POLITECNICO DI MILANO
DEPARTMENT OF ENERGY
DOCTORAL PROGRAM IN ELECTRICAL ENGINEERING

RENEWABLE ENERGY COMMUNITIES

Doctoral Dissertation of:
Matteo Moncecchi

Supervisor:
Prof. Marco Merlo

Tutor:
Prof. Davide Falabretti

The Chair of the Doctoral Program:
Prof. Gabriele D'Antona

2021 – XXXIII Cycle

ad Anna e Marilisa
(e anche a Franci)

Abstract

WHEN we speak about Energy Communities (ECs) we generally refer to groups of citizens who organize themselves to actively contribute to the energy transition, producing energy and meeting their energy needs through the exploitation of renewable sources. Beyond this, the EU has recently provided formal definitions for the ECs and all the Member States are required to introduce them into their national legislation, ensuring an enabling framework to promote and facilitate their development. These recent innovations have stimulated new interests in methods and models to properly deal with the ECs peculiarities.

ECs are not isolated microgrid; the energy produced is shared among the members of the community using the public infrastructure or also exchanged with other actors on the market. Therefore, self-sufficiency is an important aspect but it is not a technical requirement and it is not mandatory to achieve a complete autarky. On the contrary, the optimal planning and operation of an EC are driven by economical evaluations that take into account both energy exchanges among community members and with the external energy system.

This thesis provides some elements to investigate benefits and risks correlated to ECs, evaluating the issue from three different perspectives: the one of the EC as a whole, the one of the EC members (i.e. citizens, municipalities and SMEs that participate to the EC), and the one of the system in which they are hosted (i.e the public distribution network).

The first part of the thesis concerns the definition of a reference framework, that is composed by a legislative framework and a research one. In the legislative framework, the models of ECs defined in the European Directives are presented and analysed. These are the Renewable Energy Community (REC) and the Citizen Energy Community (CEC). Moreover, a detailed description of the Italian scenario is proposed starting from the historical energy cooperatives to the current process of transposition of the European Directives, and the characteristics of the experimental phase currently ongoing in Italy is analysed. The second element of the reference framework focuses on the ECs state of the art in the scientific literature. This clearly shows that the interest in ECs has grown very fast in recent years, but most of the studies are not yet aligned with the new EU definitions. Some classifications of community-based initiatives are reported and a review of the most interesting research projects currently focusing on ECs is provided.

The second part of the thesis deals with methods and models for the analysis of ECs. A model capable to evaluate energy and economical exchanges within a REC is proposed. The peculiarity of the model is the ability to consider separately the self-consumed energy and shared one, to properly evaluate their economic values based on the different tariff structures. The goal of the model is to find the optimal DERs portfolio in terms of installed generators and storage capacity, optimizing the net present value of the EC investment. The proposed model and methodology constitute a tool that supports the EC planning. Then, the issue of benefit distribution among the EC members is addressed. Game theory algorithms are identified as a suitable approach for this purpose. Therefore, some elements from the cooperative and non-cooperative game theory are presented and examples of application in energy sharing situations are considered. The proposed REC model is formalized as a cooperative game, and a two steps distribution rule, based on the Shapley value among clusters of users followed by a proportional allocation, is proposed. The methodology is applied to a real-life case study of EC with more than one hundred members based on the Italian scenario.

Finally, changing perspective, the point of view of the distribution system operator is also considered, and the impact that ECs could have on the MV distribution network is tackled. The relationship between distributed generation and EC is discussed and a review of the hosting capacity concept is provided. Then, a methodology based on Monte Carlo simulation is proposed to evaluate the capacity of a network to host new ECs. Two study cases with different characteristics have been built and the procedure is tested on different real-life MV networks.

Contents

CHAPTER 1

Introduction and motivations

This doctoral thesis copes with methods and models for the analysis of renewable energy communities. Even though there are various forms of citizen participation in the energy sector around the world, this theme is specifically developed within the context of the European legislative framework recently redesigned with the "Clean Energy for all European Package". In this framework, energy communities have been officially recognized and a formal definition common to the 27 Member States of the EU has been provided.

1.1 Background

When we speak about energy communities we generally refer to groups of citizens who organize themselves to actively contribute to the energy transition, producing energy and meeting their energy needs through the exploitation of renewable sources.

This form of organization has experienced an important growth since the 2000s thanks to the liberalization of the electricity markets, the implementation of stricter environmental policies and the falling price of renewable energy plants. Several successful "bottom-up" projects have been developed over the past two decades [1, 2] and the evolution process reached an important milestone with the recognition from the European Union of the importance that energy communities have in the energy transition. In fact, with two Directives, the EU has recently provided formal definitions for the energy communities and has required to all the Member States to introduce this subject into their national legislations, ensuring an enabling framework to promote and facilitate their development.

The context in which energy communities are emerging is a huge transformation of the electrical systems. The paradigm based on centralized generation is being abandoned, and the transition to a system always more based on distributed generation is a fact. According to the Directive of the European Union 2018/2001 - a relevant document that will be deeper analysed in the following chapter - "The move towards decentralised energy production has many benefits, including the utilisation of local energy sources, increased local security of energy supply, shorter transport distances and reduced energy transmission losses. Such decentralisation also fosters community development and cohesion by providing an economical income sources and creating jobs locally". This statement makes clear the complexity of the ongoing transformation and the multidisciplinary nature of the problem. Focusing on the elements of the aforementioned citation, decentralized energy production has to deal with four factors.

1. *Local energy sources*. The exploitation of local sources requires specific attention to the environmental impact and specifically to the ecosystems preservation. It also has an important impact on the architecture and it can completely change the landscapes. Finally, a crucial aspect is the competition for the use of the resources with other sectors of the local economy such as agriculture, farming and tourism.

2. *Local security of energy supply*. Energy security is a sensitive problem for many European countries, since more than half of the EU's energy needs are met by net imports[1]. The diversification of the suppliers and the infrastructural enhancement can significantly reduce the risks. However, it is clear that the definitive solution would be the reduction of the dependency from third countries, especially because this has political, economical and financial implications.

3. *Shorter transport distances and reduced energy transmission losses*. The distributed generation reduce the usage of the transmission infrastructure and, consequently, the transmission losses and the reinforcement needs. On the other hand, new challenges are required to the distribution networks to deal with the more complex local energy management.

4. *Community development and cohesion*. The social acceptability of new power plants and infrastructures it often a problem[2] and the lack of involvement and participation of citizens in the process is one of the main cause for the opposition to new installations [4]. This interest of people can be turned into an opportunity to involve them in the energy project. This form of inclusion can reduce opposition to new installations and, at the same time, it can generate benefits for local citizens and economic value that fosters the local economy.

The change of paradigm in the energy sector has a wide impact in all the mentioned aspects of our society. Energy communities can be a tool that provides a positive approach to foster distributed generation, since they naturally have an holistic view on all the aspects of their local reality.

But how can the energy communities participate to this process, and what are the differences when compared to individual users participation? In Figure 1.1, different levels of citizens participation in the electrical sector are considered and a comparison between the individual and the collective forms is proposed. Starting from the simple

---

[1] The dependency rate of the entire European Union in 2018 was equal to 58% [3]

[2] In Italy, the NIMBY forum registered that 57% of the cases of protest against new infrastructure and facilities are referred to the energy sector. Among these, 73% are against new renewable power plants [4].

energy consumption, where there is no reason to participate to a community project, the schema moves toward a more complete involvement of the users. The next step is the self-production, i.e. an individual could install a PV power plant with the purpose of satisfying his energy needs. This concept can be applied also to a community. In this case, the scale of the project can increase and other sources - that normally require important sizes to be competitive - can be exploited, such as wind, biomass and hydroelectric power plants. The last step in the participation process is the energy management. For the individual, this means to control his loads in order to maximise self-consumption or adapt his behaviours to price signals. For a community, this can be a more complex but also interesting opportunity. The possibility to coordinate a set of users makes it possible to participate to the energy markets in an aggregated form. To describe this kind of participation, we will use the term Community-based Virtual Power Plant (cVPP) proposed in the homonym Interreg Project [5]. Just to make an example, this can be the case in which the charge and discharge of the electric vehicles of the community members is controlled in a coordinated way, in order to satisfy the request of the individuals but, at the same time, to provide flexibility and generate revenues for the entire community. In this thesis, the main focus is on the activity of production, since it is experiencing a phase of great rise, while the community management as cVPP is still in a preliminary stage.

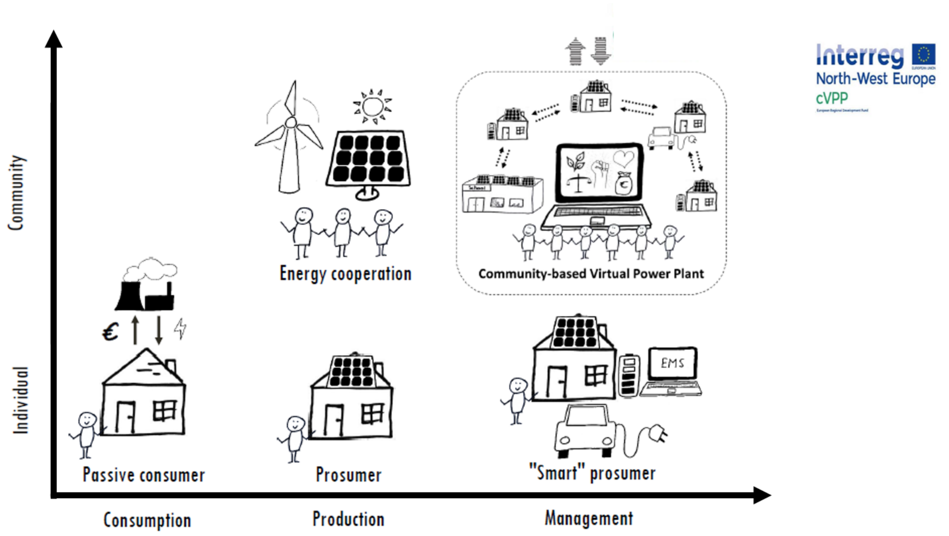


Figure 1.1: *From individual to community participation in the electrical energy sector. Picture from cVPP Interreg North-West Europe project [5].*

According to the EU definitions - as it will be explained in Chapter 2 - two forms of communities are allowed: Renewable Energy Communities (RECs) and Citizen Energy Communities (CECs). This thesis provides a contribute in modelling and analysing the RECs from a technical perspective. This means to deal with sets of loads, generators and storage systems that are connected to the same electrical network, with the main purpose of self-producing the energy consumed locally. In the EU definitions, there are no common rules for the geographical boundaries of the energy communities. Nevertheless, it is clear that they need to have a local dimension[3]. In this thesis, to adapt the

---

[3] REC is a legal entity "effectively controlled by shareholders or members that are located in the proximity of the renewable

meaning of local production to the technical aspects, a definition of the boundaries of the community based on the electrical aspects is considered. RECs are modelled on the same distribution network, this means that they are supposed to limit the usage of the transmission system for their energy sharing. ECs are not isolated microgrid; the energy produced is shared among the members of the community using the public infrastructure or also exchanged with other actors on the market. Therefore, self-sufficiency is not a technical requirement and it is not mandatory to achieve a complete autarky. On the contrary, the optimal planning and operation of an EC are driven by economical evaluations that take into account both energy exchanges among community members and with the external energy system. This thesis provides some elements to investigate benefits and risks of this new configuration. This is carried out by evaluating the problem from the perspective of the EC as a whole, from the perspective of the single members of the EC (i.e. citizens, municipalities and SMEs that participate to the EC), and from the point of view of the system in which they are hosted, that is the public distribution network.

