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LCA driven solar compensation mechanism for Renewable Energy Communities: the Italian case

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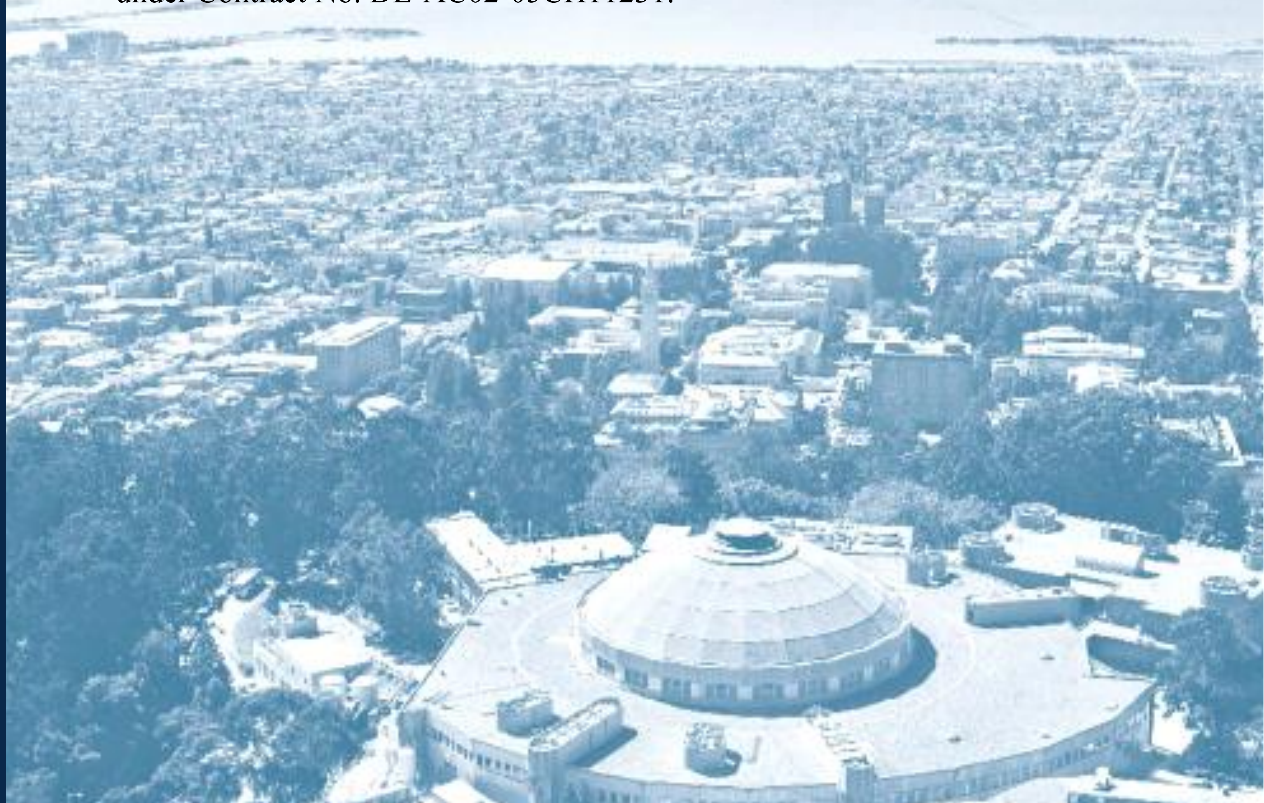

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Abstract

Renewable energy communities are multi-users energy systems that are expected to become popular in all countries, including Italy. This paper discusses environmental-driven solar compensation mechanisms, specifically designed for energy communities. Such mechanisms consider the adoption of Distributed Energy Resources by the communities and reflect their overall life cycle environmental benefit. Notably, an innovative three-steps iterative methodology is adopted to design new feed-in tariffs including: (i) the optimal economic sizing of solar technologies, (ii) the life cycle assessment and (iii) the evaluation of a solar compensation mechanism. In the last step, the emissions avoided by communities are converted into economic solar compensation mechanisms (via feed-in tariffs) using the current value of carbon taxes. After the general methodology description, the proposed approach is applied to a specific Italian case study. In case carbon taxes are set to the current value, namely 15.4 EUR/tonCO_2eq, the yearly national emissions are mitigated by the adoption of the proposed solar compensation from 121.1 MtonCO_2eq/yr to 108.2 MtonCO_2eq/yr. Differently, if taxes are increased to 20 EUR/tonCO_2eq, the emissions are reduced to 84.3 MtonCO_2eq/yr; in case carbon taxes are extended over this value, the grid gets saturated by communities electricity and the additional environmental advantages are negligible.

Keywords: Renewable Energy Communities, Photovoltaic Systems, Batteries, Life Cycle Assessment, Incentives.

Declarations of interest: none

1. Introduction

This paper addresses the problem of designing a sustainable policy to promote photovoltaic (PV) and energy storage systems installed in Renewable Energy Communities (RECs) by proposing a novel approach for solar compensation applied to an Italian case study. RECs are defined by the European Union Renewable

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Energy Directive (RED II) [1], which is part of the European Commission's Clean Energy Package [2], as non-commercial entities whose purpose is providing environmental, economic and social benefits. They are composed of a group of users investing in energy production technologies from renewable sources and storage systems, whose costs are shared among the community members; this is particularly useful because such technologies can have high investment costs [3]. Moreover, RECs allow to face energy poverty issues [2] affecting many areas of the World, including some parts of Italy [4, 5]. Some of the most commonly deployed technologies in RECs are PV modules for the energy production and battery energy storage systems (BESSs) to store the PV energy surplus. For instance, a REC has been recently installed in Crevillent (Spain) where about 70 households deployed 125 kW of PV and a 200 kWh BESS [6].

RECs belong to the category of behind the meter installations and several types of economic benefits, named incentives, can be used to promote their deployment. Some European countries like Germany and Denmark have already designed an energy policy framework for RECs [2]; differently, in Italy a specific policy is still under evaluation [7]. Notably, coherently with the RED II principles [1], the Italian Energy Authority [8] is working on the development of a bonus (that could be formalized soon) promoting the self-consumption (SC) of the energy shared by RECs members [8]. Nevertheless the following incentives for PV systems are already available [9]:

- Net metering: users can get a reimbursement calculated as the product between the exchanged energy (namely the lower value between the electricity imports and exports) and a reference remuneration; moreover electricity can be sold to the utility at market value. In Italy this mechanism is known as "scambio sul posto" and the reference remuneration is approximately equal to 70% of the energy cost [10]. Currently, this incentive applies for PV installations whose size is lower than 500 kW [9].

- Feed-in tariffs (FITs): the electricity exported to the grid can be sold by providing a guaranteed, above-market price for producers [11]. Currently in Italy, according to a mechanism known as "ritiro dedicato", the minimum price guaranteed is generally lower than the price set by the market, and therefore electricity is commonly sold at market value [9].

- Tax deductions: users can get a reimbursement for the cost of PV installations or other residential interventions increasing the energy efficiency of a building. In Italy such incentive reimburses a percentage between 50% and 110% of installation costs depending on the type of intervention [12].

Different economic tools like bidding systems [13], Green Certificates [14, 15] and Renewable Portfolio Standards [16] are instead applied to power plants, but they are out of the scopes of this paper.

Another way to indirectly promote renewable energy systems is adopting carbon taxes that penalize the massive consumption of fossil resources. Carbon taxes obligate energy producers from fossil resources to pay a fee for the amount of carbon dioxide released to the atmosphere. The mechanism of carbon taxes is carefully described in a report published by the Organisation for Economic Co-operation and Development (OECD) [17]. Nevertheless, this report underlines that most of the OECD countries have not adopted an adequate carbon taxes policy, especially in some strategic sectors like electricity production; indeed, in Italy carbon dioxide emissions are taxed at 15.4 EUR/tonCO_2, whereas in USA it is not taxed at all [17]. Differently, Northern European countries have taxed carbon dioxide emissions at a higher rate; some examples are Denmark (104.57 EUR/tonCO_2), Sweden (193.08 EUR/tonCO_2), Norway (1344.38 EUR/tonCO_2) and Iceland (4168.18 EUR/tonCO_2). Moreover, carbon taxes only affect the carbon dioxide direct emissions from electricity production through fossil resources, whereas the life cycle greenhouse gases (GHGs) emission of renewable energy technologies is not considered as a negative externality.

