An Algorithm for Renewable Energy Communities Designing by Maximizing Shared Energy

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ABSTRACT

Renewable Energy Communities are a new paradigm promoted by the European Union as a promising solution to reduce both the carbon footprint and the impact of Renewable Energy Sources in distribution grids. Promoting the transition to a sustainable energy system involves several strategies and initiatives. A key aspect is the regulatory frame- work established by each member state to effectively manage the aggregation and management of new customers. In Italy for example, specific eligible configurations, incentives, and bureaucratic procedures have been defined to facilitate the creation of Energy Communities. However, these regulatory frameworks do not provide guidelines on the optimal design and management of such communities. To address this gap, new research projects such as "SAMOTHRACE - SiciliAn MicronanOTecH Research And innovation CEnter" aim at developing new technologies and approaches that can promote the development of Energy Com- munities. In this context, this paper presents the definition of an algorithm to choose the optimal mix of consumers within the energy community to maximize the economic benefit from self-consumption for a given PV plant or conversely to choose the best size of the PV system, for a given set of consumers. In both cases, loads will not be either shifted or curtailed and electricity will not be stored. In order to ease the widespread adoption of the method, the optimization problem was conceived to be developed in a spreadsheet environment. The algorithm was applied to the case study of the island of Pantelleria, thus deriving the potential economic benefits for the components of the community.

INDEX TERMS

Energy Communities, optimal design, self-consumption, energy transition, Samothrace.

1. Introduction

Renewable Energy Communities (RECs) are a new arrangement of energy resources aimed at promoting the transition to a sustainable and decentralized energy supply system [1]. These communities actively involve citizens, local companies, and other interested entities in the production, sharing, and use of renewable energy. Based on the principle of sharing the renewable energy produced within them, RECs can play a key role in reducing the carbon footprint and grid impacts of Renewable Energy Sources (RES) in distribution networks [2].

In Europe, RECs are gaining increasing attention and support at the political level. The 2018 European Renewable Energy Directive (RED II) introduced a legal definition of RECs and provided a regulatory framework for their development [3]. This directive promotes self-consumption, local renewable energy production, and the sharing of energy resources among community members. In Italy, the concept of RECs was introduced into the national legislation with Legislative Decree 199/2021 [4], which transposes the RED II Directive. The Italian regulatory framework provides incentives to encourage the development of RECs and promote self-consumption of renewable energy. The incentive established by the decree is a feed-in premium, *i.e.* a cost reduction not related to the purchase of the renewable energy production. It is calculated hour by hour and based on the self-consumed electrical energy. The decree distinguishes between shared energy in the case of Jointly Acting Renewable Self-Consumers (JARSC) groups and RECs. The main difference is that JARSC components are all in the same building and the feed-in premium, granted for 20 years, is 100 €/MWh. In the case of RECs, the premium is 110 €/MWh. The purpose of the incentive is to encourage the widespread of self-consumption and to gradually replace the Net-metering mechanism while avoiding increases in power system management and energy costs. The creation of JARSC and RECs, in addition to economic benefits, offers several environmental benefits, enabling their members to reduce carbon emissions, improve energy efficiency and reduce dependence on conventional energy sources [5]. They also promote active citizen participation in the energy process, creating opportunities for economic and social involvement at the local level. Despite this, both JARSC and RECs struggle to spread. The reasons are many, including limited information available to common citizens, administrative and bureaucratic complexity, an unconsolidated regulatory framework, resistance to change, and technical and economic obstacles. The issue of management after the establishment, although not explored at the legislative level, plays a very important role because the environmental benefit and the social and economic benefit for members, for which the community was created, may fail or be not optimal. In what follows, we will not explicitly refer to JARSCs, as all conclusions drawn for RECs are also valid for JARSCs. In general, a REC operates the electricity produced and consumed by a group of end users; therefore, it is important to properly choose the mix of renewable energy users and systems that will be part of the REC in order to maximize the economic benefit for the RECs participants. This aspect is crucial since the scientific literature on the topic is mainly focused on the operational phase of the REC rather than on the design process [6]–[10].