It is worthwhile to observe that, when we talk about ECs, we refer to a new paradigm for distributed generation development. For this reason, attention must be paid to the typical misunderstandings and ideological struggle that arise considering the centralized/decentralized dichotomy. On the one hand, it is true that ECs represent a virtuous case of decentralization, as they implicitly encourage the development of distributed generation in a coordinated manner, responsive to local needs. On the other hand, it is important to underline that ECs alone cannot be the solution for the decarbonization of the electricity and energy system in general. This observation, although trivial, is quite important because, as it happens for private self-consumption, energy communities also stimulate a strong temptation to claim energy autonomy and self-sufficiency, considering superfluous the existing interconnected electrical system. On the contrary, a systemic analysis shows that only a mix of more or less centralized technologies and coordination mechanism can deliver an energy supply which is climate-friendly, secure and competitive [6].

1.2 Research activities' framework

This thesis contributed to the research activities of the electric power system research group at the Energy Department of the Politecnico di Milano. Thanks to the group network with distribution system operators, local policy makers, NGOs and other academia, it was possible to actively collaborate on several projects that highlighted how the energy communities are becoming an important player in the future energetic scenario. To cite the most relevant:

Projects in the energy community field

- *Consultancy for Valle d'Aosta Region* to study local energy communities and the potential developments towards electrical self-sufficiency of the Region. The Aosta Valley (*Valle d'Aosta*) is an autonomous region in northwestern Italy. As local policy maker, the Regional Energy Agency is required to define an Energy and Environmental Program (*Programma Energetico Ambientale Regionale (PEAR)*).

---

energy projects that are owned and developed by that legal entity".

This is the strategic planning tool used to define the regional objectives of energy saving and development of renewable energy sources. The aim of the consultancy was to assess what role ECs could play in the future regional energy scenario.

- *Consultancy for CVA s.p.a.* to analyse at regional level of the energy communities and the proposition of a pilot action. CVA s.p.a. is the Aosta Valley Water Company, an important actor of the Italian energy sector strongly rooted in the Aosta Valley Region. It is the owner of the main renewable power plants of the area (mainly hydroelectric) for a total installed power of more than 800 MW. The company is interested in analysing the evolution of the energy community context to understand the possible impact on the market and the possible roles of the company and its subsidiaries in this field (including the main local distribution system operator).

- *Cooperation with Eilhicha s.a.*. The company is an energy community based in Chacas, a village on the Peruvian Andes. It has been founded by the missioners of the Italian NGO "Operazione Mato Grosso" and the shareholders are the local parish and municipality. It operates in the production, distribution and retailing of electricity, providing clean and accessible energy to the local population. Within the collaboration, the research group supported Eilhicha s.a. in building the GIS and electrical models of their distribution network. The cooperation resulted really useful to understand how a nonprofit company active in the energy sector could generate local benefits for the community in which it operates. For more details about the project, we recommend the reader to refer to Appendix D.

Other projects

- *inteGRIDy Project* - This Horizon 2020 project aims to integrate cutting-edge technologies, solutions and mechanisms in a framework of replicable tools to connect existing energy networks with diverse stakeholders, facilitating optimal and dynamic operation of the distribution grid, fostering the stability and coordination of distributed energy resources and enabling collaborative storage schemes within an increasing share of renewables. Even if some collaborative schemes are considered, the project is not directly related to the ECs. Nevertheless, the knowledge of the most recent approaches for the dynamic operations of distribution networks is a crucial aspect to understand challenges and opportunities of the context in which EC will operate.

- *IoT-StorageLab* - This project, started in 2016 and partially funded by the Politecnico di Milano, is devoted to the research on the Internet of Things (IoT) concept. The new laboratory facilities aim at creating a suitable environment for the research, design, development and test of IoT solutions, with specific reference to energy and power system applications. Advanced energy communities will require to connect and control loads, generators and storage systems in a coordinated way, to optimize the energy management of the community. A widespread usage of the IoT is essential to achieve this goal. Furthermore, testing and operating interconnected energy storage systems, as the one available in the lab, provides a useful test-bed for EC purposes.

1.3 Motivation of the work

The recent innovation in the energy community legislative framework has stimulated new interests in the research. The topic is not technically bounded since it has impacts on many aspects of the society such as environment, politics and social science. Different stakeholders can be identified and, given their natural attitudes, they focus their attention on the aspects of REC that interest them most closely. Nevertheless, most of the issues can be grouped in three different sets. First, citizens, local authorities and SMEs are the subjects that can constitute a REC, which means they are the main actors and it is trivial to say that their point of view is the most relevant. They need to understand which benefits the energy community could bring to them, and to decide whether to constitute an energy community and how to arrange it. Second, since we are talking about energy communities that use the public infrastructure to share energy, distribution system operators are a cornerstone for an effective deployment. Last, considering that this kind of projects have impacts in many aspect of the society, the local policy maker has to consider carefully the contribution that energy communities could bring to local needs in terms of energy, evaluating also environmental, economical and social issues. These three visions are complementary and the spreading of energy community is possible only if all the stakeholders give their contribution. Nevertheless, many issues have to be addressed before saying that all these subjects are ready for a wide deployment of renewable energy communities. The main aspects belonging to the identified stakeholders are reported in the following paragraphs.

Energy community members

In the last two decades, common citizens, municipalities and enterprises have started producing their own energy, mainly with small private PV systems. Nowadays, the concept of self-production is quite well known and the term "prosumer" to indicate a consumer that is also a producer is widely used. Nevertheless, the idea to participate in an EC sharing resources with others is still far from going mainstream. For many European citizens, the idea of participating in an aggregated form to the energy sector is a new concept and so it is not clear which are the benefits and the practical consequences of this. Subjects that could participate in an energy community project need to to have a clear understanding of the benefits they could have. They need to know if the energy community will bring them economical benefits or if the only goals are being social and environmental sustainable. It is important to know if an energy community can be economically profitable and if the generated value can be efficiently distributed among the members of the community.

Distribution system operators

Since we are talking about different actors that share energy using the public distribution network, the point of view of the electricity distributor has to be taken into account. Although, since distribution is a regulated activity, it can be concluded that the second stakeholder is not simply the distributor, but the national authority that regulates this public service. The issues that arise are related to the impact that the energy communities can have on the distribution networks. Indeed, if the usage of the transmission system is reduced, the distribution grids become more and more important. It is fundamental to understand if RECs will produce benefits or they will be problematic for the operation and management of the grid. Critical issues are related to the definition of the energy tariff for the energy shared through the public grid, since the distances between generators and load are reduced compared to the classical energy flows. Moreover, the possibility to involve advanced RECs in offering services to the grid operator is an opportunity to take into account.

Policy maker

Local policy makers may have interest in the development of local energy communities. In some cases, like the Italian one, they have to respect national targets for renewable energy production, and renewable energy communities could be important partners to contribute to this objectives. They also have interest in supporting local economy and they have to provide responses to social problem such as promoting local jobs and addressing energy poverty. For these reasons, local policy makers wonder what could be the benefits that energy communities can bring to the territory and if it can be useful to promote and support the creation of local energy communities.

1.4 Methodology

This thesis addresses the energy communities issue arranging the study in two main frameworks.

- Framework of reference, in which the background analysis is developed.
- Methods and models for REC development, in which the main issues to be faced in order to unlock the development of energy communities are investigated. This framework is divided into three parts that, according to the problem formulation, correspond to the main stakeholders.

Figure 1.2 shows a schematic overview of the whole methodological frame. The top part corresponds to the framework of reference, the bottom one corresponds to the modelling framework and it is in turn divided into three parts according to the considered perspectives.

The blocks that compose the framework of reference are:

- **European and Italian legislative frameworks**. Every possible initiative of energy community starts from the legislation and the regulation of the sector. In the European Union, according to the hierarchy of the sources, European legislation comes before the national one. Therefore, analyzing the European legislation related to the energy communities is the first step. On this subject, the topic is well defined since all the legislative acts have been approved and there are clear and stable definitions and rules. On the other hand, the national legislative and regulatory frameworks are still open points. Member States must revise their national laws in the next months, so that they comply with the new EU rules. Each State has some degrees of freedom in transposing the European directives and national level definitions will be provided. This thesis considers the Italian context, so the Italian national legislation and regulatory framework are analysed.

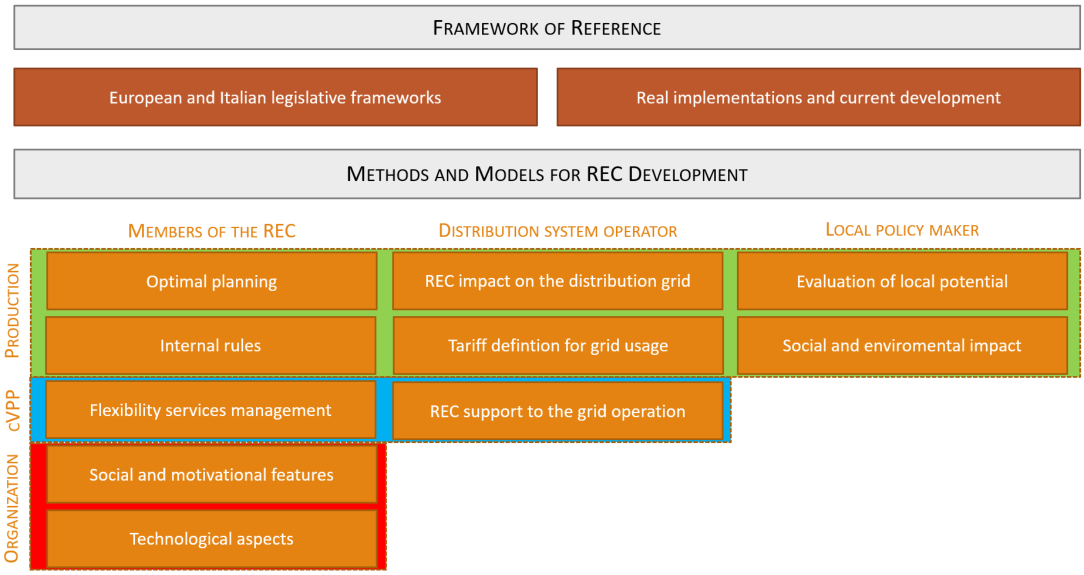


Figure 1.2: *Schematic overview of the structure adopted to organize the topics concerning RECs.*

- **Real implementations and current development**. Different forms of energy communities were already present in Europe and in other Countries also before the official recognition from the EU. Some of these communities fit with the new definitions of the CEP, while others not. In any case, they have in common some aspects as the citizen participation in a collective form for social and environmental benefits. Common patterns and activities can be identified among these realities. Some of these implementations come from a bottom-up approach, where the simplicity is supposed to be a key aspect for an effective development, while others are mainly based on research projects and try to implement more advanced solutions.

The blocks that compose the methods and models for REC development are divided according to two different criteria. On each column of the framework a different perspective is considered, on each row a different activity or aspect of RECs organization is taken into account. The first horizontal division concerns the production of energy.

- **Optimal planning**. From the perspective of the REC's member, or the one of the REC itself, the first problem is the definition of the generation portfolio given the characteristics of the community members and the energy sources availability. This aspect requires an evaluation of the energy needs of the community and provides the optimal definition of generators and, possibly, energy storage systems that could be useful to maximise the REC's objective.

- **Internal rules**. The second aspect that is important from the members' perspective is the definition of the internal rules for the distribution of the energy produced with the REC's generators and, consequently, the distribution of the economical benefits obtained with the collective behaviour. This aspect is extremely important because each member agrees on participating in a community project only if he considers that the rules are fair and no one is taking advantage of other participants.