All these incentives and economic tools are thought to promote rapid adoption of renewable energy technologies because they are generally considered as sustainable for the environment. Nevertheless, excessive incentives may lead to over-investments in PV as demonstrated by Poponi et al. [18] analyzing Italian FITs in the last decade. Furthermore, all energy systems, including RECs, determine some environmental impacts over their life cycle. Therefore, if incentives or tariffs do not consider the full environmental performances of RECs, they might provide wrong economic signals and lead to an inadequate deployment of PV from an environmental perspective [19]. For these reasons, the current incentives have some limitations dealing with their environmental compatibility. In order to address such an issue, this paper aims to achieve three targets regarding incentives for PV adoption by RECs:

- Incentives should be directly correlated with RECs sustainability: most of policy strategies aim to push as more users as possible to purchase PV systems assuming that the more is the renewable capacity, the lower are the environmental impacts.
- Incentives should be defined through a granular evaluation: as PV energy production is variable as well as the energy mix sustainability, policymakers should define incentives on hourly basis as function of PV environmental benefits to the grid in time.
- Incentives should be adaptive to the changes that new installations apply to the grid energy mix sustainability.

In other words, it is important to design a new energy policy framework whose aim is not increasing renewable energies installed power but pursuing the sustainability of the national energy systems. In this perspective, as RECs are expected to reach a large diffusion in all countries, promoting them with adequate incentives represents a great opportunity towards a sustainable energy transition. More specifically, the problem addressed in this paper consists on including environmental impact analyses in a FITs design model through a mathematical correlation with a life cycle assessment (LCA). This problem is solved by defining a three-steps methodology that includes RECs economic Optimal Design, LCA and the FITs cost allocation. As the economic Optimal Design, that is the first step, requires as an input the FITs, that are assessed in the last step, the approach has to be iterative.

This paper is structured as following: Section 2 contains the literature background of the proposed study; in Section 3 the methodology is detailed; in Section 4 the readers can find the case study description; Section

5 contains the results description and discussion and Section 6 contains the conclusions and suggestions for future works.

2. Literature review

This section summarizes the background literature that contributed to this study and it underlines the substantial differences between the proposed model and the models discussed by previous scholars.

This study grounds on an existing algorithm, named Distributed Energy Resources Customer Adoption Model (DER-CAM) [20], that allows to design PV systems by minimizing the costs for their energy users. DER-CAM has been used in literature to forecast the deployment of behind the meter PV and storage installations, given some tariffs [21, 22]. Moreover, Cardoso et al. [23] used DER-CAM to evaluate the components size and the energy management of a system composed of PV modules and storage, also named Solar Home System [24]; batteries degradation is also included in the optimization. The model proposed by Cardoso et al. [23] has been adapted in our previous paper [25] to evaluate the economic and the environmental optimal configurations of Solar Home Systems. According to the cross-analysis of costs and impacts, economic optimization is assessed as the best methodology to design these energy systems. The same economic Optimal Design method is also suitable for RECs, that could be considered as large Solar Home System shared by multiple users. Therefore, economic Optimal Design is adopted within the proposed methodology to evaluate RECs portfolio of investments and the energy management of the communities. Similarly, the LCA analysis included in the proposed methodology is based on the environmental analysis defined in our previous paper [25] and on the LCA data-sets published by Peters and Weil [26] and previous LCA studies [27, 28, 29]. Differently from the above-mentioned studies, aimed to the design of the Solar Home Systems, this paper grounds on the models and the equations proposed by these scholars to evaluate new incentives for RECs.

Among the incentives for renewable energies over-viewed in Section 1, FITs became an issue of massive interest in scientific literature. Indeed FITs, compelling the utilities by law to purchase the renewable energy surplus produced by the users, led to a higher renewable energy deployment than other types of incentives [30, 31, 32]. For instance, Candelise and Ruggieri [33] underlined that 17 PV and wind based RECs have been installed in Italy since 2010 thanks to FITs but only 3 of them survived to the reduction of such incentives in 2013 and are currently operative. Similarly to Italy [11], FITs played a key role in RECs development also in other countries like Canada [34], United Kindom and Germany [35, 36]. Considered the importance given to FITs by literature, this type of incentive is selected to promote RECs in this analysis. Moreover, the temporal granularity of FITs, that are variable on hourly basis, is defined in Section 1 as one of the targets for the proposed design approach.

All the FITs design approaches available in literature are based only on techno-economic criteria whereas environmental analyses are never directly considered. For instance, Kim and Lee [37] developed an algorithm that allows policymakers to optimize the contribution of renewable energies to the grid; Ayompe and Duffy

[38] instead designed incentives in order to improve PV domestic installations cost-efficiency. Mpholo et al. [39] defined an innovative FITs mechanism for Leshoto (Southern Africa) to face the high poverty rate of its population. In contrast, Devine et al. [40] and Barbosa et al. [41] based their FITs evaluation on the analysis of the uncertainty affecting the investments in PV; the latter also provided a tool for policymakers to design new FITs in such uncertain conditions. Martin and Rice [42] addressed the problem of FITs design and adopted an approach named Concept Analysis and Mapping using historical data to point out the main design parameters. Among these parameters, life cycle environmental impacts evaluations are not directly included.

This literature review underlines that environmental impact assessment methods are not considered in common FITs design approaches. Nevertheless, as underlined in Section 1, RECs are responsible for some life cycle GHGs emissions over their life cycle and the adoption of inadequate incentives could lead to an excessive and not sustainable deployment of PV systems [43]. For such reason, the environmental performances of renewable energy technologies should be accounted when evaluating environmental friendly FITs for RECs. LCA is the main methodology to assess the environmental impact of products and processes [44, 45] and it is frequently used in literature to describe future scenarios of the energy mix eco-profile [46, 47]; nevertheless, it has never been directly used to design incentives.

According to the above literature review, FITs are an important tool to promote the diffusion of RECs and of renewable energy systems in all countries. Previous scholars proposed valuable FITs design models that could be suitable for all countries, including Italy, but they only involve some techno-economic variables of the problem. Differently, the model proposed aims to fill such literature gap by combining a techno-economic assessment based on DER-CAM [20] with an environmental analysis for the calculation of new LCA-driven solar compensations. The proposed methodology can be easily extended to other countries, but in this paper we limited ourselves to Italy as a case study. Moreover, a sensitivity analysis is performed to assess the results variations depending on the main parameters of the problem.

3. Methodology

In this section, the methodology used to evaluate new FITs for RECs is described. This approach assumes economic rationality in RECs' adoption of technologies: the size and utilization of PV and storage devices are determined in order to minimize the annualized costs of energy from the RECs perspective. We define their PV and storage investments based on an economic rational model [25], which calculates the optimal investments taking into account technology costs as well as specific RECs data, such as load and solar radiation. We assume that many communities will spread throughout the Italian territory, thus providing positive environmental effects to the national energy system. The novel FITs design approach proposed in this paper grounds on the following three-steps iterative methodology.

In Step 1, RECs are designed using an economic optimization model that allows to evaluate the optimal portfolio of investments and the optimal energy management: the electricity produced by RECs can be self-consumed or injected to the grid depending on the economic convenience. Producing electricity with their PV systems, RECs allow to reduce the energy injected to the grid by other producers.

In Step 2, the environmental performances of RECs are calculated. RECs electricity production from renewable sources allows, in principle, to reduce the amount of GHGs emitted. Nevertheless all energy systems, including PV and storage, have a carbon footprint over their life cycle. Therefore the GHGs emissions avoided by RECs are calculated, net of their own impact, using LCA.

In Step 3, the emissions avoided by RECs electricity injection to the grid are converted into additional solar compensations and added to the current FITs. Indeed, the GHGs avoided by RECs also represent an economic advantage because carbon dioxide emissions are subject to taxation. For such reason an economic surplus resulting from RECs avoided emissions exists and it is used to reward their members. Differently from the policy currently adopted in OECD countries, in this work carbon taxes application is extended to all life cycle GHGs. Therefore, hereinafter carbon taxes will be expressed per ton of equivalent carbon dioxide (EUR/tonCO_2eq instead of EUR/tonCO_2).

If the analysis stops at this level, it is possible to calculate RECs environmental performances using the current FITs. Nevertheless, communities could take advantage of the additional incentives evaluated in Step 3 and change the optimal size of components and the optimal energy management accordingly. Therefore, in the proposed approach, the FITs calculated through Step 3 are used as inputs for Step 1 in the second iteration. Nevertheless, the emissions avoided at the second iteration are lower because the energy mix has already been improved at the first one; therefore additional FITs are lower as well. In other words, this adaptive methodology iteratively leads to an equilibrium condition where RECs cannot provide further environmental benefits to the grid. A sketch of this methodology is illustrated in Figure 1. This scheme highlights that the model is constructed in a general and objective way and that the case study just provides some representative inputs for Italian communities to the model; therefore, the approach proposed can be considered as valid for all countries.

Figure 1: Sketch of the applied methodology.

The input data required to apply such methodology are the current FITs, the carbon taxes, the energy demand and production mix, and some meaningful load profiles for RECs. Therefore, the proposed FITs design approach could be applied to all countries just using specific values for the previous inputs. For such reason the innovative methodology detailed in this section has a general value that goes beyond the choice of the country.

