the current value of 110 EUR/kWh. In other words, the results in this paper demonstrate the increment would be in fact unjustified and would not significantly push the achievement of SE.

Furthermore, the results of this paper lead to a more fundamental discussion concerning the actual opportunities in RECs. For all the considered policy options, the difference between the KPI $\Omega^{'}_{Ox}$ (8) and the KPI $\Omega^{'''}_{Ox}$ (10) revealed that the fundamental rules of RECs would prevent the members from achieving remarkable electricity cost reductions. It results that the share of SE revenue that can be directly used for financial gain (thus reduction of the total electricity costs of the REC) is relatively small compared to the whole revenue stream associated to the SE. Nonetheless, it is worth noting that although the SE revenue cannot be used directly to maximize the REC's financial profit, it may still provide *indirect* financial benefit. The SE revenue may be used to reduce or entirely cover CapEx and OpEx of community projects and activities e.g. the realization of EV-charging infrastructure. These, in turn, may positively contribute to the electricity demand of the REC. However, an increment in the portion of SE revenues to be used for financial purposes may effectively facilitate the spread of RECs and the consequent integration of distribution-connected RES. For example, increasing the use-of-network charge λ^{i} or letting a small part of the incentive premium λ^{pr} be used for financial scopes (e.g. actual reduction of the electricity costs) could foster the spread of RECs in Italy. The latter measure could be implemented without breaching Article 2(16)(c) of the RED-II and Article 31(1)(a) of the *Decreto Legislativo 199*. In fact, allowing only a fraction of λ^{pr} to financial gain would still keep the environmental, economic or social community benefits the *primary* purpose of the REC. The authors therefore call for further clarifications from the ARERA, which represents the competent entity to modulate the applicable incentives' regime.

The results also highlight the appearance of undesirable side effects. These arise with those case studies that foster the most the BESS flexibility i.e. CS2 and CS4. Driven by a high value of the SE incentive ($\lambda^{i} + \lambda^{pr}$), the BESS may end up charging at moments of high λ^{pun}_t or discharging with low λ^{pun}_t if such operation increases the SE. However, the formulation of $\Omega^{'''}_{Ox}$ highlights the actual impossibility of cashing in the entire SE revenues. This may eventually increase the total operating cost of the RECs i.e. the actual electricity cost for the REC is eventually higher than with the BC. If prospective members only aim at reducing the electricity costs, it would be more profitable to give up the REC framework and simply install PV and/or BESS. This shortcoming demonstrated in this paper could be alleviated by changing the optimal objective to operate the BESS in the REC. For example, restricting the weight of the SE revenue in the objective function only to the share allowed for financial purposes would eventually reduce the actual energy costs. At the same time, this choice would still enable the achievement of SE revenues to be used for other purposes. Building up on the results of the proposed paper, an initial analysis on the value of different operational schemes for BESS in RECs is carried out in (De Juan-Vela et al., 2023a).

Finally, it is worth highlighting that the *Decreto Legislativo n.199* and the other related acts of the GSE and the ARERA envisage the presence of a flexible EV-charging infrastructure in RECs, although the policies concerning its contribution to the SE and associated incentives have not been detailed by the relevant legal acts. Furthermore, the *Decreto Legislativo n.199* and the documents from the ARERA do not mention the case of EV-charging infrastructure with vehicle-to-grid capabilities. Due to the lack of clear legislation for EV-charging infrastructure, the provisions for BESS could fill the gap. In line with the outcomes of (Grid Connection European Stakeholder Committe, 2019), the authors wish to emphasize that straightforward extension of the provisions on BESS to the EV-charging infrastructure may not always be correct or possible. An intervention of the competent entities is strongly advised in order to provide clear rules for the contribution of the SE of EV-charging infrastructure.

6.3. Future work

The proposed paper highlights also some limitations. The authors wish to emphasize that the important result discussed above may change with different compositions of the REC. For instance, if the RES penetration within the REC and the size of the BESS increase, the reduction in the amount of SE and consequent revenue would increase. Moreover, this assessment of the transposition of the RED-II only produce qualitative results. Future work should focus on a quantitative assessment concerning the impact of national provisions not complying with the corresponding EU ones would require the knowledge of a large variety of data and information that are not available at the moment due to the limited number of active RECs in Italy (Legambiente, 2022). Moreover, a detailed quantitative assessment should be based on the outcomes of the formal monitoring activity of the transposition of the RED-II at national level which is carried out by the EC in accordance with Article 33 of the RED-II.