- **REC impact on the distribution grid**. Energy production and sharing activities performed by the REC on the public distribution network can impact the operation of the grid. For this reason, the distribution system operator has an interest in evaluating how the energy fluxes on the network will change due to new generators sized and controlled according to REC's logics.

- **Tariff definition for grid usage**. Another issue that arises is the definition of the tariff for the usage of the distribution infrastructure. In fact, if production and consumption of the REC users are synchronized, the REC is not impacting on the transmission system. Furthermore, if it can guarantee this synchronization, it may reduce the need for dispatching and balancing of the system. However, these hypothesis need to be verified and they require an investigation from the distribution system operator or, more in general, from the national authority that regulates the activities of the electrical system.

- **Evaluation of local potential**. The third actor that has interest in understanding the potential of REC is the local policy maker. From its point of view, it is fundamental to understand the potential of the territory in terms of source availability in order to drive an effective energy evolution. One of the specific target will be promoting a fast decarbonization of the energy sector.

- **Social and environmental impact**. The policy maker is also interested in the topic because RECs can have a positive impact on the local economy and provide social benefits. They can keep money in the local area, contributing in creating a more local and circular economy, they can educate people on the issues of energy, climate and democracy and they can reduce energy poverty.

The second horizontal aspect of the problem is composed by the activities that the REC can perform as a community-based virtual power plant. These activities have an impact on the REC members and on the DSO, while the local policy maker has a marginal interest in it.

- **Flexibility services management**. Virtual Power Plant (VPP) is a software-based solution that aggregates distributed energy resources (distributed generators, demand response, storage) to act as a coordinated single entity similar to a conventional power plant. This control architecture allows to perform new roles in the electricity system. Virtual Power Plant can be based on energy community, in this case, we can refer to this as a community-based Virtual Power Plant [5]. These forms of advanced energy community can use their flexibility for the internal optimal management of the energy, or they can offer flexibility services to the DSO, to the Balance Responsible Party (BRP)[4] or to the Transmission System Operator (TSO). More details and examples are provided in Chapter 3. This kind of services could increase the revenues of the community, but some issues arise. The participation of each user may be different, depending on the risk that the user want to accept (risk, for example, of not finding the car completely charged when

---

[4] A Balance Responsible Party (BRP) is responsible for actively balancing supply and demand for its portfolio of Producers, Aggregators, and Prosumers. In principle, everyone connected to the grid is responsible for his individual balance position, but the Prosumer's balance responsibility is generally transferred to the BRP, which is contracted by the Supplier. Hence the BRP holds the imbalance risk on each connection in its portfolio of Prosumers. [7]

it is needed). Consequently, the revenues obtained from these services need to be distributed based on the effective contribution of each user.

- **REC's support for grid operation**. The DSO may take advantages from the direct participation of the energy communities to a local services market since they could offer flexibility services such as congestion management and voltage support for the distribution grid.

The third and last set of aspects of the REC are the organizational ones. These are internal aspects and they do not interest neither the DSO nor the policy maker, but they are crucial for the effective success of REC projects.

- **Social and motivational features**. This aspect makes the difference between a traditional market player and an energy community. People can decide to form a REC for the simple objective to produce their own renewable energy and without any economical benefits. Projects that could be economically interesting may stall or fail if the community members are opposing for some reasons, while project that are not so good in terms of expected revenues can be pushed by a strong community participation. This does not mean that the RECs formation process is not rational, but it means that the economical aspects are not the only elements considered in the rational process.

- **Technological aspects**. As stated by REScoop, energy communities are not primarily "about technical smart energy systems innovations" [8]. The main aim of energy communities is to self-organise around an energy-related activity in order to provide services or other socio-economic benefits to the members and/or the local community. The degree of innovation in the technological aspects of these activities may vary as for all the others traditional market players. The basic form of an energy community requires to have generators, loads, and a metering system to know who is producing and who is consuming energy in each instant of time. As already introduced, more advanced activities can be performed, and they generally require to control loads, generators and storages in real time to provide enhanced services. This requires an advanced metering infrastructure, together with a stable and safe connection. Furthermore, it requires to have controllable loads and actuators that can send them orders, based on set-points that can be calculated locally or received by a central controller. The need of collecting and storing measurements in real time and the control strategies of the community for providing internal or external flexibility services are examples of the software importance in this field.

  The development of shared energy management systems involves the application of new methods, that could be based on peer-to-peer models (P2P). A specific innovation in this field is about the application of the blockchain technology. As already seen, one of the key aspects of transition of the electrical sector is the decentralization. Talking about market and contracts, this brings to the idea that a centralized actor that manages the transition may be neither necessary nor the best solution, since the usage of a blockchain for energy representation and exchange may provide several advantages [9]. In an energy community, the blockchain could give the possibility to have a trusted and decentralised direct exchange between two parties, without the need of centralized control and intermediaries or third parties. At the same time, it allows a control over what is actually private and sensitive information, since data can be stored and shared safely.

1.5 Thesis outline and contributions

This thesis is a compilation of results published in scientific journals and conferences. It addresses some blocks of the frameworks of analysis. With reference to the structure already proposed (Figure 1.2), the contributions are illustrated in Figure 1.3 and summarized in the following. The framework of reference is analysed in detail, while for the methods and models framework only some blocks are considered. Specifically, the focus is on the blocks related to the activity of production, since it will be the first step in the development of ECs. Some preliminary investigations have been performed also for the cVPP activities, but an organic study has not been developed since the participation of energy communities in this field is at the very beginning. Therefore, these aspects are reported only in the appendix. Organizational aspects have not been considered either: social and motivational features have been neglected since they are not technical topics, while the technological aspects have not been considered because they are not the main core of this form of innovation. Each of the considered block has its own original contribution as for the specific research topic (which is often independently studied from the other). Therefore, each chapter of the methods and models part is structured according to: problem identification and literature analysis, method and/or model description, application(s).

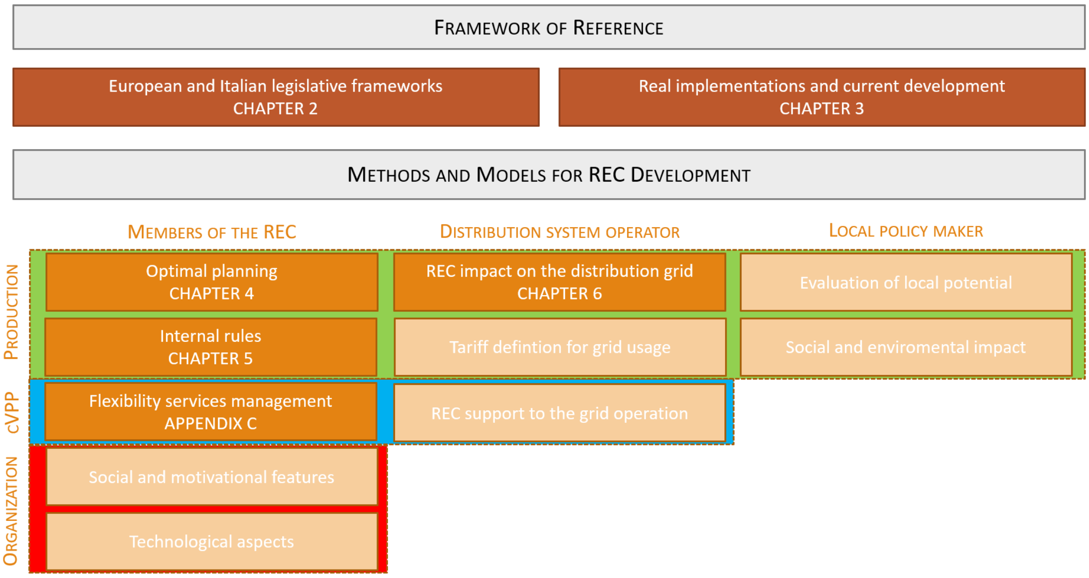


Figure 1.3: *Schematic overview of the structure adopted and identification of the blocks considered in this thesis.*

Chapter 2: European and Italian legislative framework

This chapter introduces the concept of energy community and energy democracy in a wide sense. Then, it focuses on the models of energy communities defined in the European Legislation, the Renewable Energy Community and the Citizen Energy Community. Finally, it provides a specific description of the Italian scenario, starting from the historical energy cooperatives to the current process of transposition of the European Directives.

Chapter 3: Review on energy communities

This chapter describes the state of the art of energy communities, their real implementations and the research activities currently focusing on them. It is worthwhile to point out that, before the formal definitions provided by the EU directives, the term energy community had been interpreted in different ways. A description of these aspects is provided to help understanding the on-going projects and the related research field. A review of the research contribution in this field is provided.

Chapter 4: Energy community modelling

This chapter introduces the model developed for the evaluation of the energy flows within an energy community and the computation of the economic value of an investment in renewable generators and storage. It is based on the Italian case, but most of the equations can be generalized to a similar situation where self-consumption and energy sharing are considered. Thanks to this model, the optimal investment for the REC is identified. The model has been applied to a case study based on a real low voltage network in Italy, according to the current Italian transitional regime for RECs. The results of Chapters 4 are mainly capitalized in the following publication:

- *Energy sharing in renewable energy communities: The italian case.*
  M. Moncecchi, S. Meneghello, and M. Merlo
  (2020) 55th International Universities Power Engineering Conference UPEC [10]

Some other works that address the optimal microgrid planning have been performed. They are not deeply detailed in this thesis since they have not been the main focus of the research activity. Nonetheless, they represented an important intermediate step towards the planning of ECs (both from a conceptual and methodological perspectives). The related publications are:

- *A novel software package for the robust design of off-grid power systems*
  Brivio C., Moncecchi M., Mandelli S., Merlo M.
  (2017) Journal of Cleaner Production, 166, pp. 668-679.

- *Microgrid design and operation for sensible loads: Lacor hospital case study in Uganda*
  Bosisio, A., Moncecchi, M., Cassetti, G., Merlo, M.
  (2019) Sustainable Energy Technologies and Assessments, 36, art. no. 100535

- *Battery energy storage systems in microgrids: Modeling and design criteria*
  Moncecchi, M., Brivio, C., Mandelli, S., Merlo, M
  (2020) Energies, 13 (8), art. no. 2006 [11]

Chapter 5: Appropriate rules for benefits sharing

This chapter analyses the problem of benefit sharing in an energy community. The cooperation of multiple subjects could generate economical revenues that are not achievable from individuals. The problem of fair distribution of this value is faced by mean of the coalitional game theory. The results of Chapters 5 are capitalized in the following publication:

- *A game theoretic approach for energy sharing in the Italian renewable energy communities.*
  M. Moncecchi, S. Meneghello, and M. Merlo.
  Applied Sciences (Switzerland), 10(22):1-25, 2020 [12]

Chapter 6: Evaluation of the impact on the distribution network

This chapter analyses the impact that an energy community could have on the medium voltage distribution network to which it is connected. The hosting capacity concept is explained and the relation with the capability of a network to host RECs is motivated. A methodology based on a Monte Carlo approach is proposed to evaluate the impact of the RECs on the network variables. Two different case studies are presented: the first represents a rural area, the second a urban one. For each one, the MV grid is modelled and the proposed methodology is applied. The results of Chapters 6 have not yet been collected in a publication, nevertheless preliminary applications of the Monte Carlo methodology and hosting capacity evaluation can be found in the following publications:

- *Regional energy planning based on distribution grid hosting capacity.*
  M. Moncecchi, D. Falabretti, and M. Merlo.
  AIMS Energy, 7(3):264-284, 2019 [13]

- Hosting capacity evaluation in networks with parameter uncertainties
  Mirbagheri S.M., Moncecchi M., Falabretti D., Merlo M.
  (2018) Proceedings of International Conference on Harmonics and Quality of Power, ICHQP, 2018-May, pp. 1-6. [14]

Chapter 7: Conclusions

A summary of the thesis contributions is given to the reader.