According to this methodological overview, the equations presented in this section contain variables depending on time (t), on the iteration number (i) and on the community type (j). Notably, 72 representative community types (Nt) with a prototypical load are considered. Furthermore, in order to reach the required penetration level, each type of REC should reach a certain number of installations (Nc). Further details about the definition of RECs representative communities and their number are provided in the following section.

3.1. Optimal Design

An economic Optimal Design model has been developed in our previous paper [25] to evaluate the best portfolio of solar and battery investments. Such model is based on a mixed integer linear programming (MILP) optimization algorithm and requires the following inputs:

- the energy costs (EC_t) for the users;
- the feed-in tariffs at the previous iteration ($FIT_{t,i-1}$);
- the fixed costs of the k-technology ($CFix_k$) which do not depend on its capacity;
- the variable costs of the k-technology ($CVar_k$) which depend on its capacity.

In order to stress the generality of the approach, it is underlined that these inputs are PV and storage investement and operation costs that in principle could be related to any country. Using these data, the optimization model allows for the evaluation of the following outcomes:

- the choice of the adoption of the k-technology through a binary decision variable ($i_{k,i,j}$);
- the capacity of the k-technology ($cap_{k,i,j}$);
- the electricity imported from the grid ($ui_{t,i,j}$);
- the electricity exported to the grid ($ue_{t,i,j}$);

The variables of the model are evaluated through the minimization of an objective function, represented by the costs for energy users (investment costs are annualized using a discount rate ir of 3%). As shown in [25], this model is constrained by the energy balance of the BESS, of the charge controller (CC), of the inverter (In) and of the overall system. Moreover constraints include the maximum PV productivity, the maximum power exchanged by the storage, its maximum capacity and the ageing of storage devices. Notably, thanks to an ageing model valid for different lithium-ion batteries, economic optimization allows to minimize the costs guaranteeing that the BESS lifespan reaches a target value set by the user (10 years). Depending on batteries characteristics, the Optimal Design model can select the most suitable battery to minimize costs.

According to the above description of the problem, the objective function minimized by the optimization algorithm is set to the annualized costs of energy communities ($C_{i,j}$) (1). The first term of the equation contains the fixed ($CFix_k$) and variable ($CVar_k$) costs of components whereas the second term contains the costs due to energy imports and the revenues from energy exports. This MILP optimization model is solved using CPLEX [48], via a python (Pyomo) implementation [49]. All values for input costs and revenues are defined in Section 4 whereas the outputs of the minimization are listed in the previous bullet points.

$$C_{i,j} = \sum_{k=1}^{Nk} \Big(CFix_k \cdot i_{k,i,j} + CVar_k \cdot cap_{k,i,j}\Big) Ann_k + \sum_{t=1}^{\bar{T}} (ui_{t,i,j} \cdot EC_t - ue_{t,i,j} \cdot FIT_{t,i-1}) \quad (1)$$

Where Nk is the number of components installed by the communities and Ann_k is an annualization factor of costs (2):

$$Ann_k = \frac{ir}{1 - \big(1 + ir\big)^{-L_k}} \quad (2)$$

In this equation, L_k is the k-component lifespan.

Another result that will be useful in the following of the methodology is the communities SC ($sc_{t,i,j}$) calculated as the difference between the community load ($load_{t,j}$) and the energy imported from the grid (3):

$$sc_{t,i,j} = load_{t,j} - ui_{t,i,j} \quad (3)$$

The full model, including the techo-economic constraints, is detailed in [25].

3.2. LCA analysis

Concerning the environmental performances of energy communities, LCA is one of the best approaches to estimate them. In this study the analysed technologies are not responsible for direct GHGs emissions, but some burdens occur anyway during their construction and end of life. According to ISO standards [44, 45], LCA analyses should follow four different phases: Goal and Scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation.

3.2.1. Goal and Scope definition

The first phase of LCA is the Goal and Scope definition. The environmental analysis performed in this study aims to calculate energy communities GHGs emissions from cradle to grave to estimate the net environmental benefits of the electricity injection and SC. In this phase, the following information about the LCA study is also provided:

- RECs function is to guarantee the energy supply to their members but they can also export electricity to the grid.
- The reference flow of the product system is the load supply whereas the electricity injection to the grid is considered as a by-product; a physical allocation of impacts is done to address this issue.
- The functional unit of the analysis is set to 1 kWh.

- The system boundaries include the energy imports from the grid and the production and end of life of components. Concerning batteries waste management, the system is supposed to be disassembled to recover the cells housing and other external materials; then hydro-metallurgical and pyro-metallurgical processes are used to recover the electrodes metals [28, 29, 27].

- Coherently with the scope of the analysis, the environmental indicator Global Warming Potential (GWP) is adopted to summarize all the GHGs emissions; indeed, results are expressed as equivalent carbon dioxide emissions (kgCO_2eq).

3.2.2. Life Cycle Inventory

The second phase is creating a LCI; this operation is done using openLCA [50] and the database Ecoinvent 3.6 [51]. A LCI represents a data collection of all the energy flows and materials consumption and of the emissions occurring during the communities life cycle. Similarly to the model defined in our previous work [25], the proposed algorithm requires as inputs the environmental impact of a 1 kW PV system, a 1 kWh BESS, a 1 kW In, a 1 kW CC and a 1 kWh of energy imported from the grid. In light of these considerations, the LCI is detailed in Table 1. This table collects as inputs all the processes occurring during the components life cycle, namely the production and waste treatment, and the Italian electricity production mix. In case some of these processes are not directly provided by Ecoinvent [51], the data source is cited. The input quantities are expressed as a mass or as number of items depending on the data source. All the outputs are converted to the aforementioned functional units (1 kWh or 1 kWh) according to the components' characteristics declared by the data source. Since every community can purchase their components from the market, the LCI grounds on Ecoinvent market processes.

Inputs			
market for photovoltaic slanted-roof installation, 3kWp, single-Si, panel, mounted, on roof	0.33	pieces	PV system production, In excluded [51]
photovoltaic system waste treatment	102.33	kg	Reproduced from [52]
Outputs			
PV system	1	kW	LCI of a 1 kW PV
Inputs			
lithium-ion batteries production	1.00	kWh	Reproduced from [26]
lithium-ion batteries waste treatment	1.00	kWh	Reproduced from [53]
Outputs			
BESS system	1	kWh	LCI of a 1 kWh BESS
Inputs			
market for inverter, 2.5kW	0.40	pieces	In production [51]
market for waste electric and electronic equipment	7.40	kg	In waste treatment [51]

Outputs			
In	1	kW	LCI of a 1 kW In
Inputs			
market for charger, electric passenger car	1.71	kg	CC production [51]
market for waste electric and electronic equipment	1.71	kg	CC waste treatment [51]
Outputs			
CC	1	kW	LCI of a 1 kW CC
Inputs			
market for electricity, low voltage IT	1	kWh	Italian energy production mix [51]
Outputs			
Energy Imports	1	kWh	LCI of 1 kWh energy imports

Table 1: LCI of RECs components and imported energy.

3.2.3. Life Cycle Impact Assessment

The third phase of LCA analyses is the LCIA, namely the evaluation of the environmental impact of the product system thanks to a standard LCIA method. Particularly, the European Commission is engaged in the construction of a reliable method, named ILCD [54], providing results for several impact categories including GWP. Therefore in this study, ILCD is adopted to evaluate this midpoint indicator, expressed as the amount of equivalent carbon dioxide emissions. Calculations are run using openLCA [50].

Environmental impacts can be classified as fixed ($kgCO_2eq$) or variable ($kgCO_2eq/kW$ or $kgCO_2eq/kWh$) according to their relation with the size of the components [25]. In order to calculate the GHGs emissions of the overall RECs ($kgCO_2eq$), the fixed ($IFix_k$) and the variable ($IVar_k$) environmental impacts are respectively multiplied by the binary decision variable $i_{k,i,j}$ and the components capacity $cap_{k,i,j}$, namely the outputs of the Optimal Design model. Such emissions are physically allocated to the energy injection ($Eue_{t,i,j}$) (4) and SC ($Esc_{t,i,j}$) (5), that are the two energy outputs of the PV system electricity production model. All the impact values related to components and energy are collected in Section 4.

$$Eue_{t,i,j} = \frac{\sum_{k=1}^{Nk} \left(IFix_k \cdot i_{k,i,j} + IVar_k \cdot cap_{k,i,j}\right) EAnn_k}{OT_{i,j}} \cdot \frac{ue_{t,i,j}}{ue_{t,i,j} + sc_{t,i,j}} \tag{4}$$

$$Esc_{t,i,j} = \frac{\sum_{k=1}^{Nk} \left(IFix_k \cdot i_{k,i,j} + IVar_k \cdot cap_{k,i,j}\right) EAnn_k}{OT_{i,j}} \cdot \frac{sc_{t,i,j}}{ue_{t,i,j} + sc_{t,i,j}} \tag{5}$$

In these equations $EAnn_k$ is an annualization factor of the k-component environmental impact calculated as the reciprocal of its lifespan value [25] and $OT_{i,j}$ is the operative time of RECs. Coherently with our previous study [25] and with the LCI in Table 1, all the impacts of components can be considered as variable because they depend on their capacity.