For these reasons, new research projects such as "SAMOTHRACE - SiciliAn MicronanOTecH Research And innovation CEnter" [11] aim at developing new technologies and approaches that can promote the development of RECs since the design phase.

SAMOTHRACE is an ambitious project covering several areas of interest, including energy, health, smart mobility, environment, and smart agriculture. The aim is to realize the vision of a global collaborative environment among key players in energy, microelectronics, microsystems, materials, and microtechnology by working in accordance with most of the "Global Sustainable Development Goals": improving sustainable agriculture, ensuring healthy lives, achieving gender equality and inclusion, providing modern and efficient energy, promoting sustainable growth, and supporting sustainable industrial growth. One of the goals of the Energy sector is to develop energy management technologies within RECs in order to overcome some of the obstacles that are currently limiting their deployment. In this context, this paper presents the definition of an algorithm to choose, alternatively, the optimal mix of users that should build-up the community or, conversely, the size of the PV system to be installed with the goal of maximizing the economic benefit for a given set of users. In order to enhance the widespread of the method, the optimization problem was formulated as a Non-Linear Programming algorithm and was solved using the Solver available in MS Excel with the Generalized Reduced Gradient algorithm.

As a demonstrative case study for the testing of the algorithm, the Italian island of Pantelleria was selected. Pantelleria is a very interesting test environment since it is non- interconnected with the mainland and mainly powered by diesel-fired electric power plants. In order to ensure an energy transition in line with national and European trends, it is necessary to look for innovative solutions for the integration of renewable sources also in weak systems such as it happens in small non-interconnected islands, in order to maintain their reliability at adequate levels. In the authors' mind, one solution might be the development of RECs. Moreover, as social acceptance of using innovative technologies might be limited in remote islands/areas, the design of the REC assessed in the present study was performed without the use of any storage system or any control action on user loads.

This paper is organized as follows. Section II provides the details of the REC model, including the optimization algorithm. In Section III, the case study of the island of Pantelleria is described. Section IV illustrates the results of the numerical simulation applied to Pantelleria Island and results are presented to demonstrate the effectiveness of the proposed method. The conclusions and future works are presented in Section V.

2. ENERGY COMMUNITY MODEL

A. *Energy Community Members*

Energy communities are made up of consumers and producers or prosumers. Participants may vary depending on local regulations and specific community goals [12], but in general, they include:

- *Citizens and consumers*: citizens who live or work in the area served by the energy community may be participating members. These individuals may be homeowners or renters, businesses, or institutions.
- *Owners of renewable energy systems*: owners of renew- able energy systems, such as solar panels, wind turbines, or other renewable sources, can be part of the energy community and contribute to energy production.
- *Local governments and public agencies*: local governments and public agencies can participate and support the energy community initiative, possibly by providing incentives or logistic support.

- *Small businesses and farmers*: small businesses or farmers with renewable energy facilities can join the energy community and contribute with their own energy production.
- *Energy service providers*: some energy communities may include energy service providers who facilitate interaction among members and manage the technical and administrative aspects of the community.

The following Fig. 1 shows a general REC configuration consisting of all possible actors.