List of related publications

The following publications are the result of the research activities on topics directly linked with the PhD research goals. The development of the research required studies and insights on the following aspects: network operation and hosting capacity, flexibility and ancillary services, forecasting, microgrid sizing and energy storage system. These publications are not included and detailed in this thesis, but they contributed to the definition of the author's background and to the understanding of the energy community framework. They are reported in groups according to the specific research topics.

Smart grids

- Monte Carlo Procedure Reveals Limits to E-mobility Penetration on A Real Electric Distribution Grid
  Mirbagheri S.M., Bovera F., Falabretti D., Delfanti M., Moncecchi M., Fiori M., Merlo M.
  (2018) Electrical and Electronic Technologies for Automotive, International Conference on IEEE, June 2018.
  DOCUMENT TYPE: Conference Paper
- San Severino Marche Smart Grid Pilot within H2020 inteGRIDy project.
  Merlo M., Delfanti M., Falabretti D., Mirbagheri M., Moncecchi M.
  (2018) Renewable Energy Storage (IRES), 12th International Conference
  DOCUMENT TYPE: Conference Paper
- Grid-tie and off-grid operations of an innovative microgrid realized in Leonardo campus of Politecnico di Milano

Merlo, M., Delfanti, M., Blaco, A., Bovera, F., Pozzi, M., Moncecchi, M., et al.
(2019) 5th International Forum on Research and Technologies for Society and Industry, Firenze September 9-12 2019
DOCUMENT TYPE: Conference Paper

Flexibility and ancillary services

- E-mobility scheduling for the provision of ancillary services to the power system
  Gulotta, F., Rancilio, G., Blaco, A., Bovera, F., Merlo, M., Moncecchi, M., Falabretti, D.
  (2020) International Journal of Electrical and Electronic Engineering and Telecommunications, 9 (5), pp. 349-355.
  DOCUMENT TYPE: Article

Forecasting

- PV Forecast for the Optimal Operation of the Medium Voltage Distribution Network: A Real-Life Implementation on a Large Scale Pilot.
  A. Dimovski, M. Moncecchi, D. Falabretti and M. Merlo
  Energies 2020, 13, 5330 [15] DOCUMENT TYPE: Article
- Short term load forecasting in a hybrid microgrid: A case study in Tanzania
  Mbuya, B., Moncecchi, M., Merlo, M., Kivevele, T.,
  (2019) Journal of Electrical Systems, 15 (4), pp. 593 606.
  DOCUMENT TYPE: Article

Microgrid

- Microgrid design: Sensitivity on models and parameters
  Corigliano, S., Moncecchi, M., Mirbagheri, M., Merlo, M., Molinas, M.
  (2019) Proceedings - 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2019, art. no. 8783760
  DOCUMENT TYPE: Conference Paper
- Pre-feasibility techno-economic comparison of rural electrification options: Exploitation of PV and wind
  Scazzosi, F., Mandelli, S., Bertani, A., Moncecchi, M., Merlo, M.
  (2019) 2019 IEEE Milan PowerTech, PowerTech 2019, art. no. 8810802
  DOCUMENT TYPE: Conference Paper

Energy Storage System (see Appendix E)

- *Numerical and experimental efficiency estimation in household battery energy storage equipment*
  Moncecchi, M., Borselli, A., Falabretti, D., Corghi, L., Merlo, M.
  Energies 2020, 13 (11), art. no. 2719 [16]
  DOCUMENT TYPE: Article
- Battery modeling for microgrid design: A comparison between lithium-ion and lead acid technologies
  Moncecchi M., Brivio C., Corigliano S., Cortazzi A., Merlo M.
  (2018) Proceedings: International Symposium on Power Electronics, Electrical Drives, Automation and Motion SPEEDAM 2018, art. no. 8445343, pp. 1215-1220
  DOCUMENT TYPE: Conference Paper

CHAPTER 2

European and Italian legislative frameworks

European countries are experiencing a huge transformation in their energy systems. One of the innovative solutions the EU proposes to face this challenge is the active participation of citizens to the energy sector in the form of energy communities. In this chapter the definitions of Renewable Energy Communities and Citizen Energy Community are analysed. Then, the Italian context is considered. Since a key aspect of the energy community is the self-consumption of the produced energy, a taxonomic analysis of the self-consumption schemes in Italy is provided. Finally, the status of the transposition of the Directives is detailed and the ongoing experimental phase for collective self-consumption and RECs is described.

2.1 European context

2.1.1 European energy policy and strategy

The commitment of the European Union (EU) towards climate and energy is embedded into the fundamental Treaties that shaped the EU in its founding. First of all, the Treaty on European Union commits the EU to "work for the sustainable development of Europe (...) aiming at full employment and social progress, and a high level of protection and improvement of the quality of the environment" (Art 3) [17]. Moreover, the Treaty of Functioning of the European Union highlights the importance of the environmental protection in the Union's policy, affirming that its "requirements must be integrated into the definition and implementation of the Union's policies and activities, in particular with a view to promoting sustainable development" (Art 6). The same Treaty states that energy and environment are areas in which the Union shares competence with the Member States (Art 4) and affirms that "Union policy on energy shall aim, in a spirit of solidarity between Member States, to (...) promote energy efficiency and energy saving and the development of new and renewable forms of energy" (Art 194) [18].

Driven by this strong commitments, throughout the years the EU set objectives for increasing the shares of renewables and promoting energy efficiency. An important step in this direction has been made in 2010, when the European Commission, headed by José Manuel Barroso, proposed the "Europe 2020" strategy to restart after the financial crisis [19]. In the field of climate and energy, the strategy set targets for 2020 known as the "20-20-20" targets: a 20% reduction in EU greenhouse gas emissions from 1990 levels; raising the share of EU energy consumption produced from renewable resources to 20%; a 20% improvement in the EU's energy efficiency. The commitment to these targets brought to the adoption of a set of binding legislation that includes the Directive 2009/28/EC on the promotion and use of energy from renewable sources (the first Renewable Energy Directive - RED), Directive 2010/31/EU on improving energy performance in buildings, Directive 2012/27/EU on energy efficiency.

Substantial progress has been made towards the attainment of the EU targets for 2020 and, in October 2014, the European Council agreed on the 2030 climate and energy policy framework for the European Union, which laid down three key targets for the EU by 2030: a minimum 40% cut in greenhouse gas emissions compared to 1990; at least a 27% market share for renewable energy; and an improvement in energy efficiency of not less than 27%.

In November 2014 the European Commission, headed by Jean-Claude Juncker, set among its top 10 priorities "A resilient energy union with a forward-looking climate change policy" and, in February 2015, launched its "European Energy Union Strategy" [20]. The strategy "aims at building an energy union that gives EU consumers - households and businesses - secure, sustainable, competitive and affordable energy". One of the main results of this strategy has been the presentation from the European Commission, on 30 November 2016, of a package of proposals, called the "Clean Energy for all Europeans Package" or "Clean Energy Package" for short (CEP) [21]. The aim of the package is to contribute to the definition of the Energy Union and implementing the commitments made by the EU under the Paris Agreement, entered into force in the same month. The proposal led to the adoption of eight legislative acts between 2018 and the first half of 2019, with which the European Union has reformed its energy policy framework. Thanks to this reform, the European Union established the regulatory prerequisites for the transition to clean energy. The documents that make up the package are:

- The Energy Performance of Buildings Directive 2018/884;
- The recast Renewable Energy Directive 2018/2001, also known as REDII [22];
- The revised Energy Efficiency Directive (EU) 2018/2002;
- Regulation on the Governance of the Energy Union and Climate Action 2018/1999;
- Regulation on risk-preparedness in the electricity sector 2019/941;
- Regulation establishing a European Union Agency for the Cooperation of Energy Regulators 2019/942;
- Regulation on the internal market for electricity 2019/943;
- Directive on common rules for the internal market for electricity 2019/944, also known as Electricity Market Directive (EMDII) [23].

The proposals have three main goals: putting energy efficiency first, achieving global leadership in renewable energies and providing a fair deal for consumers. With respect to this last point, it is important to notice, already in the name of the package, the central role of the citizens: energy has not only to be "Clean", but it has also to be "for all Europeans". As a consequence, a central and active role in the energy market is defined for the consumers, together with a number of measures aimed at protecting the most vulnerable consumers. Is in this context - and specifically in Directive 2018/2001 (REDII) and Directive 2019/944 (EMDII) - that the energy communities are officially defined for the first time in the European Legislation. According to the REDII, the participation of local citizens and local authorities in renewable energy projects through renewable energy communities implies a substantial added value in terms of local acceptance of renewable energy and such local involvement is all the more crucial in a context of increasing renewable energy capacity.

The most recent developments strengthen the position of the EU in the energy sector. The European Commission formed in 2019 and headed by Ursula von der Leyen announced the implementation of the "European Green Deal" [24], a set of policies with the ambitious purpose of making the EU carbon-neutral by 2050 through measures that include the massive decarbonisation of the energy sector and the improvement of energy efficiency in buildings. Coherently with this objective, in December 2020 the European Union leaders raised the bar, agreeing on the goal to cut greenhouse gas emissions by at least 55% by the year 2030, instead of 40% as already defined. These decisions confirm that EU wants to play a leading role in the world energy transition, and enforce the importance of the energy sector in the future economy. To achieve these results, the participation of the citizens is mandatory, since deep habit changes will be required. They must be involved in the change to not undergo it, and it is fundamental for them understanding the benefits they can get from the clean energy transition. Energy communities could play an important role in the citizens' involvement.

2.1.2 Community energy potential in the EU

As it was mentioned in the previous section, one among the innovative aspects in the CEP is the intent to pursue the "democratization" of the European energy sector and bring closer the European citizens to the clean energy transition. The recognition of energy communities in Europe will allow European citizens to come together as final users of energy and cooperate in the generation, distribution and supply of electrical energy from RES and participate to energy services such as energy efficiency or demand side management. Considering that the European electricity market was first designed for large and centralized actors, the geographical, economical and social characteristics of the Member States hide a potential for decentralized energy production that still needs to be fully exploited. In countries where energy ownership or co-ownership is a diffuse phenomenon as in Germany, private users and farmers own more than 40% of the renewable energy capacity [25] as shown in Figure 2.1. Furthermore, due to a long tradition of citizen participation, the Energy Atlas about renewables in Europe [26] highlights that the energy managed by citizens of Germany is comparable with the sales of the biggest energy retailers.

A study published in 2016 by the Dutch consultancy firm CE Delft, on account for Greenpeace European Unit, Friends of the Earth Europe, European Renewable Energy

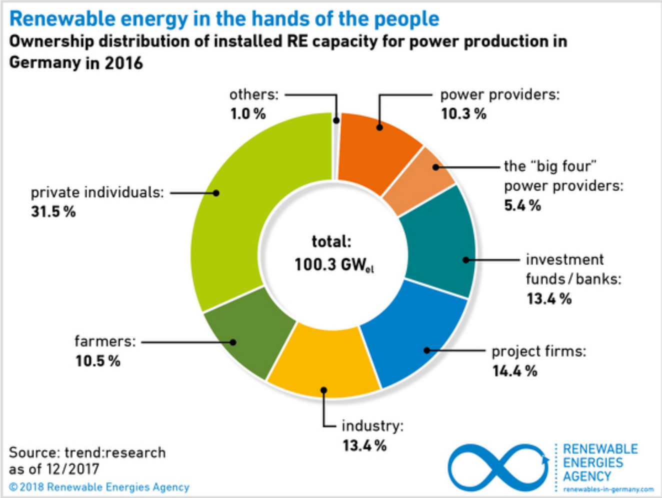


Figure 2.1: *RES ownership in Germany in 2016.*

Federation and REScoop, showed promising results in the development of the participation of European citizens in the energy sector [27]. The report states that in 2050, 83% of the population in the EU, here called energy citizens, could become energy producers and contribute to flexible demand services through the use of electric vehicles, smart electric boilers and storage systems. In particular, almost half of the 2050 European citizens have the potential to generate electricity through RES. The study found that 37% of this "citizen-owned electricity" will come from energy collectives, 23% from households, 39% from small-medium businesses and 1% from public entities.