During the operation RECs import electricity from the grid: the load supply is partially covered by the SC and partially by the grid; therefore, the impact of RECs electricity imports is totally allocated to the load. Accordingly, the equivalent carbon dioxide released for the load supply ($Eload_{t,i,j}$) is expressed by Eq. (6)

$$Eload_{t,i,j} = ui_{t,i,j} \cdot Imix_{t,i} + Esc_{t,i,j} \tag{6}$$

According to the functional unit definition, the RECs impacts must be expressed as $kgCO_2eq/kWh$. Therefore the load and the energy injection impact values are calculated as the ratio between the equivalent carbon dioxide emissions ($Eload_{t,i,j}$, $Eue_{t,i,j}$) and the corresponding energy flows ($load_{t,j}$, $ue_{t,i,j}$).

The electricity mix environmental impact changes because RECs injected energy avoids some carbon dioxide emissions whereas SC reduces the electricity needs from the main grid. The energy mix impact in time ($Imix_{t,i}$), expressed as equivalent carbon dioxide per kWh of energy in the network ($kgCO_2eq/kWh$), is assessed by the following balance (7):

$$Imix_{t,i} = Imix_{t,i-1} - \frac{Nc \cdot \sum_{j=1}^{Nt} \left((ue_{t,i,j} - ue_{t,i-1,j}) \cdot Imix_{t,i-1} - (Eue_{t,i,j} - Eue_{t,i-1,j})\right)}{D_t - Nc \cdot \sum_{j=1}^{Nt} sc_{t,i,j}} \tag{7}$$

In this equation, D_t is the national electricity demand profile supplied by the grid before RECs deployment. Similarly to the economic data, also the energy and environmental inputs like the national energy demand and energy mix impact could be referred, in principle, to all countries.

3.2.4. Interpretation

The fourth phase of LCA analyses is the Interpretation. All the previous steps are suitable to interpretation because both the LCI and LCIA results should match with the goal and scope of the analysis. The overall LCA analysis adopted in this study is schematized in Figure 2

3.3. Cost allocation

During the Step 3, at every iteration the environmental benefits of RECs are converted to additional economic incentives. The environmental benefits due to the additional emissions avoided by RECs exports are calculated and converted to economic savings through the product with carbon taxes. These GHGs savings are divided by the energy exports to the grid to evaluate the additional FITs to the previous step (8). All these operations that bring to the evaluation of the new FITs are included in Eq. (8).

$$FIT_{t,i} = FIT_{t,i-1} + \frac{Nc \cdot \sum_{j=1}^{Nt} ((ue_{t,i,j} - ue_{t,i-1,j}) \cdot Imix_{t,i-1} - (Eue_{t,i,j} - Eue_{t,i-1,j})) \cdot CT}{Nc \cdot \sum_{j=1}^{Nt} ue_{t,i,j}} \tag{8}$$

In this equation, CT represents carbon taxes and the terms addressed as ue and Eue are respectively the energy exports assessed by the Optimal Design and the emissions evaluated during the LCA analysis.

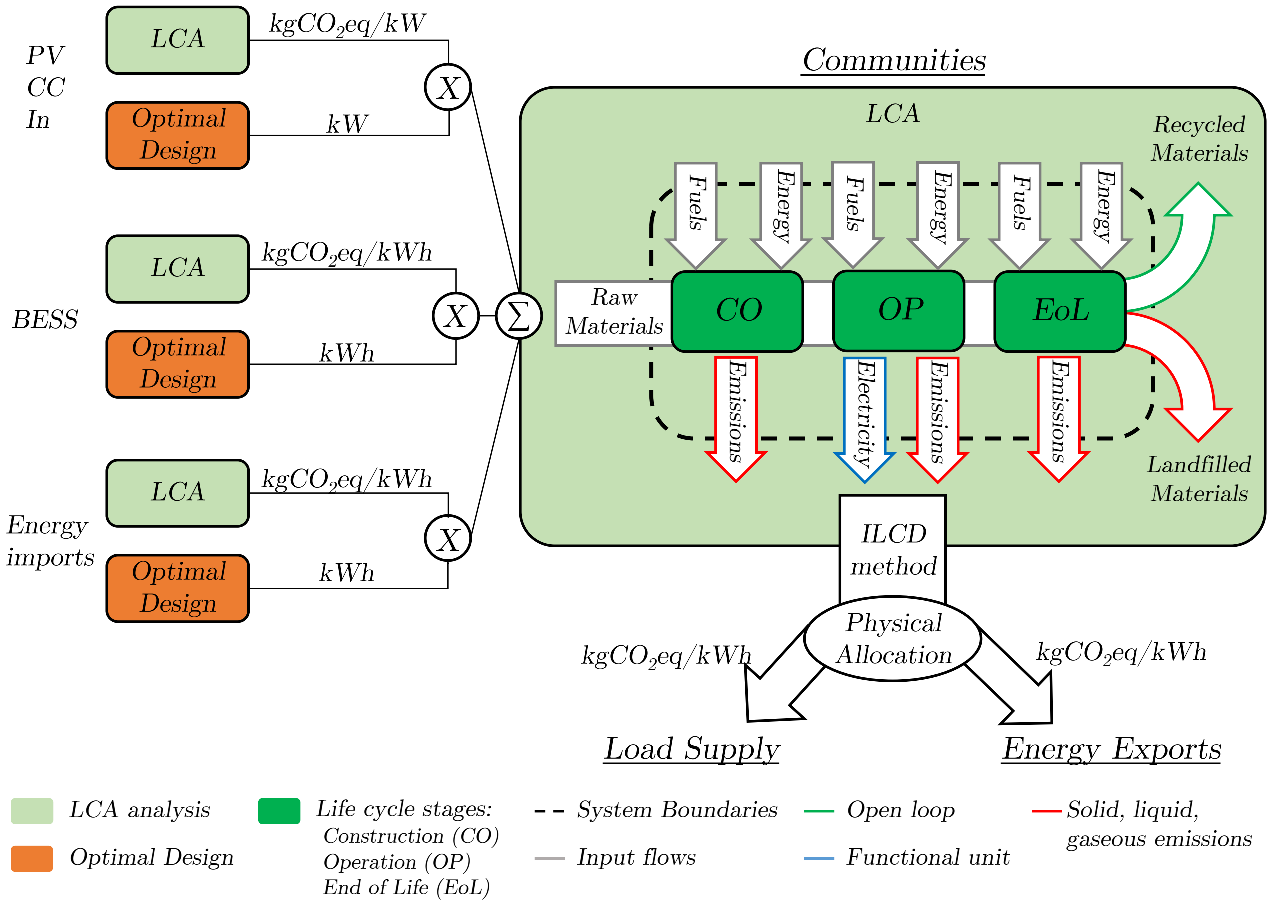

Figure 2: Sketch of the LCA analysis.

4. Case study

This section describes the characterization of RECs and collects all the data necessary to apply the methodology. As demonstrated by the equations in the previous section, the proposed model is constructed in a general and objective way. Nevertheless, to guarantee the results reliability, the Case Study must be tailored for the Italian conditions. For instance, Italy has an elongated territory that covers a wide range of latitudes and thus of solar radiation values and load profiles. Therefore, the diversification of several representative RECs, differing for PV productivity and load profiles, is fundamental to make the model applicable to Italy.

The PV productivity profiles are evaluated by dividing the Italian territory in 4 regions according to the latitude: North, Centre-North, Centre-South and South. For each region, a representative city is selected: Milan for North, Florence for Centre-North, Naples for Centre-South and Palermo for South. In all these locations, the electricity production profile of a 1 kW PV installation is calculated using the online tool photovoltaic geographical information system (PV-GIS) [55].

Concerning the electric load of communities, Quoilin et al. [56] published a data-set containing several profiles obtained through a statistical analysis of direct measurements in micro-grids. 154 profiles are related to Italy and for each one of them an average daily load profile is evaluated. This operation allows to simplify the classification: those profiles having a peak during the morning, the afternoon and the evening are selected and grouped by category. Then the profiles can be classified in two groups, depending whether the peak load occurs in the summer or in the winter. Communities are formed by aggregating these profiles into different sizes: small, medium and big communities respectively have an average demand of 100 kW, 200 kW and 300 kW.