In addition, future work will deal with alternative operational paradigms. The optimal operation of the assets of the REC assumes a cooperative approach towards the collection of different revenue streams; future expansions would evaluate the economic benefits of letting individual members of the REC to compete between each other in order to maximize their individual objectives. Relevant studies in this research pattern are (Norbu et al., 2021) and (Moncecchi et al., 2020).

Finally, the proposed methodology may be expanded to assess the impact of different policy options and economic metrics on technical aspects regarding RECs. Besides the expected benefits, a large integration of distribution-connected RES and BESS in RECs may potentially contribute to more severe overloads and troublesome reverse power flows in distribution networks. The occurrence of reverse flows would result in over voltage on the feeders and incorrect operation of protections (Sgouras et al., 2017). Similarly, driven by significant SE revenues, BESS may be requested to perform a large number of charging-discharging cycles which could eventually accelerate their state of health and their energy capacity fade. An initial assessment is performed in (De Juan-Vela et al., 2023b).

CRediT authorship contribution statement

Pablo De Juan-Vela: Conceptualization, Software, Validation, Writing, Visualization. **Asja Alic:** Validation, Investigation, Writing. **Vincenzo Trovato:** Conceptualization, Methodology, Supervision, Writing, Funding acquisition, Project administration, Validation.

Declaration of competing interest

There is no competing interest.

Data availability

Data will be made available on request.

Acknowledgments

The authors would like to express their true gratitude to the anonymous reviewers for the insightful comments on the manuscript. Pablo De Juan-Vela is grateful to Atlante s.r.l. for financially supporting his Ph. D. research. Asja Alic is funded by the Italian National Doctoral Program on Photovoltaics.

Appendix

The data refer to actual measurements over one year with 15min granularity. Initial input data have been averaged to obtain annual data with $\Delta t =$ 1h granularity. The minimum, mean and maximum aggregate consumptions are 6.25 kW, 38.85 kW and 129.93 kW, respectively. Details on the aggregate PV generation are in 9. The annual PV generation (83.5 MWh) represents 25% of the annual load consumption (340.6 MWh).

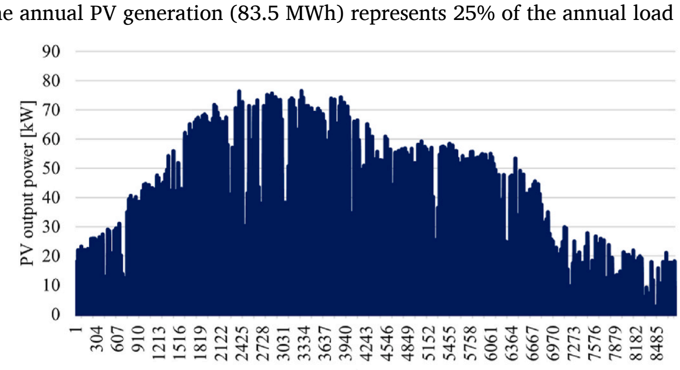

Fig. 9. Time series of the PV power output.

The charts in 10(a) highlight remarkable overall increments in the PUN prices as result of the recent worldwide geo-political events. Similar trends occur in 10(b) displaying the tariff λ_t^{ta} set by the ARERA for end-user customers. The tariff λ_t^{ta} is adjusted every three months. Two regimes are implemented; the highest one applies from 08:00–19:00 Monday to Friday, whereas the lower one is established for the remaining hours of weekdays and anytime over the weekend