The analysis may appear too optimistic, but the orientation toward decentralised production is clear and other studies confirm the possibility to obtain positive results in the future. For example, the Joint Research Centre of the European Commission computed the PV capacity that could be installed on roofs and the estimated energy production [28]. The calculations where performed at regional level as in Figure 2.2 and it resulted that it could be installed about 600 up to 1200 GW of PV compared to the 117 GW cumulatively installed in 2018 [29]. It is without any doubt that the installation of such amount of generators will have an impact on the life of millions of citizen, modifying their buildings and the places where they live, and that such a huge transformation requires to involve them in some way. CEP sets a milestone in the formal recognition of the concept of Energy Community in the European legislation. They will enable citizens to be protagonists of the energy transformation and to achieve it more faster, with social and economical fairness, "unleashing the power of community renewable energy" [30].

2.1.3 The definitions of the Clean Energy Package

Community energy projects have been around Europe for decades, involving citizens generating energy collectively or providing management of small distribution infrastructures. In the matter of energy communities, a report of ClientEarth [31] in 2014 observed that the EU framework posed limits to what they called the "community power agenda". The EU legal framework lacked explicit recognition and support for the community participation. In addition, it was largely treating citizens as passive consumers

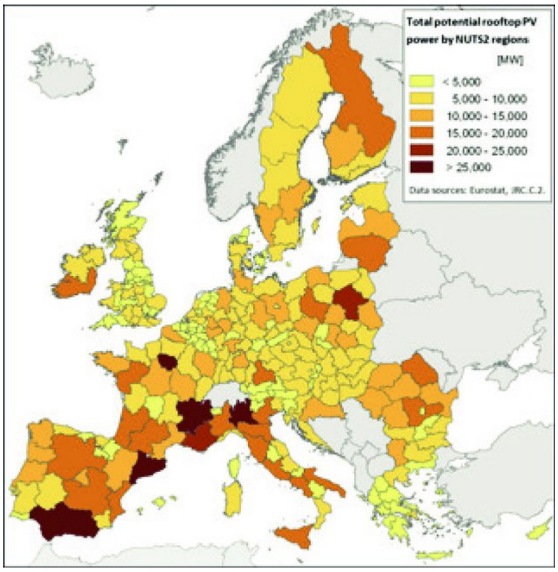


Figure 2.2: *Rooftop Potential for PV Systems in the European Union per region.*

and beneficiaries of the energy transition, rather than potential active participants. The formalization of the energy communities as legal entities in the CEP allows their recognition as actors of the energy market in those Member States where they already exist and encourage their formation in those Countries where they are not present [32]. During the drafting process of the Directives the name Local Energy Communities was first considered, but this denomination became too close to technical concepts as a synonym of micro-grid or collective self-consumption [33]. As a consequence, the Clean Energy Package contains two definitions of energy community: Renewable Energy Community (REC), which is contained in the REDII, and Citizen Energy Community (CEC) which is contained in the EMDII.

Renewable Energy Community (REC)

The definition of Renewable Energy Community provided in Article 2 (16) of the REDII is the following.

Definition 1: Renewable Energy Community

Renewable energy community means a legal entity:

(a) 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;

(b) the shareholders or members of which are natural persons, SMEs or local authorities, including municipalities;

(c) 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.

The article 22 of the Directive is named "Renewable energy communities" and defines what Member States shall do in order to introduce the RECs in the national framework. The complete text of the article can be found in Appendix A, while a summary is reported in the following. The participation is a key aspect of the REC, and some aspect are particularly relevant. Final customers, in particular household customers, are entitled to participate in a renewable energy community while maintaining their rights or obligations as final customers. Member States shall ensure that RECs are entitled to produce, consume, store and sell renewable energy, share, within the REC, renewable energy that is produced by the production units owned by that renewable energy community and access all suitable energy markets both directly or through aggregation. It is specified that Member States shall carry out an assessment of the existing barriers and potential of development of RECs in their territories, and they shall provide an enabling framework to promote and facilitate their development. One of the requirement is that the participation in the renewable energy communities is accessible to all consumers, including those in low-income or vulnerable households.

Citizen Energy Community (CEC)

On the other hand, the definition of Citizen Energy Community (CEC) (Article 2 (11)) provided by the EMDII is the following.

Definition 2: Citizen Energy Community

Citizen energy community means a legal entity that:

(a) is based on voluntary and open participation and is effectively controlled by members or shareholders that are natural persons, local authorities, including municipalities, or small enterprises;

(b) has for its primary purpose to provide environmental, economic or social community benefits to its members or shareholders or to the local areas where it operates rather than to generate financial profits; and

(c) may engage in generation, including from renewable sources, distribution, supply, consumption, aggregation, energy storage, energy efficiency services or charging services for electric vehicles or provide other energy services to its members or shareholders.

Article 16 of the Directive is named "Citizen energy communities" and the full text is reported in Appendix B. Here it is summarized that CECs can operate in the limits of the energy sector, and their purpose has to be the provision of environmental, economic or social benefits to their shareholders. Electricity generation is not restricted to renewable sources, and it is also allowed to store energy, offer energy efficiency services and charging electric vehicles. Moreover, CECs can own or lease distribution networks and manage them autonomously. The participation is open and voluntary by natural persons, local authorities, including municipalities and companies of any size, but medium and large enterprises cannot take control of CECs. CECs can exist in any form or entity recognised in each Member State, such as an association, a cooperative, a partnership, a non-profit organization and they are not subjected to any geographic limitation, as CECs can also be open to cross-border participation. Member States must create for CECs a level playing field in the market to allow them to compete. It is also asked to define rights and obligation for CECs in the legislative framework of the Member State.

REC and CEC comparison

Both definitions describe a way to organise collective cooperation of an energy related activity around specific ownership, governance and a non-commercial purpose (as opposed to traditional market actors). For both RECs and CECs, the primary purpose is to provide environmental, economic or social benefits for its members or the local areas where they operate rather than financial profits. Both definitions emphasise participation and effective control by citizens, local authorities and smaller businesses whose primary economic activity is not in the energy sector. Finally, participation in CECs and RECs must be open and voluntary.

However, there are some differences regarding scope of activities and eligibility criteria, based on which renewable energy communities can generally be seen as a subset, or type, of citizen energy community[1]. The main differences between citizen and renewable energy communities are reported in Table 2.1.

	CEC	REC
Participation	Open and voluntary by natural persons, local authorities, micro, small, medium and large enterprises	Open and voluntary by natural persons, local authorities, micro, small and medium enterprises
Activities	Across the electricity sector: electricity generation, distribution and consumption (e.g. energy efficiency services, EV charging, management of distribution networks...)	Only renewables: Production, consumption, sale and sharing of renewable energy
Control	Medium and large companies are excluded	Members in proximity to the project
Support	Create a level playing field in the market	Create a level playing field in the market, remove administrative barriers, enforce support schemes

Table 2.1: *Main differences among CECs and RECs*

The conditions for qualifying as a REC are more demanding because RECs are not only entitled to receive a fair playing field, but Member States must grant financial support to these communities (through support schemes) and facilitate their creation with national enabling frameworks. A deeper investigation on the difference between RECs and CECs can be found in many documents [8, 33]. Finally, it is worthwhile to point out that there is a degree of freedom in the transposition of the Directives and customized approaches could rise at national level.

Other related definitions

The considered Directives also introduce some legal entities such as the active customer, the renewables self-consumer and the jointly acting renewable self-consumers that can be related to the two definitions of energy community.

The Article 2 (8) of the EMD defines the active customer.

---

[1] As a matter of fact, in order to consider true the sentence, a REC is also a CEC if its activities are limited to the electrical sector and no medium sized enterprises have control on it.

Definition 3: Active customer

"Active customer" means a final customer, or a group of jointly acting final customers, who consumes or stores electricity generated within its premises located within confined boundaries or, where permitted by a Member State, within other premises, or who sells self-generated electricity or participates in flexibility or energy efficiency schemes, provided that those activities do not constitute its primary commercial or professional activity.

The Article 2 (14) of the RED II defines the renewable self-consumer.

Definition 4: Renewables self-consumer

"Renewables self-consumer" means a final customer operating within its premises located within confined boundaries or, where permitted by a Member State, within other premises, who generates renewable electricity for its own consumption, and who may store or sell self-generated renewable electricity, provided that, for a non-household renewables self-consumer, those activities do not constitute its primary commercial or professional activity.

These definitions are similar to the legal entities of the self-consumer already present in the regulatory framework of most Member States. In both cases, the consumer is granted the title of final customer, meaning that it holds the rights related to this title such as full access to the grid. The area of intervention of these consumers must have declared boundaries. While the renewable self-consumer can just produce, consume and sell its electricity, the active customer can also take part in flexibility or energy efficiency schemes. In both cases the activities performed by the subject do not have to be the primary source of revenue. The definition of active customer of the Electricity Market Directive considers also the collective action of the customers. The same idea has a specific definition in the REDII, where the Article 2 (15) defines the jointly acting renewables self-consumers.

Definition 5: Jointly acting renewables self-consumers

"Jointly acting renewables self-consumers" means a group of at least two jointly acting renewables self-consumers (...) who are located in the same building or multi-apartment block.

It can be noticed that the main difference is the clear specification of the confined boundaries. The innovation brought with this characterization is that the REDII recognises consumers in the same building or multi-apartment block that act collectively as jointly self-consumers, meaning that the advantages in terms of grid charges and levies and taxes in the framework of self-consumption will apply to this category [34].

The fact that jointly acting renewables self-consumers is a form of collective initiative may create some confusion for the apparently overlapping with the ECs' definitions. Nevertheless, it has to be noticed that the former describes an action and it is not related to any legal entity, while the EC is a new legal entity and a way to organize users and activities [33]. Moreover, the geographical limitations are stricter and clearly defined for the collective self-consumption ("same building or multi-apartment block") while they are larger and not explicitly defined for the ECs.

2.2 Energy communities in Italy

The following Section will focus on the development of energy communities in Italy. A first part will draw its attention to the current regulatory status of self-consumption systems in the Country that will undoubtedly represent a determining factor in the regulatory definition of ECs. Self-consumption systems' definitions and incentives will be analysed in depth. In the second part, the documents and the laws recently published and concerning the transposition of the CEP in the Italian legal system are analyzed. At the time of writing of this thesis, the reception is still an open process and the most recent updates are provided.

2.2.1 The existing regulatory framework

Self-consumption systems in Italy are intended to be the starting point, at a legislative and technological level, for the future development of EC in the Country. In 2018, the overall self-consumed energy was 28 TWh, only 20.4% of which coming from RES [35]. This data shows how self-consumption is not still bounded to renewable energy, rather than a coexistence between producer and consumer. Generally speaking, the configurations allowed by law for self-consumption can be divided into two main categories [36]: Closed Distribution Systems (CDS), in Italian "Sistemi di Distribuzione Chiusi" (SDC) and Simple Systems of Production and Consumption, in Italian "Sistemi Semplici di Produzione e Consumo" (SSPC). The possible classifications of the systems are quite numerous, with some definitions overlapping others or at least very similar in the content as the results of years of legislative layering. It is anyhow interesting to analyse the main characteristic of the most relevant, to identify any possible similarity with the energy communities presented in the CEP.