When combining 4 different PV productivity geographic profiles with 18 load profiles, we obtain 72 representative communities at the national level (Nt). Assuming that all communities are uniformly distributed in the Italian territory, it is possible to evaluate the number of communities by type Nc to reach the penetration level P as following (9):

$$Nc = P \cdot \frac{\bar{NL}}{\bar{CL} \cdot Nt} \tag{9}$$

Where $\bar{NL}$ and $\bar{CL}$ are respectively the average national load and communities load.

Technology costs are classified as fixed and variable costs and are adapted from [25] whereas the environmental impacts are calculated using Ecoinvent 3.6 [51] database and ILCD impact assessment method [54]. All the fixed environmental impacts are null [25] whereas the variable impacts are the carbon footprint of the energy imports, the PV, the In, the CC (respectively addressed with the subscripts pv, in and cc) and the BESS considering seven battery types (addressed using the subscripts $s1$,...,$s7$ according to the nomenclature adopted in [25]). All the economic and environmental cost parameters are collected in Table 2.

Costs			**Impacts**		
Parameter	Value	Unit	Parameter	Value	Unit
$CFix_s$	200	EUR	$IFix_s$	0	$kgCO_2eq$
$CVar_{s,1}$	305.2	EUR/kWh	$IVar_{s,1}$	156.6	$kgCO_2eq$/kWh
$CVar_{s,2}$	305.2	EUR/kWh	$IVar_{s,2}$	181.6	$kgCO_2eq$/kWh
$CVar_{s,3}$	449.2	EUR/kWh	$IVar_{s,3}$	274.7	$kgCO_2eq$/kWh
$CVar_{s,4}$	265.2	EUR/kWh	$IVar_{s,4}$	120.9	$kgCO_2eq$/kWh
$CVar_{s,5}$	291.7	EUR/kWh	$IVar_{s,5}$	104.1	$kgCO_2eq$/kWh
$CVar_{s,6}$	296.2	EUR/kWh	$IVar_{s,6}$	105.1	$kgCO_2eq$/kWh
$CVar_{s,7}$	296.2	EUR/kWh	$IVar_{s,7}$	116.4	$kgCO_2eq$/kWh
$CFix_{pv}$	400.6	EUR	$IFix_{pv}$	0.0	$kgCO_2eq$
$CVar_{pv}$	1216.6	EUR/kW	$IVar_{pv}$	156.6	$kgCO_2eq$/kW
$CFix_{in}$	50	EUR	$IFix_{in}$	0.00	$kgCO_2$
$CVar_{in}$	539.4	EUR/kW	$IVar_{in}$	99.5	$kgCO_2eq$/kW

$CFix_{cc}$	500	EUR	$IFix_{cc}$	0.0	$kgCO_2eq$
$CVar_{cc}$	141.3	EUR/kW	$IVar_{cc}$	99.5	$kgCO_2eq/kW$

Table 2: Environmental impact and cost parameters.

Concerning the electricity mix, hourly data about the energy flowing through the national grid are available in a database provided by the Italian transmission system operator (Terna S.p.a.) [57] for all energy sources: the total power is the sum of the electricity produced by thermal plants, from renewable sources (PV, wind, hydro, geothermal) and the energy imported from other countries. Ecoinvent 3.6 [51] contains LCA models for all the energy production pathways contributing to the Italian mix (such as natural gas combined cycles, different types of PV, hydro and wind installations and many other power plants). Keeping constant the Ecoinvent 3.6 [51] proportions among all the production pathways based on the same energy source, the impact of the electricity produced from geothermal (0.071 $kgCO_2eq/kWh$), from PV (0.075 $kgCO_2eq/kWh$), from thermal power plants (0.656 $kgCO_2eq/kWh$), wind (0.020 $kgCO_2eq/kWh$), hydro (0.032 $kgCO_2eq/kWh$) and of the electricity imported from other countries (0.267 $kgCO_2eq/kWh$) can be assessed. From the economic point of view, a reference database containing the current FITs [58] and the energy costs [8] are provided by the national authorities. All the other parameters required to run the model (like the ageing and operational parameters of the batteries) are set as in [25].

This section demonstrates that all the data necessary to perform the analysis are valid and reliable for Italy because they are obtained by processing primary data provided by National Energy Authorities [8, 58], transmission system operators [57] and reliable international databases for LCA [51]. Differently, CT is uncertain because policymakers may change taxes to improve the effectiveness of the adopted policy [17] and the communities penetration P is still unknown and it is arbitrarily estimated to 25%.

5. Results and discussion

In this section, the main outcomes of the analysis are collected and discussed. Although the results are calculated and presented sequentially in this section, they are all interdependent and comprise an equilibrium between three aspects:

- RECs components size and energy management.
- RECs environmental performances.
- Proposed FITs that allocate the environmental benefits to costs.

In order to highlight the effectiveness of the proposed incentives, results are also calculated using the current FITs as terms of comparison; furthermore the situation before RECs deployment is also considered for comparison. Two parameters must be set before running the calculations: the penetration of RECs inside the territory (P), determining the number of communities, and the carbon taxes (CT). First, a Base Case Scenario where P is set to 25% and CT to 15.4 EUR/tonCO_2eq (the current value of carbon taxes in Italy) will be considered, and then a sensitivity analysis will be performed.

5.1. Base Case Scenario

This section illustrates the main results evaluated in the Base Case Scenario. Figure 3a and Figure 3b respectively represent the optimal size of the PV system and of the BESS providing the geographical resolution of the results. Analyzing the similarities between the communities designs, 12 representative RECs can be pointed out: these communities differ for their installation site and size. Particularly, moving from the north to the south of the country, the components capacity values increase, especially the BESSs. Indeed, southern RECs members can take advantage of a larger solar energy surplus to be stored in batteries. Comparing the existing FITs with the incentives proposed in this paper (which reflect RECs environmental performances), the average size of PV systems increases with the new FITs; contrarily storage capacity is still about the same. The main reason is that the FITs proposed in this paper reward RECs for the net environmental benefits of the electricity injected. This creates a slightly higher incentive for PV injection and does not produce any value for storage. As expected, the higher the REC electricity consumption, the larger the PV and storage installed capacities. Furthermore the Optimal Design model evaluates that, among the batteries considered by Peters and Weil [26], the lithium manganese oxide (LMO) devices analysed by Notter et al. [59] allow to minimize the cost. This outcome results from the cross evaluation of the costs and the ageing parameters of all the considered batteries in RECs operative conditions.

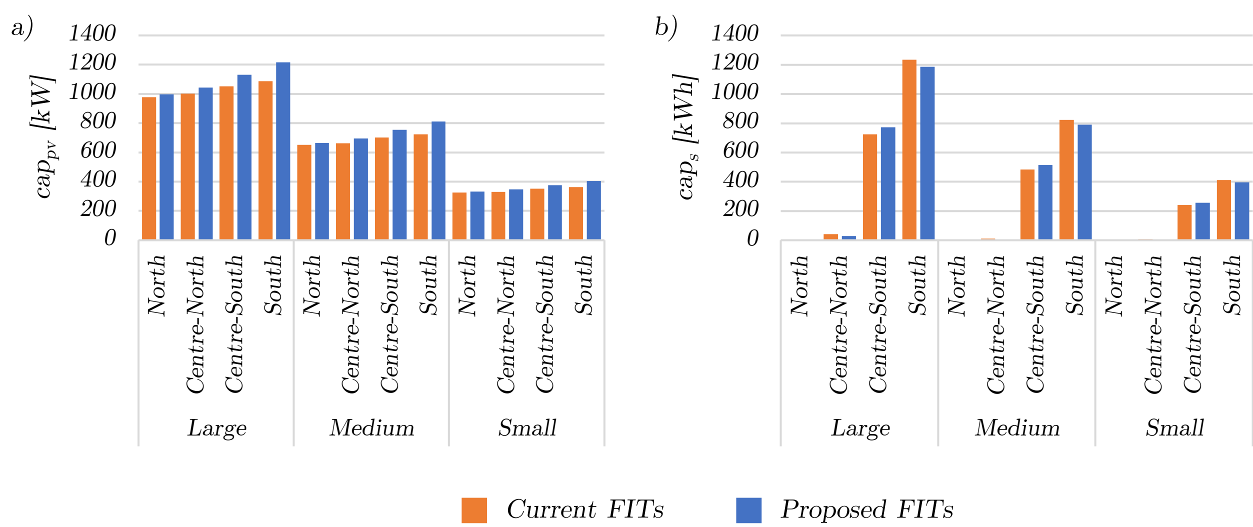

Figure 3: Representative sizes of a) the PV and b) the batteries.