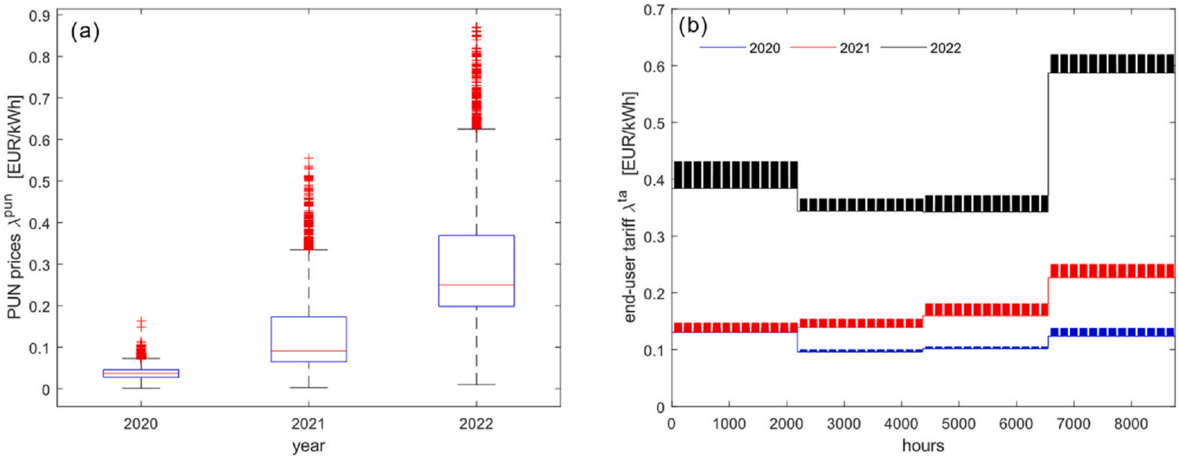

Fig. 10. (a) Box and whiskers plots of the Italian wholesale prices λ_t^{pun} from 2020 to 2022; (b) evolution of the ARERA's tariff for end-user customers λ_t^{ta} from 2020 to 2022.

References

ARERA, 2022. Cocumento per la consultazione 390/2022/R/EEL, 2 August [Online]. Available: https://www.arera.it/allegati/docs/22/390-22.pdf.

ARERA, "Delibera 318/2020," [Online]. Available: https://www.arera.it/it/docs/20/318-20.htm.

ARERA. Tariffa per il servizio di trasmissione [Online]. Available: https://www.arera.it/it/elettricita/trasmissione.htm.

ARERA. Tariffe di distribuzione [Online]. Available: https://www.arera.it/it/elettricita/distr.htm.

ARERA. Condizioni economiche per i clienti del mercato tutelato [Online]. Available: https://www.arera.it/it/dati/condec.htm.

ARERA. Maggior tutela [Online]. Available: https://bolletta.arera.it/bolletta20/index.php/glossario/servizio-di-maggior-tutela#:~:text=%C3%88%20il%20servizio%20di%20fornitura,un%20venditore%20nel%20mercato%20libero%20.

Caramizaru, E., Uihlein, A., 2020. Energy Communities: an Overview of Energy and Social Innovation - Publications Office of the European Union [Online]. Available: https://publications.jrc.ec.europa.eu/repository/handle/JRC119433.

Casalicchio, V., Manzolini, G., Prina, M.G., Moser, David, 2022. From investment optimization to fair benefit distribution in renewable energy community modelling. Applied Energy 310 (11447).

Ceglia, F., Esposito, P., Marrasso, E., Sasso, M., 2020. From smart energy community to smart energy municipalities: literature review, agendas and pathway. J. Clean. Prod. 254, 120118.

Cielo, A., Margiaria, P., Lazzeroni, P., Mariuzzo, I., Repetto, M., 2021. Renewable Energy Communities business models under the 2020 Italian regulation. J. Clean. Prod. 316, 128217.

Codice ATECO, "35.11.00 Produzione di energia elettrica," [Online]. Available: https://www.codiciateco.com/sezioni/d-fornitura-di-energia-elettrica-gas-vapore-e-aria-condizionata/35-fornitura-di-energia-elettrica-gas-vapore-e-aria-condizionata/35-1-produzione-trasmissione-e-distribuzione-di-energia-elettrica/35-11-produzione-di-ener.

Codice ATECO, "35.14.00 Commercio di energia elettrica," [Online]. Available: https://www.codiciateco.com/sezioni/d-fornitura-di-energia-elettrica-gas-vapore-e-aria-condizionata/35-fornitura-di-energia-elettrica-gas-vapore-e-aria-condizionata/35-1-produzione-trasmissione-e-distribuzione-di-energia-elettrica/35-14-commercio-di-energ.

Conradie, P.D., De Ruyck, O., Saldien, J., Ponnet, K., 2021. Who wants to join a renewable energy community in Flanders? Applying an extended model of Theory of Planned Behaviour to understand intent to participate. Energy Pol. 151, 112121.

Cruz Torres, F., Babí Almenar, J., Rugani, B., 2023. Photovoltaic-green roof energy communities can uphold the European Green Deal: probabilistic cost-benefit analyses help discern economically convenient scenarios. J. Clean. Prod., 137428 (in press).

De Juan-Vela, P., Alic, A., Trovato, V., 2023a. Optimal Operation of Battery Storage Systems in Renewable Energy Communities. IEEE ISGT, Grenoble.

De Juan-Vela, P., Alic, A., Trovato, V., 2023b. Impact of policy options on battery storage in renewable energy communities. In: 19th European Energy Market Conference. Lappeenranta, Finland.

De Santi, F., et al., 2022. To join or not to join? The energy community dilemma. Energies 15 (7072).

Department of Energy and Climate Change, 2015. Electricity Market Reform - Announcement of De-rating Methodology for Interconnectors in He Capacity Market [Online]. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/404260/Inteconnector_de-rating_methdology_final_final.pdf.