Sistemi di distribuzione chiusi

Closed distribution systems are private systems that distribute electricity within a geographically confined industrial, commercial or shared services site and they generally does not supply household customers. This configuration is motivated if, "for specific technical or safety reasons, the operations or the production process of the users of that system are integrated, or if that system distributes electricity primarily to the owner or operator of the system or their related undertakings."[2] These systems are the result of the transposition into national law of the Directive 2009/72/CE and their definition has been recovered in the EMD of the CEP[3]. In the SDCs multiple final customers and producers may be present. In Italy, two types of systems are categorized as SDC: Reti Interne di Utenza (RIU) and Altri Sistemi di Distribuzione Chiusi (ASDC). It is important to highlight that the Italian definition of SDC includes only systems that were already existing at the moment the definition of RIU, that is when Law n. 99/09 entered into force[4], therefore currently in Italy the creation of new SDC is not allowed. Given their very narrow field of application, that excludes domestic users, and considering their specific definition and purposes, SDC are not compatible with energy communities.

---

[2] Directive 2009/72/CE - Article 28

[3] Article 38

[4] 15 August 2009

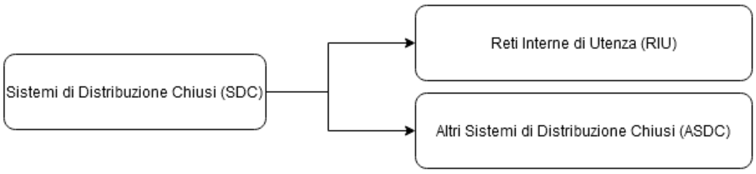


Figure 2.3: *Classification of closed distribution systems in the Italian framework.*

Sistemi semplici di produzione e consumo

SSPC are electric systems for which power plants and consumption units are connected to the public grid and for which the transport of energy does not fulfill an activity of transmission or distribution, but it is considered as self-supply. These configurations are regulated by mean of the *Testo integrato dei sistemi semplici di produzione e consumo* (TISSPC) and they can be divided into two main groups: Historical cooperatives or consortium with their own grid (*Cooperative e Consorzi Storici dotati di rete propria*), and all the others cases of SSPC (*Altri Sistemi Semplici di Produzione e Consumo* - ASSPC).

Historical cooperatives and consortium are the result of a historical tradition that has survived the nationalisation of the electricity market. Electric cooperatives were mainly born between the 19th and the 20th century, in remote areas of the alpine arch in Northern Italy, with the purpose of exploiting the hydroelectric resources offered by the territory. Due to the harsh conformation of territory and the low population density, the electric cooperatives developed private connections between production and consumption sites, carrying de facto, in the absence of other networks, the service of distribution and retail also to non-members final customers. Due to their peculiar characteristics and the public service they performed, electric cooperatives were exempted to the nationalization of the electric sector of the ’60s and afterwards were legally recognized as "historical cooperatives" during the liberalization phase[5]. Historic cooperatives and consortium are regulated by Autorità di Regolazione per Energia Reti e Ambiente (ARERA) with a resolution approved in 2012. Historical cooperatives are societies with voluntary participation of members, aimed at the production and consumption of electric energy, whose particular characteristics are similar to those presented in the CEP for energy communities. Nevertheless, the limit of these peculiar operator of the electrical system is in their definition, since only historical cooperatives are recognized and it is not possible to create new systems. To try to overcome this limit, new cooperatives were born after the nationalization of the energy sector and they are formally recognized as "cooperative elettriche di nuova costituzione". They aim to provide their members with self-produced electric energy by using the national transport and distribution grid. These kind of cooperatives typically have members spread all over the national territories and RES production plants in different location. They are not included in the schema of SSPC since production and consumption units are not directly connected. They have their own plants and/or they operate on the energy markets to collect energy to satisfy the requests of the cooperative’s members.

The other SSPC are then divided into the following categories:

- Sistemi in Scambio sul Posto (SSP)

---

[5] Decreto legislativo 16 marzo 1999, n. 79, known as Decreto Bersani, from the name of the Minister of Economic Development.

- Altri Sistemi di Auto-Produzione (ASAP)
- Sistemi Efficienti di Utenza (SEU)
- Altri Sistemi Esistenti (ASE)
- Sistemi Esistenti Equivalenti ai Sistemi Efficienti di Utenza (SEESEU) diversi dalle cooperative storiche e dai consorzi storici

The more spread among the SSPC configurations are SSP and SEU.

The SSP is a form of self-consumption that allows to compensate the energy produced and injected into the grid with the energy withdrawn in different instant of time (net metering). The electrical system is used as a virtual storage for the energy produced but not consumed in the same time. The production and the consumption units have to be connected to the same point of delivery.

The sub-category of the SEU consists in a configuration in which only one producer (that can have multiple production units) and only one consumer (optionally different from the producer) are directly connected by a private connection that is continuous and not interrupted by artificial or natural obstacles. The production units have to be RES or high efficiency cogeneration units with a maximum installed capacity of 20 MW. If more users are connected to the private connection, only one can benefit from the reduced tariffs that the SSPC grants (i.e. that is the exclusion of transmission, distribution and system charges and excises) while the other users have to pay the full electric bill.

The limits of these configurations it the request to have only one producer and one final customer (one-to-one). The innovation that the energy communities and collective self-consumption bring is the development of "one-to-many" or "many-to-many" configurations.

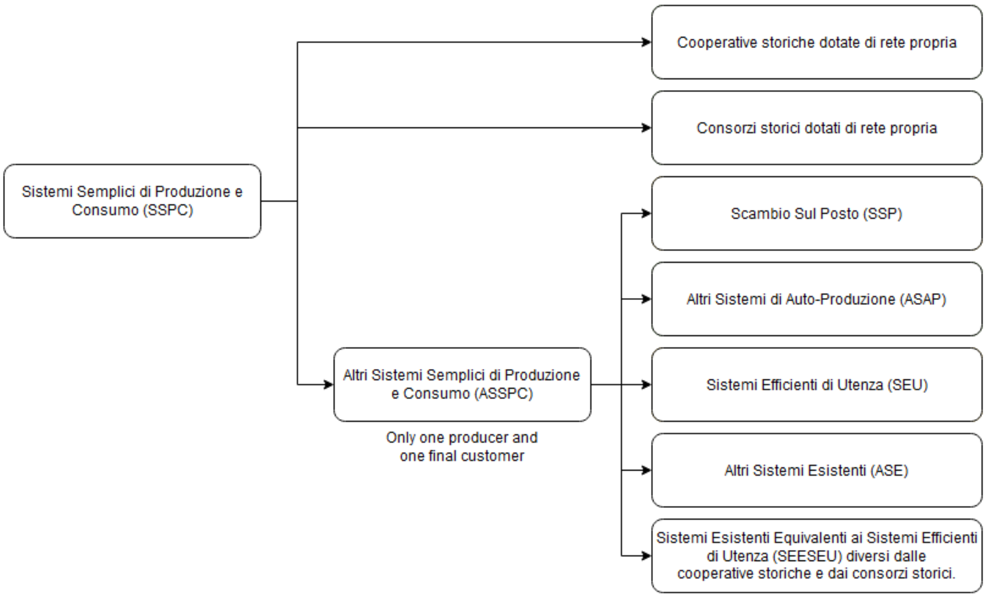


Figure 2.4: *Classification of Simple Systems of Production and Consumption (SSPC) in the Italian framework.*

2.2.2 The transposition of the EU Directives

Italy, as the other European Member States, has to transpose the EMD and RED II into its national law respectively before the 30th December 2020 and the 30th June 2021. For the Italian law, the legislative measure used to incorporate the legal norms produced by the European Union into the national system is called "Legge di delegazione europea". The process of adaptation of Italian legislation with respect to European directives is carried out through decrees of the government (Decreti legislativi) based on specific laws named "Leggi delega" with which the Parliament delegates the Government to exercise the legislative function. The trasposition of both Directive 2018/2001 and Directive 2019/944 are included in the "Legge di delegazione europea 2019-2020" and, at the time of writing of this thesis, is not yet completed. Nevertheless, besides the final transposition process, energy communities have stimulated a great interest in the Italian context and other legislative initiatives have been preliminary introduced. In this Section, an overview of the Italian initiatives is provided based on the following points: the role of the energy communities in the national energy strategies, the regional laws for the RECs promotion, the transitional form of REC approved in February 2020 and the final transposition of the Directives.

The National strategy

The Strategia Energetica Nazionale (SEN) and the National Energy and Climate Plan (NECP) - in Italian Piano Nazionale Integrato per l'Energia e il Clima (PNIEC) - are two documents born from different necessities, which delineate the Italian strategy in the short and in the long term in the field of energy. The SEN is a document foreseen by the national law and written in 2017 and it describes the national energy policy up to 2030 [37]. On the other hand, the PNIEC is required from the Regulation 2018/1999 contained in the CEP. The document is partially inspired by the SEN, but is more recent, it was published on December 2019, and reflects more the future Italian plans devoted to move forward the EU policy [38]. In both cases, self-consumption and energy communities are mentioned. The SEN identifies the legal recognition of the EC as a necessary intervention that must be implemented in the view of the CEP (the SEN was written in 2017), as a tool to promote the decarbonisation of the energy sector and to empower the active participation of consumers into the energy market. Energy communities, alongside self-consumption systems, will require legal simplifications and adequate support schemes, possibly in the form of explicit incentives. In case of an active user, the self-consumed energy is exempted from the variable costs of the items of wholesale cost of electricity, network costs and operating costs[6]. In the matter of incentives for self-consumption, the SEN judges the aforementioned exemptions as a necessary tool to support their development in the short-term. However, considering the steep increase of self-consumption systems foreseen in 2030, also due to the introduction of the energy communities, and the decrease of the cost of the technologies, it will be necessary to reintroduce the operating costs in the tariff structure, to manage a reduction in the costs of transmission and a rise in the cost to assure security of supply. The PNIEC reiterates the concepts expressed by the SEN by classifying the energy communities in the framework of the development of distributed generation,

---

[6] See DL 244/2016 (Decreto Milleproroghe 2016)

which "will require the definition of government instruments to ensure system security, consumer protection and the fair allocation of network and system charges". In the matter of support schemes, the PNIEC confirms that operating costs should be exempted in the payment of the electricity bill, to sustain the initial growth of energy communities, however system charges should be paid in a second moment to balance the reformed energy markets and incentives should be given with a more explicit mechanism.

The Regional laws

Some Italian regional policy makers anticipated the National legislator and promulgated Regional laws for the establishment of EC on their territory. The first cases of Regional law were promulgated by Piemonte [39] (2018) and Puglia [40] (2019), while more recently also Liguria [41], Calabria [42] promulgated specific laws and Lombardia deliberated the initiatives for the promotion of energy communities [43]. The laws are very similar in their form and highlight the interest of local authorities for the EC. As a matter of fact, regional policy makers are attracted by the possibility of exploiting local resources and, beyond the electricity generation from RES, the possibility of creating new local jobs and pursue the social aspect, for example tackling energy poverty [44]. The laws recognise EC as legal entities in the modalities delineated by the European Directive, even if they do not consider a distinction between RECs and CECs. The main purpose of these EC is the maximization of self-consumption and energy efficiency. Local authorities such as municipalities are designated as promoters of the EC in the involvement of citizens and SMEs, while Regions offer their support in facilitating their formation by easing the bureaucratic burden. Generally, the energy communities are required to evaluate their energy balance and to define a strategic planning for the energy efficiency and for the increasing of their renewable energy production.