The dispatch of technologies, including the exports and imports to/from the main grid, is determined using an optimization algorithm [25]. Each REC can decide hour by hour to import electricity from the grid or to consume its own energy production; in case a solar surplus exists, it can be injected to the grid or accumulated to be consumed or exported later.

In order to assess the effects of RECs at national level, the overall amount of electricity exported, imported and self-consumed by all communities is calculated. Differently from the situation before RECs deployment, part of the national energy demand is self-consumed by RECs and it is not supplied by the grid. Therefore the new energy mix is composed of the electricity exported to the grid by communities (RECs exports) and that injected by other producers. Part of the latter contribution is consumed by RECs (RECs imports) and part by other users not belonging to RECs (Non-RECs imports).

Figure 4 describes these results throughout an average day of the year and provides the annual value of all cumulative energy flows. The annual results show that, in case the current FITs are adopted, RECs reduce the amount of electricity on the grid by self-consuming 29.3 TWh/year and they export 4.0 TWh/year. When considering the changes brought by the proposed FITs, the further PV power installed by RECs allows to increase exports from 4.0 to 6.3 TWh/year whereas SC is slightly affected. Therefore, the amount of energy self-consumed by RECs is much bigger than the energy injection: with the proposed FITs around 83% of the electricity produced by RECs is self-consumed and only 17% is exported to the grid. Although RECs SC is relevant, 59% of RECs load is supplied by the grid and 41% through SC. These values represent a national average but results can be different depending on the installation site. Indeed, in north of Italy, SC contributes to 29% of communities load whereas in south, such percentage can reach 53% because storage is largely deployed.

The daily profile illustrated in Figure 4 provides the hourly impact of the proposed FITs. The electricity flows inside the grid are represented with different shades of yellow whereas the electricity outside the grid, namely communities SC, is illustrated in grey. RECs decide to self-consume their own electricity from 5 AM to 10 PM and to inject power only from 7 AM to 4 PM. This finding confirms that SC is generally preferred to the injection to the grid: all RECs directly consume the PV energy they need and store the surplus in batteries (when available). All the energy accumulated is used to extend the SC time range. Therefore RECs only inject electricity to the grid when storage systems are full or not available.

Similarly to the previous energy balance, it is possible to make the GHGs balance of the Italian energy system through evaluation of RECs environmental performances. Such GHGs balance consists on the evaluation at national level of the carbon dioxide emissions due to RECs self-consumption, imports, exports and to Non-RECs imports. Figure 5 depicts these results in terms of GHGs release over the year and throughout the average day of the year. The results obtained by applying the current FITs show that the deployment of RECs allows for a relevant mitigation of the yearly national emissions from 121.1 to 109.8 MtonCO_2eq/yr. The proposed FITs allows to further decrease this value to 108.2 MtonCO_2eq/yr; therefore the additional benefits brought by the proposed FITs is quite small compared to those provided by the current ones.

Dividing the annual GHGs emissions by the corresponding energy flow, some representative specific environmental impacts can be evaluated. Above all, the electricity produced and injected to the grid by

Annual energy flows [TWh]				
	Before RECs	*Current FITs*	*Proposed FITs*	
RECs self-consumption	*0.0*	*29.3*	*29.8*	*Outside the grid*
RECs imports	*0.0*	*43.2*	*42.8*	*Inside the grid*
RECs exports	*0.0*	*4.0*	*6.3*	
Non-RECs imports	*290.3*	*213.8*	*211.4*	
Total ———	*290.3*	*290.3*	*290.3*	

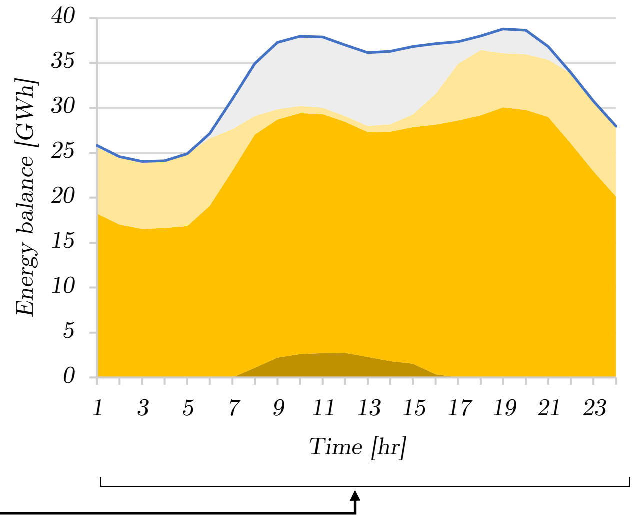

Figure 4: National energy balance during the average day of the year (evaluated using the proposed FITs) and on annual basis.

RECs has a specific impact of 0.09 $kgCO_2eq/kWh$, which is very low compared to the grid one, assessed 0.40 $kgCO_2eq/kWh$. These results represent a national average; southern RECs have a larger productivity and the impact of their electricity is around 0.07 $kgCO_2eq/kWh$ whereas the burden of northern communities energy production is around 0.12 $kgCO_2eq/kWh$. Concerning instead the energy consumption, even though RECs produce low-carbon electricity, the importation of electricity from the grid brings the specific impact of the consumed electricity to 0.29 $kgCO_2eq/kWh$. Nevertheless, because of the lower contribution of SC, the impact of northern RECs load supply is 0.34 $kgCO_2eq/kWh$ whereas that related to southern RECs is 0.24 $kgCO_2eq/kWh$. Concerning the daily emissions profile during the typical day of the year, the gap between the black dotted line and the orange dashed line represents the amount of avoided emissions using the current FITs whereas the small gap between the blue and orange lines represents the additional emissions savings due to the proposed FITs. Coherently with the energy balance temporal resolution, regardless of the adopted FITs the avoided emissions are concentrated from 7 AM to 10 PM.

As shown in Figure 1, the final step of the analysis is the cost allocation rewarding RECs members of their environmental advantages. The average FITs throughout the day are represented in Figure 6a: the orange one represents the current FITs whereas the blue one is evaluated through the novel methodology presented in this paper. These two profiles are very important because they, respectively, represent the starting and ending points of the overall analysis. Indeed, using the current incentives (orange profile), the algorithm designs RECs as illustrated in Figure 3 (orange columns). RECs inject electricity to the grid from 7 AM to 4 PM (Figure 4) avoiding carbon dioxide emissions within this time range (Figure 5). By the multiplication with carbon taxes, the environmental benefits are converted to economic ones increasing FITs only in those hours when some energy is exported. At the following iteration RECs decide to install more PV modules

Annual carbon flows [$MtonCO_2eq$]				
	Before RECs ·····	Current FITs - - -	Proposed FITs —	
RECs self-consumption	0.0	2.8	2.8	Outside the grid
RECs imports	0.0	18.8	18.6	Inside the grid
RECs exports	0.0	0.2	0.3	
Non-RECs imports	121.1	88.0	86.5	
Total	121.1	109.8	108.2	

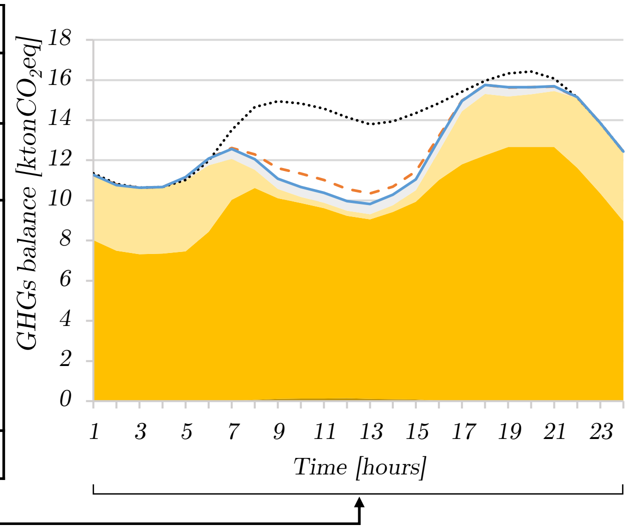

Figure 5: National GHGs balance during the average day of the year (evaluated using the proposed FITs) and on annual basis.

and devote them to increase the electricity injection to the grid taking advantage of FITs increments. As demonstrated by Figure 6b, iteration by iteration, FITs continue growing but the increments gradually get smaller because the energy mix is improving and RECs avoid less emissions. After some iterations the incremental incentives are unable to justify relevant further investments in PV and an equilibrium FITs condition (the blue profile) is reached.