Di Silvestre, M.L., et al., 2021. Energy self-consumers and renewable energy communities in Italy: new actors of the electric power systems. Renew. Sustain. Energy Rev. 151, 111565.

Rescoop.eu, 2020. Energy communities under the clean energy package [Online]. Available: https://www.rescoop.eu/toolbox/how-can-eu-member-states-support-energy-communities.

EUR-lex. Primacy of EU law [Online]. Available: https://eur-lex.europa.eu/EN/legal-content/glossary/primacy-of-eu-law.html#:~:text=The%20principle%20of%20the%20primacy,)%2C%20EU%20law%20will%20prevail.

EUR-Lex. Recasting of legislation [Online]. Available: https://eur-lex.europa.eu/EN/legal-content/glossary/recasting-of-legislation.html#:~:text=The%20recasting%20of%20legislation%20means,and%20any%20amendments%20to%20it.

EUR-Lex, 2023. Transposition [Online]. Available: https://eur-lex.europa.eu/EN/legal-content/glossary/transposition.html#:~:text=Transposition%20is%20the%20process%20of,their%20rules%20into%20national%20legislation.

European Commission, 2018. DIRECTIVE (EU) 2018/2001 [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN.

European Commission, 2019. Directive 2019/944 of the European Parliament and of the Council on Common Rules for the Internal Market for Electricity [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019L0944.

European Commission. Clean energy for all Europeans package [Online]. Available: https://energy.ec.europa.eu/topics/energy-strategy/clean-energy-all-europeans-package_en.

European Commission. Applying EU law [Online]. Available: https://commission.europa.eu/law/law-making-process/applying-eu-law_en.

European Commission. Types of EU law [Online]. Available: https://ec.europa.eu/info/law/law-making-process/types-eu-law_en.

European Commission. Commission Recommendation 2003/361, 2003. [Online]. Available: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:124:0036:0041:en:PDF.

Gazzetta Ufficiale, 2020. Decreto Milleproroghe. [Online]. Available: https://www.gazzettaufficiale.it/eli/id/2020/02/29/20G00021/sg.

Gestore dei Mercati Elttrici (GME), "downloads - data - MGP prices," [Online]. Available: https://www.mercatoelettrico.org/En/Download/DownloadDati.aspx?val=MGP_Prezzi.

Gestore dei Servizi Energetici, 2022. Gruppi di auto-consumatori di energia rinnovabile che agiscono collettivamente e comunità di energia rinnovabile. April, p. 4 [Online]. Available: https://www.gse.it/documenti_site/Documenti%20GSE/Servizi%20per%20te/AUTOCONSUMO/Gruppi%20di%20autoconsumatori%20e%20comunita%20di%20energia%20rinnovabile/Regole%20e%20procedure/Regole%20Tecniche%20per%20accesso%20al%20servizio%20di%20valorizzazione%20e%20.