The position of the energy Authority

In March 2019, the 10th commission for Industry, Trade and Commerce of the Italian Senate held a public consultation regarding the transposition of the CEP, in order to involve the stakeholders in the process [45]. The energy Authority ARERA published then a report, stating its opinion on the consultation [35]. First of all, the Authority encourages a simplification of the national framework in the matter of self-consumption that, as it has been shown, is fragmented and repetitive. ARERA suggests that the new classification could take into consideration the number of producers and final customers. In particular the many definitions of the ASSPC should be harmonized into one that considers one-to-one configurations, SDC's definition, that comes from the European norm, should be kept as it is, considering the possibility of creating new units of this kind, when they can be efficient. Lastly on this matter, ARERA considers to add the definition of energy communities to cover the many-to-many configuration.

On the exemption of the network and operating costs for self-consumers, the Authority agrees on the Government position, saying that while the exemption on network costs might reflect the benefit that these systems bring on the electric network, the exemption on operating costs is an implicit incentive equal to 1.4 billion per year. It would be better for promoting decentralized renewable energy, to use explicit incentives, that can be controlled and proportionate to the goal. Nonetheless, ARERA warned that even if the support schemes for self-consumption systems might be used as a starting point to promote energy communities, their incentives should be different in the legal framework, in order to take also into account the positive social purposes of these entities.

The national law

On first March 2020 came into force the first law that anticipate the transposition Article 21 and Article 22 of the RED II, concerning collective self-consumption and Renewable Energy Communities [46]. The law is the "Legge n. 8 2020" and it has been approved on the 28th of February, converting the Decree "D.L. n. 162 del 30 dicembre 2019" know also as "Decreto milleproroghe". The article 42-bis of the law is named "Autoconsumo da fonti rinnovabili" (Self-consumption from renewables sources) and allows to activate in Italy the first cases of collective self-consumption and Renewable Energy Communities. The proposed configurations are transitional and one of the purpose is to obtain lessons from the regulatory point of view and study the reactions of the various stakeholders, such as citizens and network operators. This experimental phase has some limits in the time windows for the activating of the project and the characteristics of the configurations. In order to access this model of experimentation, the plants of the renewable energy communities or collective self-consumption must have come into operation after the date of entry into force of Legge n. 8 and within sixty days from what will be the date of the measure transposing Directive (EU) 2018/2001 (scheduled for June 2021). In practice, the time window for implementing these configurations is less than one year.

In these new configurations, energy is produced by mean of new plants powered by renewable sources to satisfy members' consumption. The maximum power of each plant cannot exceed 200 kW. In the case of RECs, both consumers and generators are connected to the same low voltage grid, while in the case of collective self-consumption they are located in the same building. The energy produced is shared using the existing distribution network[7]. The shared energy is equal to the minimum, in each hourly period, between the electrical energy produced and fed into the grid by the renewable plants of the community and the electrical energy withdrawn by all the associated end customers. Although it is possible that in the future participation to RECs will be opened also to existing plants, it is evident that the legislator wants to use the transitional regime as a tool for creating new RES capacity [47]. Within the REC however, the members still detain their end customers rights, such as free choice of their energy retailer and freedom of being self-consumers. Furthermore, the energy withdrawn from the grid will be charged with the individual contracts between the members and their retailers. From the commercial point of view, the energy is retired from the publicly-owned company Gestore dei Servizi Energetici (GSE), that provides a revenue that comprise the market value plus an incentive for the amount of energy that results to be shared. The revenues are given to a reference subject chosen by the community and then the members regulates the internal redistribution via private contracts. It is important to notice that, with the proposed schema, the actual legislation tries to emulate a "pure" mechanism of energy sharing with another one, that has the same economical effect for users. Specifically, the energy that is formally "shared" is actually retired from the GSE, while the members continue to buy the energy from their retailer. The

---

[7] It is interesting to notice that also jointly acting self-consumers formally use the distribution network to share energy. Indeed, even if they are located in the same building, each user is connected to the network by mean of a different POD.

incentives is intended to give back to the users the value already payed to their retailers. A more "direct" energy sharing should be based on aggregated net metering. The energy produced by the generators of the community should be directly discounted from the electricity bill of the community members, without the intervention of a third party (GSE). Despite the simplicity of the concept, the implementation of this model requires important changes in the current regulation. On the contrary, the schema of energy sharing chosen for the transitional regime is very simple and allows immediate implementations.

The Authority, with Resolution 318/2020/R/eel [48], defined that the unitary tariff components related to transmission and distribution network are not applicable to the shared energy. Furthermore, it defined that jointly acting self-consumers receive an extra revenue for shared energy, motivated by the reduction of network losses. This revenue is evaluated as percentage of the zonal price (1.2% if the generator is connected to MV network, 2.6% if it is connected to LV network).

The Ministry of Economic Development identified the incentive tariff to reward instantaneous self-consumption and to ensure return of investment ("Decreto 16 settembre 2020" [49]). The incentive is differentiated for RECs and jointly acting self-consumers and will last for 20 years. In Table 2.2, the economical benefits obtained sharing energy in the two configurations are summarized[8].

Table 2.2: *Savings and incentive for the Italian Renewable Energy Communities and jointly acting renewable self-consumers (i.e. Collective Self-Consumption, CSC).*

Element	**REC**	**CSC**
Saving transmission	7.61 €/MWh	7.61 €/MWh
Saving distribution	0.61 €/MWh	0.61 €/MWh
Incentive	110.00 €/MWh	100.00 €/MWh
Total benefit	118.22 €/MWh	108.22 €/MWh (+ losses reduction)

To conclude this section and summarize the major steps in the process of transposition of the EU Directives with respect to ECs, a timeline is provided in Tables 2.3 and 2.4.

2.3 Summary

The information presented in this chapter are fundamental to define the basic blocks on which to build methods and models for the analysis of energy communities. Each type of analysis related to ECs is strongly dependent on the legislative framework in place, i.e. the geographical boundaries of an EC, the generator size limits, the tariff for shared and self-consumed energy, the presence of incentives... The model of REC presented in Chapter 4 and the rules for benefits distribution presented in Chapter 5 are based on the Italian experimental phase and, given the strong similarity, they could be applied also to cases of collective self-consumption. On the contrary, the methodology presented in Chapter 6 focuses on the type of REC expected for the final transposition of the European directives (larger scale REC).

---

[8] The values of transmission and distribution components are reported for year 2019. The tariff components to which they corresponds are redefined by the Authority each year.

Table 2.3: *Timeline of the Italian process of development for the Energy Communities. European legislative process is in blue, Italian legislative process in red and regional initiatives in green. Part 1/2*

30th Nov 2016	The European Commission presented the proposal for the Clean energy for all Europeans package [50].
3rd Aug 2018	Regione Piemonte promulgated the Regional Law n. 12 for the promotion and the institution of energy communities [39].
Oct 2018	Pubblic consulation of Senate of the Republic named "Green energy. Il sostegno alle attività produttive mediante generazione, accumulo e autoconsumo di energia elettrica".
11st Dec 2018	Directive (EU) 2018/2001 that defines Renewable Energy Communities was approved.
12nd Mar 2019	The Italian Authority ARERA published its memory related to the public consultation. [35].
26th Mar 2019	The results of the public consultation of the Senate of the Republic were presented [45].
5th Jun 2019	Directive (EU) 2019/944 that defines Citizen Energy Communities was approved.
9th Aug 2019	Regione Puglia promulgated the Regional Law n. 45 for the promotion and the institution of energy communities [40].
28th Feb 2020	The Italian Parliament approved Law n.8 2020, introducing the transitional phase for collective self-consumption and RECs [46].
1st Mar 2020	Start of the transitional phase for collective self-consmption and RECs.
9th Jul 2020	Regione Liguria promulgated the Regional Law n. 13 for the promotion of the institution of energy communities [41].
28th Jul 2020	Regione Lombardia approved OdG n.1121 concerning initiatives for promoting the creation of energy communities [43].
4th Aug 2020	The Italian Authority published Resolution 318/2020/R/eel, regulating the economic items related to collectively self-consumed and shared energy [48].
16th Sep 2020	The Ministry of Economic Development defined the incentive tariff for collectively self-consumed and shared energy [49].

Table 2.4: *Timeline of the Italian process of development for the Energy Communities. European legislative process is in blue, Italian legislative process in red and regional initiatives in green. Part 2/2*

29th Oct 2020	The Senate of the Republic approved the law that defines principles and criteria for the transposition of the Directives 2018/2001 and 2019/944 [51].
10th Nov 2020	Regione Calabria promulgated the Regional Law n. 25 for the promotion of the institution of renewable energy communities [42].
22nd Dec 2020	GSE published the technical rules for the experimental phase.
29th Dec 2020	Regione Calabria promulgated the Regional Law n. 38, defining the regional direction for the constitution of energy communities [52].
30th Dec 2020	Deadline for EMDII transposition.
4th Mar 2021	GSE launched a public consultation named "Gruppi di autoconsumatori di energia rinnovabile che agiscono collettivamente e comunità di energia rinnovabile".
30th Jun 2021	Deadline for REDII transposition.
30th Aug 2021	End of the experimental phase for collective self-consmption and RECs (expected[a]).

---

[a] The last useful day for the activation of projects within the experimental phase is 60 days after the final transposition of the Directive 2018/2001

CHAPTER 3

Review on energy communities

3.1 Review of key issues for energy communities

The interest in Energy Communities has grown very fast in recent years [53]. The literature review on energy communities shows that there is a large diversity of initiatives and no fixed boundaries that defines what can be considered to be community-based [54]. Some keywords have been used to define this initiatives such as sustainable energy communities, local energy communities, community energy systems, community microgrids and peer-to-peer energy trading. With respect to the European context, definitions and role are more clear given the restructuring of the legislative context, but most of the studies are not yet aligned with the new definitions. In this chapter, a framework for EC initiatives is defined and some classifications are proposed. Then, an overview of the main European research projects that focus of the ECs is proposed to highlight current developments and state of the art.

3.1.1 Options for energy system integration

As already discussed in the introduction of this thesis, the key challenge of the future energy systems is the integration of increasing levels of distributed generation, mainly renewable-based. To enable the decentralization of the energy production, it is required to deal also with controllable loads and storage, i.e. with Distributed Energy Resources (DERs). Different options have been developed to empower DERs integration, an overview of these options is proposed in [55]. In order to provide a taxonomic classification, the main options for the energy system integration are reported in the following.

- **Community microgrids**. Community microgrids comprise locally controlled clusters of DERs which can be seen as single demand or supply from both electrical and market perspectives. The main characteristic of this configuration is the presence of a single point of connection with the national grid, such that microgrids can be disconnected and operated autonomously when needed. These systems are important in cases of reliability issues in the main grid since they can increase the continuity of the supply, but they can be interesting also from the economical perspective if the energy exchanges inside the microgrid are not subject to tariff of taxes due for the usage of the public network.

- **Virtual Power Plants**. Consumption, production and storage of various consumers can be aggregated to form flexibility capacity similarly to a power plant, hence creating a Virtual Power Plan (VPP).
- **Energy hubs**. An energy hub manages the energy flows in a district through optimal dispatch of multiple energy carrier [56]. It includes storage, conversion and distribution technologies to supply electricity, heat, gas and other fuels to the end users.
- **Prosumer Community Groups (PCG)**. According to [57], "PCG is defined as a network of prosumers having relatively similar energy sharing behavior and interests, which make an effort to pursue a mutual goal and jointly compete in the energy market".
- **Community energy systems**. According to [58], "community energy systems refer to electricity and/or heat production on a small, local scale that may be governed by or for local people or otherwise be capable of providing them with direct beneficial outcomes".
- **Integrated Community Energy Systems (ICES)**. ICES capture attributes of all energy system integration option and apply them to a community level energy system. The goal is in increasing self-consumption and matching supply and demand at the local level. According to [59] "ICES entail the planning, design, implementation, and governance of integrated energy systems at the community level in a way that maximizes energy performance while cutting costs and reducing environmental impacts".