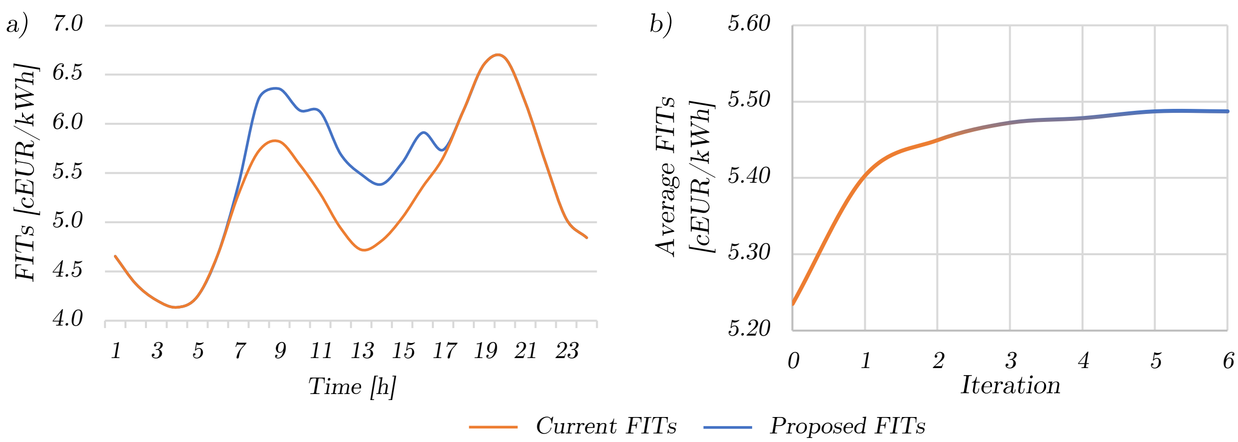

Figure 6: Average FITs a) during the representative day of the year and b) as function of iterations.

5.2. Sensitivity Analysis

The Base Case Scenario evaluation requires setting two parameters: CT and P. A sensitivity analysis for the parameter P is important because the expected number of communities on the Italian territory is uncertain; nevertheless its result does not highlight differences between the proposed and the current FITs (results are provided as Supporting Information).

Different considerations can be derived regarding the parameter CT. Although Italian carbon taxes are currently set to a specific value, the OECD [17] report underlines that some countries may increase taxes in the future to fight climate change. Therefore, in this analysis CT is gradually incremented and the corresponding results variations are assessed.

Figure 7a and Figure 7b respectively represent the average PV and the storage system sizes as function of CT and show that the former has an increasing trend whereas the latter is decreasing. The reason is that FITs increase with CT according to Eq. 8 pushing RECs to deploy larger PV systems and use them to inject more electricity to the grid. Contrarily, the size of storage systems decreases with CT because FITs promote energy injection despite of storage and SC. Notably, the components capacity variation is very fast in case CT is within the range of 17 EUR/tonCO_2eq and 20 EUR/tonCO_2eq and suddenly slows down over this range; the following results will explain this trend.

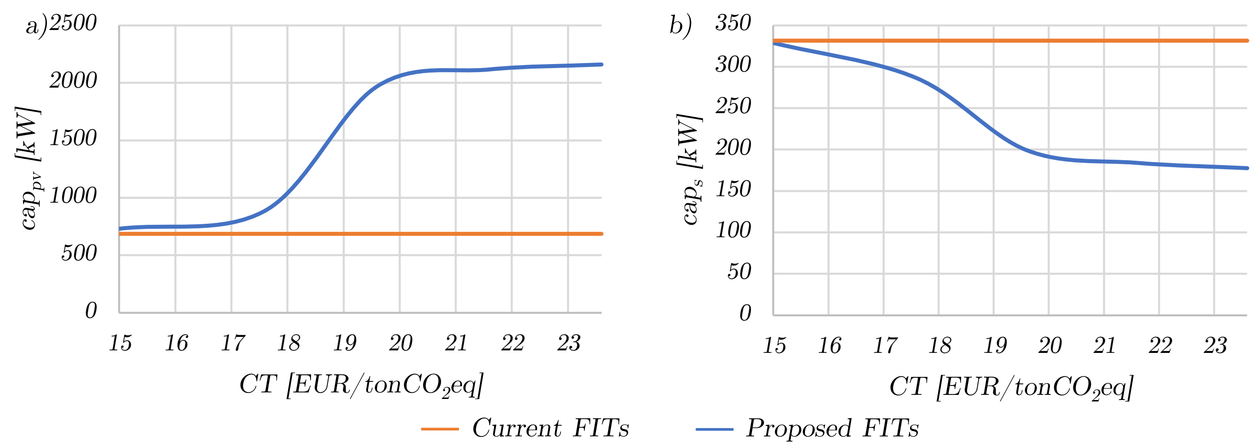

Figure 7: Optimal size of a) the PV system and b) the batteries as function of CT.

Figure 8a shows the annual energy balance of the Italian energy system, evaluated using the proposed FITs, as function of CT. This chart shows that the contribution of RECs exports to the grid rapidly rises with CT, but for a taxation higher than 20 EUR/tonCO_2eq such growth suddenly slows down. This finding can be explained by the observation of Figure 8b, representing RECs injected power as percentage of the total energy on the grid during the average day of the year. This chart shows that in case CT gets higher than 20 EUR/tonCO_2eq, the grid is saturated by RECs exports from 7 AM to 4 PM; therefore, there is no need for further electricity exports from REC within this time range. Differently, out of this time range, RECs exports are not affected by CT and are null for any level of carbon taxes. Indeed higher values of CT amplify additional FITs but they do not affect the energy injection time range. Due to the same reasons, the deployment of additional PV modules stops growing for CT higher than 20 EUR/tonCO_2eq (Figure 7).

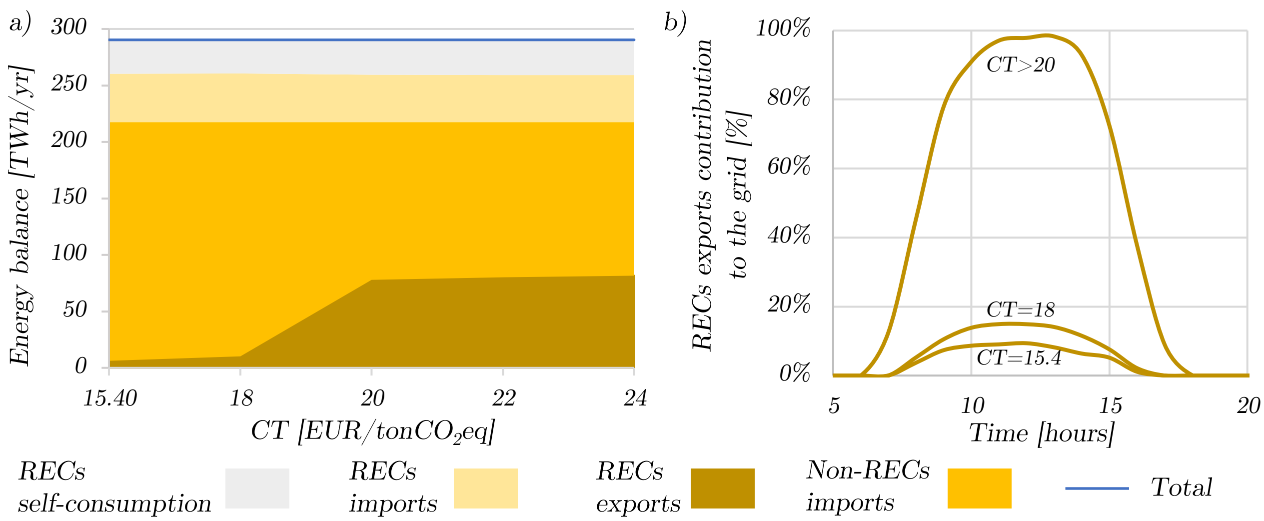

Figure 8: a) Energy balance of the grid on annual basis as function of CT; b) amount of electricity exported by RECs as percentage of the total energy on the grid during the average day of the year. Evaluated using the proposed FITs.

Figure 9 represents the annual GHGs balance of the grid calculated using the proposed FITs; contrarily to the Base Case Scenario, the proposed FITs allow to avoid a relevant amount of additional GHGs emissions compared to the current FITs. Indeed, according to the energy balance results, increasing CT allows to inject much more electricity to the grid, until CT reaches 20 EUR/tonCO_2eq. Above this value, RECs do not provide further environmental benefits by increasing CT due to the grid saturation mechanism illustrated in Figure 8. This means that, in case of adoption of the proposed FITs, carbon taxes should be set to 20 EUR/tonCO_2eq because this allows to get the maximum benefits from RECs. Concerning the LCA results, the enhanced RECs exports allow to mitigate the energy mix impact from 0.40 kgCO_2eq/kWh (Base Case Scenario) to 0.31 kgCO_2eq/kWh for CT=20 EUR/tonCO_2eq. Indeed, the impact of RECs electricity exports is very low for all values of CT and it slightly varies from 0.09 kgCO_2eq/kWh (for CT=15.4 EUR/tonCO_2eq) to 0.07 kgCO_2eq/kWh (for CT=24.0 EUR/tonCO_2eq). Concerning the impact related to RECs load supply, its value is assessed around 0.29 kgCO_2eq/kWh regardless of CT. The reason is that electricity is mostly imported during the night when, according to Figure 8, RECs electricity contribution to the grid is null and the energy mix environmental impact does not change.