Ghiani, E., Trevisan, R., Rosetti, G.L., Olivero, S., Barbero, L., 2022. Energetic and economic performances of the energy community of Magliano Alpi after one year of piloting. Energies 15 (7439).
Goncalves, C., Barreto, R., Faria, P., Gomes, L., Vale, Z., 2022. Dataset of an energy community's generation and consumption with appliance allocation. Data Brief 45, 108590.
Gong, X., Yang, M., Du, P., 2021. Renewable energy accommodation potential evaluation of distribution network: a hybrid decision-making framework under interval type-2 fuzzy environment. J. Clean. Prod. 286, 124918.
Grid Connection European Stakeholder Committe, 2019. Storage Expert Group [Online]. Available: https://www.entsoe.eu/network_codes/cnc/expert-groups/.
GSE. Garanzia d'Origine (the guarantee of origin) [Online]. Available: https://www.gse.it/servizi-per-te/fonti-rinnovabili/garanzia-dorigine#:~:text=La%20Garanzia%20di%20Origine%20(GO,Direttiva%202009%2F28%2FCE.
Hanke, F., Guyet, R., Feenstra, M., 2021. Do renewable energy communities deliver energy justice? Exploring insights from 71 European cases. Energy Res. Social Sci. 80, 102244.
Heldeweg, M.A., Saintier, S., 2020. Renewable energy communities as sociolegal institutions: a normative frame for energy decentralization? Renew. Sustain. Energy Rev. 119, 109518.
Hoicka, C.E., et al., 2021. Implementing a just renewable energy transition: policy advice for transposing the new European rules for renewable energy communities. Energy Pol. 156, 112435.
Iazzolino, G., 2022. Energy communities and key features emerged from business models review. Energy Pol. 165, 112929.
Inês, C., et al., 2020. Regulatory challenges and opportunities for collective renewable energy prosumers in the EU. Energy Pol. 138, 111212.
IRENA, 2022. World Energy Transitions Outlook: 1.5°C Pathway [Online]. Available: https://www.irena.org/publications/2022/Mar/World-Energy-Transitions-Outlook-2022.
May Legambiente, 2022. Comunità Rinnovabili [Online]. Available: https://www.comunirinnovabili.it/wp-content/uploads/2022/05/CR2022-2.pdf.
Lowitzsch, J., Hoicka, C.E., van Tulder, F.J., 2020. Renewable energy communities under the 2019 European Clean Energy Package – governance model for the energy clusters of the future? Renew. Sustain. Energy Rev. 22, 109489.
Martens, K., 2022. Investigating subnational success conditions to foster renewable energy community co-operatives. Energy Pol. 162, 112796.
Mihailova, D., Schubert, I., Burger, P., Fritz, M.M.C., 2022. Exploring modes of sustainable value co-creation in renewable energy communities. J. Clean. Prod. 30, 129917.
Ministero dell'ambiente e della sicurezza energetica, 2022. Public consultation [Online]. Available: https://www.mase.gov.it/bandi/consultazione-pubblica-attuazione-della-disciplina-la-regolamentazione-degli-incentivi-la.
Ministero Dello Sviluppo Economico, 2020. Decreto Attuativo [Online]. Available: https://www.mise.gov.it/index.php/it/normativa/decreti-direttoriali/2041414-decreto-direttoriale-1-settembre-2020-contributi-in-favore-dei-comuni-per-efficientamento-energetico-e-sviluppo-sostenibile-modalita-attuative.
Moncecchi, M., Meneghello, S., Merlo, M., 2020. Game theoretic approach for energy sharing in the Italian renewable energy communities. Appl. Sci. 10 (8166).
Montoya-Bueno, S., Muñoz-Hernández, J.I., Contreras, J., 2016. Uncertainty management of renewable distributed generation. J. Clean. Prod. 138 (1), 103–118.
Norbu, S., Couraud, B., Robu, V., Andoni, M., Flynn, D., 2021. Modeling economic sharing of joint assets in community energy projects under LV network constraints. IEEE Access 9, 112019–112042.
O'Brien, S., Monteiro, C., Gancheva, M., 2018. Models of Local Energy Ownership and the Role of Local Energy Communities in Energy Transition in Europe – , Committee of the Regions [Online]. Available: https://data.europa.eu/doi/10.2863/603673.
Presidenza della Repubblica italiana, 2021. Decreto Legislativo N. 199 [Online]. Available: https://www.gazzettaufficiale.it/eli/id/2021/11/30/21G00214/sg.
Reis, I.F.G., Gonçalves, I., Lopes, M.A.R., Henggeler Antunes, C., 2021. Business models for energy communities: a review of key issues and trends. Renew. Sustain. Energy Rev. 144, 111013.
Rommel, J., Radtke, J., von Jorck, G., Mey, F., Yildiz, Ö., 2018. Community renewable energy at a crossroads: a think piece on degrowth, technology, and the democratization of the German energy system. J. Clean. Prod. 197 (2), 1746–1753.
Rossi, F., Heleno, M., Basosi, R., Sinicropi, A., 2021. LCA driven solar compensation mechanism for Renewable Energy Communities: the Italian case. Energy 235 (121374).
Sgouras, K.I., Bouhouras, A.S., Gkaidatzis, P.A., Doukas, D.I., Labridis, D.P., 2017. Impact of reverse power flow on the optimal distributed generation placement problem. IET Gener. Transm. Distrib. 11 (18), 626–4632.
Soeiro, S., Ferreira Dias, M., 2020. Renewable energy community and the European energy market: main motivations. Heliyon 6 (7).
Trovato, V., Kantharaj, B., 2020. Energy storage behind-the-meter with renewable generators: techno-economic value of optimal imbalance management. Int. J. Electr. Power Energy Syst. 118 (105813).
Tutak, M., Brodny, J., 2022. Renewable energy consumption in economic sectors in the EU-27. The impact on economics, environment and conventional energy sources. A 20-year perspective. J. Clean. Prod. 345, 131076.
European Union, "Joint Practical Guide of the European Parliament, the Council and the Commission for persons involved in the drafting of European Union legislation," [Online]. Available: https://eur-lex.europa.eu/content/techleg/KB0213228ENN.pdf.
Wainer, A., Petrovics, D., van der Grijp, N., 2022. The grid access of energy communities a comparison of power grid governance in France and Germany. Energy Pol. 170, 113159.