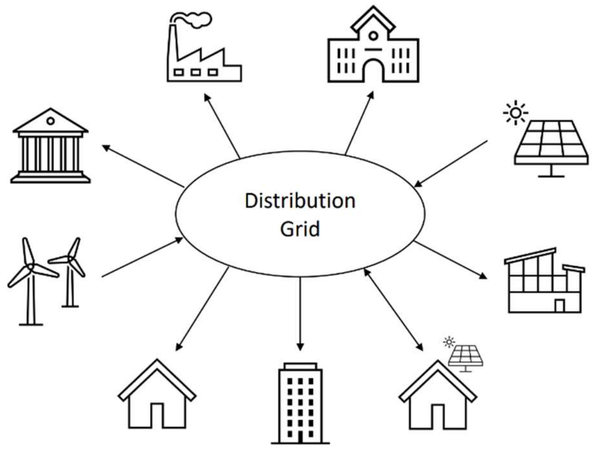

Fig. 1. General REC configuration

Each of the actors is characterized by a specific consumption/production profile. Within a REC, consumption, such as production, plays a key role and is very important. A REC is a system where multiple actors join together to share, generate and manage energy in a collaborative and sustainable way. But if renewable energy is not consumed at the same time (in the Italian legislation, in the same hour) it is produced then the benefit for which the REC is established could be lost. Consumption, such as production, is the key element in ensuring effective energy management within an energy com- munity, with the goal of maximizing efficiency, sustainability, and sharing of energy resources among participants.

Based on these considerations, the importance of choosing the right mix of actors with different consumption/production profiles becomes clear.

The next section describes the method developed for the optimal choice of REC members that maximizes benefits.

B. *Proposed Optimization Algorithm*

The problem of choosing the optimal number of participants in a REC can be formulated in mathematical terms as follows. First, we can define a list of categories of participants, *i.e.* a set of production or consumption average behavior trends. The categories of components can be divided in loads categories and generators categories. The trends of each category are assumed to be homothetic (e.g. a REC component belonging to the "single-component domestic user" category with a 6 kW contract has the same power absorption trend as the sum of two REC components belonging to the same category each one with a 3 kW contract). With this hypothesis, the behavior of each REC component is the same of the behavior of the other components belonging to his specific category, multiplied by a scale factor. In general terms, in the following equations it is assumed that the REC can be made up of k loads categories of components and m generators categories of components.

Since profiles are homothetic, each category of components is fully characterized by an average behavior trend and a rated size, namely the contracted power for load categories and the peak power of production plant for generators categories. These values are constant and are given as input to the algorithm. The unique variable of the algorithm for each category of actor is the number of components (or actors) belonging to each category, as indicated in Eq. (1). The number of actors of each category is the scale factor that can stretch and shrink the trends given as input to the algorithm.

$$x = \{N_{L,1} ; N_{L,2} ; \ldots N_{L,k} ; N_{G,1} ; N_{G,2} ; \ldots ; N_{G,m}\} \qquad (1)$$

The total power load in the REC for each time-step t is thus given by the sum of the contributions of the k

loads categories, each category multiplied by the number of actors of each category, as in Eq. (2).

$$P_{Load}(t) = N_{L,1} \cdot P_{L,1}(t) + N_{L,2} \cdot P_{L,2}(t) + N_{L,k} \cdot P_{L,k}(t) \quad (2)$$

Similarly, the total power generation in the REC for each time-step is given by the sum of the contributions of the *m* generators categories multiplied by the number of actors of each category, as in Eq. (3).

$$P_{Gen}(t) = N_{G,1} \cdot P_{G,1}(t) + N_{G,2} \cdot P_{G,2}(t) + N_{G,m} \cdot P_{G,m}(t) \quad (3)$$

Each production trend of this equation should be considered as the cumulative trend of many generation systems operating in the same conditions.
The shared energy inside the REC for each time-step is defined as the minimum between the total power generation (Eq. (3)) and the total power consumption (Eq. (2)), as in Eq. (4).

$$E_{shared}(t) = min\ [\ P_{Gen}(t)\ ;\ P_{Load}(t)\ ] \cdot \Delta t \qquad (4)$$

In order to maximize the shared energy inside the REC, the total power consumption trend should match as much as possible the total power generation trend. In an ideal case, the best REC configuration would be made up of a set of *k* load actors constituting a cumulative P_{Load} trend that is perfectly equal, time-step by time-step, to the cumulative P_{Gen} trend deriving from the set of *m* generator actors. This condition is expressed by Eq. (5).