Figure 10a depicts the average FITs as function of CT and underlines that the proposed incentives increase when carbon taxes are high; Figure 10b instead illustrates the convergence of average FITs with iterations. As described in the Base Case Scenario, for CT=15.4 EUR/tonCO_2eq, the FITs increments are so low that, after few iterations, they reach an equilibrium value where further investments in PV are not beneficial. In case CT increases to 18.0 EUR/tonCO_2eq, the economic advantages for RECs are amplified and their members continue investing in PV and accumulating additional FITs for several iterations, until incentives converge to an equilibrium value (higher than that evaluated in the Base Case Scenario). By further

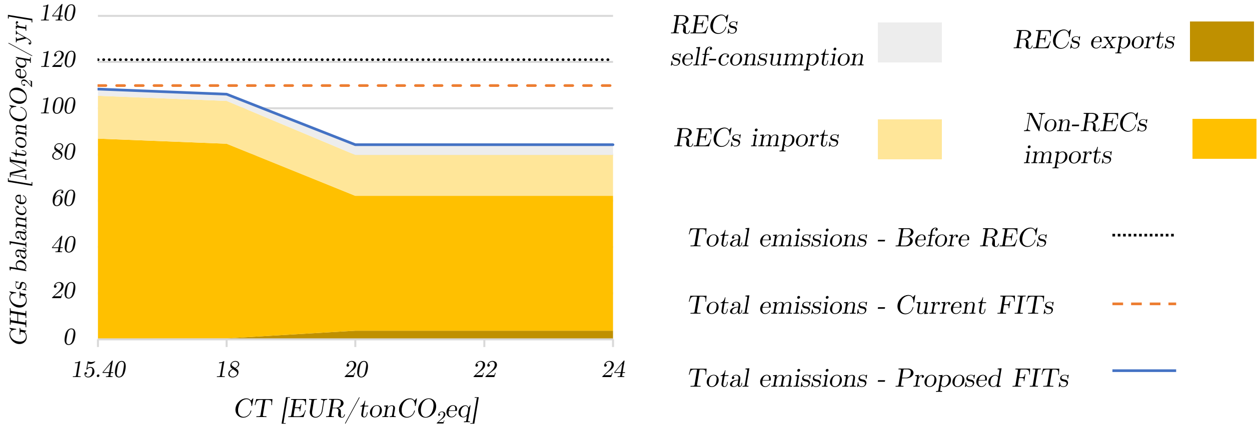

Figure 9: LCA results as function of CT.

increasing CT, FITs get more convenient and RECs continue for many iterations deploying additional PV modules. But when taxes reach 20.0 EUR/tonCO_2eq, the curve gets flat: Figure 10b shows that, for CT=20 EUR/tonCO_2eq, after 12 iterations the growth of FITs suddenly stops. The reason is that, as demonstrated by Figure 8a, the grid is saturated by RECs injection that is unable to further improve the grid energy mix. Consequently no further emissions are avoided and converted to additional FITs. Therefore, at this taxation level, RECs get the maximum FITs allowed by this incentives design approach; indeed even for higher values of CT, the proposed FITs approximately converge to the same equilibrium value (with a lower number of iterations).

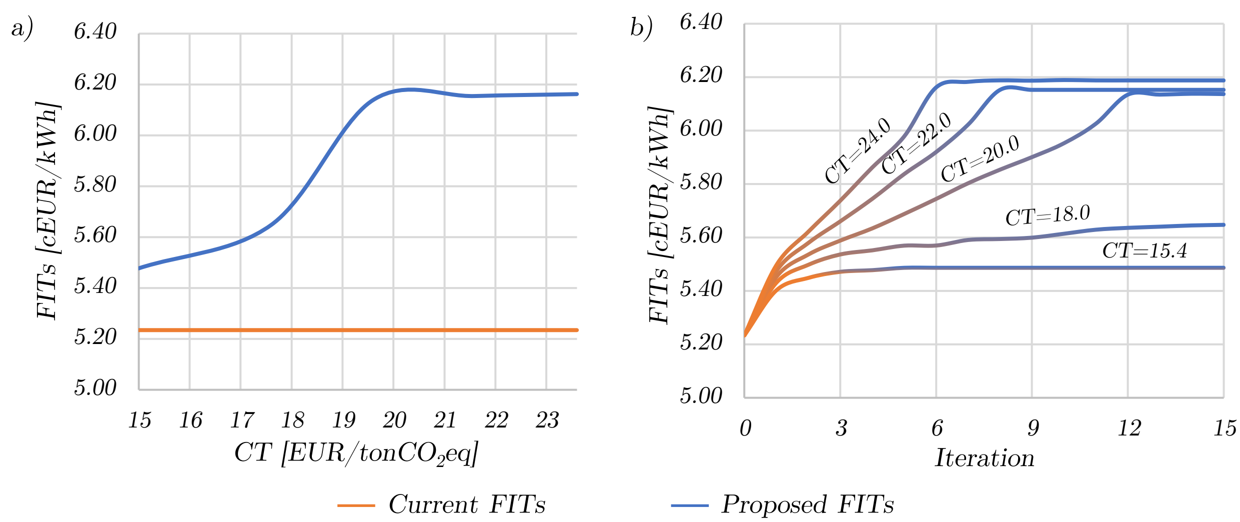

Figure 10: Average FITs a) as function of CT and b) of iterations.

6. Conclusions

This paper proposes a novel design approach for new FITs rewarding RECs members of their environmental benefits. The proposed design framework allows to consider the life cycle carbon dioxide emitted and avoided by RECs depending on time and on the changes of the energy mix. The outcomes resulting from this approach are i) the optimal RECs components size and energy management, evaluated through economic optimization; ii) the environmental performances of RECs and of the energy mix, assessed using LCA; iii) the allocation of RECs benefits on FITs. First these results are presented considering a Base Case Scenario, where carbon taxes are set to 15.4 EUR/tonCO_2eq and RECs load is 25% of the national demand; then, a sensitivity analysis is performed.

In the Base Case Scenario, first the environmental advantages provided by RECs deployment to the national energy system are assessed using the current FITs; then the additional benefits brought by the proposed FITs are calculated. Indeed, since RECs design and energy management are evaluated through economic optimization, FITs play a key role when determining the optimal portfolio of investments and the optimal energy management. Results show that RECs are effective to reduce the national GHGs emissions; indeed, in case the current incentives are adopted, the national emissions are reduced from 121.1 to 109.8 MtonCO_2eq/yr. Most of these advantages are due to SC because, according to the results, RECs prefer self-consuming energy rather than exporting it to the grid due to economic convenience. The proposed incentives instead push RECs to install further PV modules and devote them to increase the energy injection to the grid thus avoiding other GHGs emissions. Such additional advantage is actually quite small, because the injected energy only increases from 4.0 to 6.3 TWh/yr and thus the amount of GHGs emitted at national level are mitigated by RECs to 108.2 MtonCO_2eq/yr (only 1.6 MtonCO_2eq/yr than using the current FITs). This is due to the fact that, using the proposed approach, the current value of CT in Italy (15.4 EUR/tonCO_2eq) does not determine a large FITs extension. Therefore, the adoption of this energy policy framework requires to modify carbon taxes in order to increase the effectiveness of the proposed incentives. The sensitivity analysis of the parameter CT shows that, increasing carbon taxes, the proposed FITs allow to obtain larger environmental benefits for the national energy system in terms of avoided emissions. Indeed, the PV power deployment and the energy injection to the grid grows very rapidly with CT, promoted by larger additional FITs. Notably, increasing CT from 15.4 to 20 EUR/tonCO_2eq, the energy injected to the grid rises from 6.3 TWh/yr to 78.0 TWh/yr; consequently, the national emissions are strongly reduced (from 108.2 to 84.3 MtonCO_2eq/yr). Further increasing CT does not provide relevant additional environmental advantages because, within the time range when RECs inject electricity, the grid is already saturated of RECs electricity and FITs stop growing to prevent the exportation of excessive (and impactful) electricity. Therefore, in case of adoption of these incentives, carbon taxes should be adapted and set to 20 EUR/tonCO_2eq in order to get the maximum environmental advantages from RECs.

In the future, this work can be further developed by proposing new time-based incentives more focused on the temporal aspects of RECs electricity injection, taking advantage of the dispatchable characteristics of the storage devices. Furthermore, also the SC could be promoted by proposing a novel specific incentive for RECs electricity sharing.

7. Acknowledgements

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