$$P_{Gen}(t) - P_{Load}(t) = 0 \qquad (5)$$

One of the targets of a REC is to maximize the economic profit of each community member. This target can be achieved by increasing the shared energy over the whole period, which is proportional to the income of the REC, but also keeping the number of actors low, in order to maximize the individual economic profit of each actor. For what is described above, the objective function of the problem should perceive the maximization of the shared energy over the whole period (sum of the contributions over the whole timeframe) and the minimization of the total number of actors inside the REC. The objective function (O.F.) of the problem was thus formulated according to Eq. (6).

$$O.F. = max\left[\frac{\sum_{t=1}^{T} E_{shared}\%(t)}{\sum_{i=1}^{k} N_{L,i} + \sum_{j=1}^{m} N_{G,j}}\right] \qquad (6)$$

The numerator of Eq.(6) was evaluated as the percentage of the shared energy with respect to the energy generation when the optimization aims to identify the number of consumers, while it is evaluated with respect to the energy consumption when the algorithm aims at finding the optimal generation rated size.
In order to pursue the matching between generation and load, the optimization problem is constrained by the condition that the difference between generation and load should stay below a threshold value, in each time-step. In this way, Eq. (5) is rewritten as in Eq. (7):

$$-Threshold \leq P_{Gen}(t) - P_{Load}(t) \leq Threshold \qquad (7)$$

For the present study, the threshold value was assumed as a percentage α of the load of the REC in each time-step. Including this condition in Eq. (7), the constraint is reformulated as in Eq. (8).

$$-\alpha \cdot P_{Load}(t) \leq P_{Gen}(t) - P_{Load}(t) \leq \alpha \cdot P_{Load}(t) \qquad (8)$$

The set of equations described above can be used to formulate an optimization problem for the design of a new REC or to identify the best partners for existing RECs.
In order to allow this option, the algorithm allows setting a minimum and a maximum number of actors for each category. For example, given a production plant, the owner (or the owners) may want to identify the

best combination of consumers and prosumers to create a REC with. In this case, the typical trend of the production plant would constitute a category with a unique actor (minimum and maximum number of actors = 1) and the other categories of load and generator actors would not have a pre-determined number of actors. The algorithm will identify the minimum set of passive users that will maximize the shared energy hour-by-hour.

On the other hand, starting from a set of consumers who want to establish a REC, each of them belonging to a category of actors, the algorithm will select the size of the renewable source system that will maximize the shared energy with the starting set or load actors hour-by-hour.

3. CASE STUDY

In order to test the potential application of the model, the developed optimization algorithm was applied to the case study of the island of Pantelleria. This is a very interesting test environment since it belongs to the category of small non- interconnected islands, *i.e.* small geographical islands disconnected from the national power system and mainly powered through diesel-fired electric power plants [13]. Renewable energies are being installed in Pantelleria as a result of the issuance of a Ministerial Decree in 2017 aimed at greening the power system in Italian small islands [14].

For the present study, and starting from previous works [6], [7], a subset of five load categories was selected, all of them being representative domestic users without energy production. The main details of the five categories of load actors are recapped in Table I. The monthly-average daily trend for each user category was evaluated with a time-step of 10 minutes (144 measures/day).

On the other side, only one production category was used for the case study, namely a PV system with a 1 kW_p rated size whose typical daily trend was gathered from the online tool PVGIS [15]. The target of the case study is to identify the optimal number of actors belonging the five load categories and the number of actors belonging to the unique generator category.

4. NUMERICAL SIMULATION RESULTS

The proposed REC model, described in Section II, was numerically tested in the case study of the island of Pantelleria described in Section III, as already mentioned, in two different cases: consumption design and generation design.

TABLE I - Load Categories Main Features

Main Features	**Domestic Loads Categories**				
	Load 1	***Load 2***	***Load 3***	***Load 4***	***Load 5***
Rated power	3 kW	3 kW	3 kW	3 kW	3 kW
Occupants	1	1	2	3	4
Floors	1	2	2	1	2
Rooms	3	7	10	11	8
Fridge	1	1	1	1	1
TV	1	3	1	2	4
Washing machine	1	1	1	1	1
Dishwasher	1	0	1	1	1
Oven	1	2	1	1	2
Fans	1	1	0	0	0
Water pump	1	1	1	1	1
Water heater	50 L	30 L	80 L	NO	50 L

A. *Consumption design*

For the first application, the algorithm was run fixing the cumulative generation potential equal to 3 kW_p, *i.e.* setting 3 actors for the generation category having a 1 kW_p rated size. The value of 3 kW_p was selected because this is also the typical contractual power of domestic users in Italy and is thus the reference value for sizing PV systems conceived for self-consumption in domestic applications.

In this case, the main aim was to identify the minimum number of REC actors belonging to each load category able to maximize the shared energy coupling with the 3 kW_p generation profile.

The optimal number of actors belonging to each load category are illustrated in Table II. The simulations were run first considering one category by one (first five rows of the Table) and later including all five categories together in the same optimization run (last row of the Table). With reference to the latter case, the daily trend of generation, load, and shared energy for the month of January is illustrated in Fig. 2. In detail, the orange trend is the daily power production from the 3 kW_p PV system, the green trend is the power consumption by the optimal set of actors belonging to each load category (last row of Table II) and the blue trend is the resulting shared energy.

In this study, the optimal contribution of each single load category allows to reach between 36% and 54% of the shared energy, while the contribution of the five categories of load actors allows to share the 74% of the energy produced by the PV system (blue line in Fig. 2). In order to reach a higher value of shared energy, an increase in the number of actors belonging to the REC would be necessary. Nevertheless, this would excessively reduce the income for each single REC member.

B. Generation design

For the second application, the algorithm was run constraining the number of actors belonging to each load category to five (chosen arbitrarily). The result of the optimization is to identify the optimal size of the equivalent PV system to cooperate with this set of load actors. The rated size of the five categories of load actors and the resulting size of the generation category are illustrated in Table III, while the daily trend of generation, load, and shared energy for the month of January is illustrated in Fig. 3. In this case, the shared energy was equal to the 71% of the energy production. Although a higher value of the PV system rated size would allow an increase in the shared energy, this would also excessively reduce the income for each single REC member.

TABLE II - Optimal Number Of Actors For Each Load Category To Couple With A 3 kW_p PV System

Simulation	**Number of actors per category**					
	PV	**Load 1**	**Load 2**	**Load 3**	**Load 4**	**Load 5**
Load 1	3	1.30	0	0	0	0
Load 2	3	0	0.98	0	0	0
Load 3	3	0	0	1.48	0	0
Load 4	3	0	0	0	1.09	0
Load 5	3	0	0	0	0	1.34
All	3	0.22	0	0.75	0.78	0.71

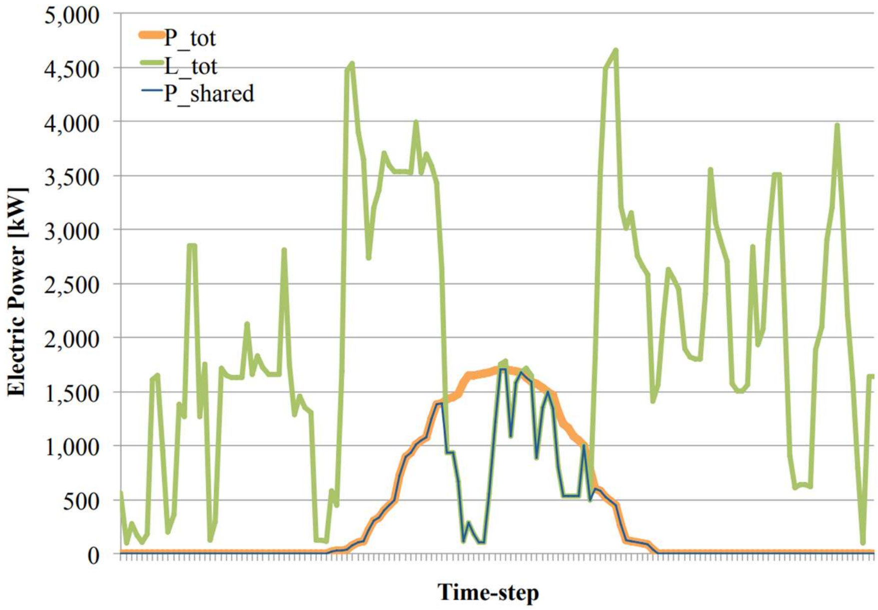

Fig. 2. Power flows trend in the average day of January for the optimized consumption set choice.

TABLE III - Optimal Size Of PV Systems To Be Coupled To A Set Of Consumers Chosen By Each Load

Category

Simulation	Number of actors per category					
	Load 1	Load 2	Load 3	Load 4	Load 5	PV
PV	5	5	5	5	5	29.39

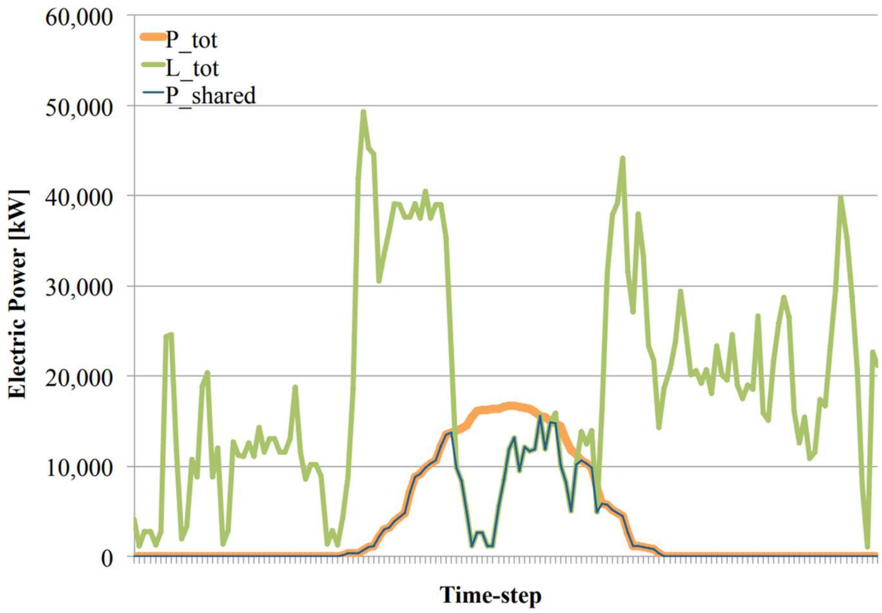

Fig. 3. Power flows trend in the average day of January for the generation design.

5. CONCLUSIONS AND FUTURE DEVELOPMENTS

In this paper, an algorithm for the optimal sizing of a REC or a JARSC group was proposed and tested. Using this algorithm, it is possible to determine the most efficient composition of users within the community, taking into account their energy demand and consumption habits, maximizing the benefits of energy sharing within the community, optimizing the use of renewable energy sources, and promoting the overall sustain- ability of the energy system.

The results of the case study show that a community can be designed with a simple algorithm implemented in a commonly available platform such as MS Excel.

Since the optimization problem is non-linear, due to the mathematical formulation of the objective function, the final solution was strongly influenced by the initial point given as input to the algorithm.

In future works, the authors will integrate the REC design optimization algorithm illustrated in the present paper with the single-user energy management algorithm developed in [16] in order to further enhance the possible integration between the actors of the REC and to allow better integration of the renewable energy in small non-interconnected islands. Furthermore, the authors will also include the assessment of other renewable energies [17] and the uncertainty related to both generation and load profiles, similar to how was performed by some authors in literature [18]–[20].

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