The definitions of ECs provided by the European Directives are not limited to one of the previous notation, but they could theoretically include all of them. The power of the definition is the formal recognition of the legal entity; the implemented solutions could be strongly different for each community depending of the existing and potential energy assets, such as electric power, natural gas, and local renewable energy opportunities. The main objectives and characteristics of the possible options are reported in Table 3.1, together with some references for each case.

3.1.2 The meaning of energy community outside Europe

The definitions of the European energy communities have to be considered in the specific context of the European electricity sector. Specifically, in Europe, transmission and distribution are a regulated monopolies and the electricity market is liberalized. Moreover, the electrical network is highly interconnected and the distribution grid is widespread.

Table 3.1: *Overview of energy system integration options (retrieved and adapted from [55]).*

Options	Objective	References
Community microgrids	Optimize electricity generation and demand for autarky and resiliency in community	[60]
Virtual Power Plants	Aggregate and manage (operate and dispatch) DERs	[54, 61]
Energy hubs	Multi-carrier optimization of electricity, gas, heat and cooling within a district	[56, 62]
Prosumer community groups	Energy exchange among prosumers having similar goals	[63]
Community energy systems	Invest and operate in systems for local energy production	[58, 64, 65]
Integrated Community Energy System	Multifaceted approach for supplying local communities with its energy requirements through DERs, flexible loads and storage together with different carriers	[66–68]

In this context, an EC is a legal entity with its own rights and it has no strict links with the local authorities[1] and the distribution system operator[2]. Given the unbundling and the liberalization of the electricity sector, ECs are only one among many actors that operate in the electricity sector. All around the world, mainly due to different structures of the electricity sector and different levels of network diffusion and interconnection, a subject equivalent the European EC may not exist, and ECs refer to similar but different concepts.

In Australia there are different forms of ECs that operate in the electrical sector, thanks to the existence of a liberalized market. According to the Coalition for Community Energy (C4CE), ECs are "communities involved in developing, producing, distributing, selling and buying energy assets and their output". They range from small scale cooperatively owned solar PV installations to large scale community owned wind farm. There are also ECs that operate as community-owned energy retailers (e.g. Enova). The Australian Government has an Energy Efficient Communities Program to deliver grants to community organisations for energy generation and storage projects. The Victorian Government is also supporting the development and implementation of community renewable energy projects.

In Canada, electric utilities vary by their dependence on large crown corporations to produce, transmit and distribute electricity to their customers. Energy markets are varied in size, ranging from isolated off-grid communities to well-connected provinces such as Québec and Ontario [69]. In this context the concept of Smart Energy Community has been proposed. According to QUEST, a non-profit organization that conducts research, engagement and advocacy to advance Smart Energy Communities in Canada, "a Smart Energy Community considers mobility networks, buildings, electricity and natural gas distribution, water management, and waste management and recovery as

---

[1] Local authorities, including municipalities, could be shareholders, but it is not a requirement (see REC and CEC definitions in Chapter 2)

[2] "Member States may decide to grant citizen energy communities the right to manage distribution networks in their area of operation [...] without prejudice to [...] regulations applying to distribution system operators". Directive (EU) 2019/944 - Article 16 (Appendix B)

deeply integrated parts of a highly efficient and localized energy system." From this holistic perspective, the subjects naturally committed to the development of Smart Energy Communities are municipalities, local governments and utilities. Another peculiar aspect of the Canadian context is the presence of an high number of remote communities. Also in these cases, EC initiatives are playing an important role for the energy transition. Thanks to government- or utility-led and community-driven projects, from 2015-2020 renewable energy projects nearly doubled across remote communities [70].

In the USA, according to the Environmental and Energy Study Institute (EESI) [71], there is a wide variety of collective and community-scale approaches that allow local energy users to share the benefits of developing local energy resources. These collective efforts are called "community energy" and take many forms, both in terms of ownership/development structures and technologies used. The US Community Energy Website (USCEW) is a database with reference to more that 6400 community energy projects across the USA [72]. It lists renewable energy projects with a "group" or "community" element. This includes group of people that share ownership of a solar/wind power plant, municipality, non-profit organization or tribal government that install renewable energy on their own property, bulk purchase group and electricity buying group.

In Japan, the first collective initiatives in the energy sector appeared in the early 2000s, but it is after the Fukushima disaster (2011), that the interest of the population on community based renewable energy planning and development increased. Moreover, in 2016, the Japanese electricity market fully opened to allow about 85 million households and small businesses to choose electricity suppliers. After this, a number of local governments, groups and businesses have started to develop hydroelectric and other renewable projects using resources available to their community [73]. In occasion of the 1st World Community Power Conference, held in Fukushima City in November 2016, the participants defined the interesting "Fukushima Community Power Declaration" [74], committing themselves "to act so that community power becomes the prevailing model of the future renewable energy supply all over the world."

Energy communities may be relevant also in developing countries. In [75], a review of ECs in the Sub-Saharan Africa is presented. ECs are considered capable to contribute to improving energy access in Africa, but it is highlighted that they need an enabling policy environment to foster their growth and sustainability. Also the authors of [76], analysing the difference between community microgrids and microgrids for single-dwellings, conclude that the promotion of community energy arrangements has to be recommended as a key way to improve the uptake of distributed generation in developing countries. Finally, in Peru, the energy community Ehilicha contributed in the past decades to the electrification of a rural area, and nowadays operate as non-profit distributor and energy retailer, ensuring affordable energy to the local community (Appendix D).

3.1.3 Possible classifications

Some classifications of these energy systems are proposed in [55] and they are reported in this chapter. The main structure of the classifications comes from the original study, but they have been adapted to the purpose of this thesis and updated according to more recent advances in the research field and to the author experience.

Location

ECs are emerging all around the world thanks to the technological innovation and the possibility to install small generators at affordable costs. Nevertheless, some key aspects can be identified when distinguish ECs in developed countries and ECs in developing ones. The first ones are driven by the liberalization of the electricity markets and favorable energy policy. The environmental awareness is a key aspect in order to achieve a full decarbonization of the economies and the exploitation of local sources is mandatory, therefore the participation of the communities is fundamental. These kind of initiatives are emerging across Europe [1, 2] but they are already implemented also in Canada [77] and Australia [78]. On the other hand, in developing countries the main objective of the energy communities is to provide an affordable access to energy. An example of an energy community with this purpose is the one of Eilhicha s.a. presented in Appendix D. These energy systems provide opportunities for the integral development of the areas. Another distinction can be made between rural communities and urban ones. In case of rural systems, they generally have a lower energy density but higher source availability. The grid is often weaker and sometimes the energy community can be based on off-grid solutions. On the other hand, in case of urban configurations, the number of users and the total consumption is higher and concentrated in a smaller area. Nonetheless, the energy sources availability is scarce but other energy vectors such as natural gas network are available and the interaction among the vectors is easier.

Scale

ECs have an intrinsic local connotation, nevertheless different scale projects are possibile. Small/micro ECs include some households/buildings, Medium ECs cover entire neighborhood or small villages, while large/macro ECs include entire cities or regions.

Initiatives

The creation of an EC is generally a bottom-up process that can start from a group of citizens. Nevertheless it requires some motivations and competences that are not always easy to find. Among the challenges for self-organising ECs there are the difficulty in obtaining trust from the other stakeholders, keeping motivation and continuity during the project, define business models that are shared among the members, define contractual arrangement between a great variety of heterogeneous individuals, companies, governmental institutions (municipalities and provinces), and non-profit organizations [79]. For this reason, the initiative can be led by common citizen, but also from private enterprises or local government, since they can meet more easily some of these deficiencies. Some projects are also driven by research initiatives (see Section 3.2).

Roles

So far, most of the ECs focused their activity in the field of energy generation [80]. However, recently, some initiatives started to adopt smart grid technologies which enables them to become involved in the distribution, trading and management of energy. Given that the possible field of action of an energy community is quite large, it is useful to define a framework with the possible roles an EC can play and the possible activities that can be performed. Focusing on the electrical sector, six different roles have been identified in [54] based on the USEF market roles model developed as part of the Universal Smart Energy Framework [7]. The roles that the EC could play are briefly explained in the following.

- **Facilitator**. The role of the facilitator is to contribute to the implementation and/or optimization of the DER portfolio. A simple example is that the facilitator could promote a buying groups for private photovoltaic plants, and in this case the community members become prosumers. Another example could be the proposal of the installation of a community/collective power plants, in this case the community itself becomes a producer. In general, the facilitator activities deals with informing, financing, advising, organizing, lobbying and joint purchasing.
- **Producer**. The role of the producer is to feed energy into the energy grid. This energy can be used by the community members (shared) or sold to other energy suppliers. The EC play the role of the producer when developing energy generation projects (e.g. solar farm, collective solar roof, wind project...).
- **Supplier**. Communities that take the role of energy supplier can supply (self-generated) energy to customers or community members, trade energy on the wholesale energy market and/or facilitate local or peer-to-peer energy trading.
- **Energy Service Company** (ESCo). The ESCo offers all kind of energy-related services to prosumers and community. These services include insight services, energy optimization services and maintenance of shared assets. If the supplier or the DSO is applying implicit demand-side flexibility the ESCo can provide energy optimization services based on these tariffs (implicit demand response).
- **Aggregator**. By acting as an aggregator a community can sell aggregated flexibility provided by dispatching generation, controllable loads and energy storage systems on wholesale energy markets or to the DSO (explicit demand response).
- **Distribution System Operator** (DSO). In some cases, ECs could play also the role of the distribution system operator, but this is not always possible since distribution is a regulated service[3].

The roles in the energy system are illustrated in Figure 3.1. It is possible to see the six roles already cited and other roles that are the Transmission System Operator (TSO) and the Balance Responsible Party (BRP). There are no reasons to think an EC could play the role of the TSO, while with respect to BRP, according to [54], ECs that take on the role of supplier typically delegate balance responsibility to a centralized (profit-driven) BRP. Indeed, from an economic perspective, the balance responsibility is best managed using a much larger portfolio of prosumers than a community typically has and it is often not practical or financially feasible for a community to take on the BRP role. In this way is an external actor that holds the imbalance risk for each connection in its portfolio of prosumers.

One of the simplest EC includes the facilitator and the producer, and this is the case of a collective investment in a new power plant. In this case the community do

---

[3] In the European scenario, Directive 2019/944 "empowers Member States to allow citizen energy communities to become distribution system operators either under the general regime or as ’closed distribution system operators’. Once a citizen energy community is granted the status of a distribution system operator, it should be treated as, and be subject to the same obligations as, a distribution system operator."

not focus on energy management and therefore do not require any kind of software implementation. A further step is to take the role of both producer and supplier, in this case the EC has the possibility to supply shared generated energy to its members (Figure 3.2(a)). Theoretically, P2P-supply could also be facilitated by the community, which would also require the community to take on the role of supplier [81]. Another option for the community is to assume the role of ESCo and/or the role of aggregator (Figure 3.2(b)). The ESCo may offer different energy-related services to prosumers and community, one of the most interesting in the energy management of the community in order to optimize individual and/or community energy profiles in response to price signals. On the other hand, the aggregator can offer explicit demand-side flexibility services. This type of services are agreed to respond to BRP, DSO or TSO requests to adjust power profiles. More details about flexibility services are provided in the following sections. Finally, the EC could take role of the DSO (Figure 3.2(c)), this may be the case in which the EC build its own grid.

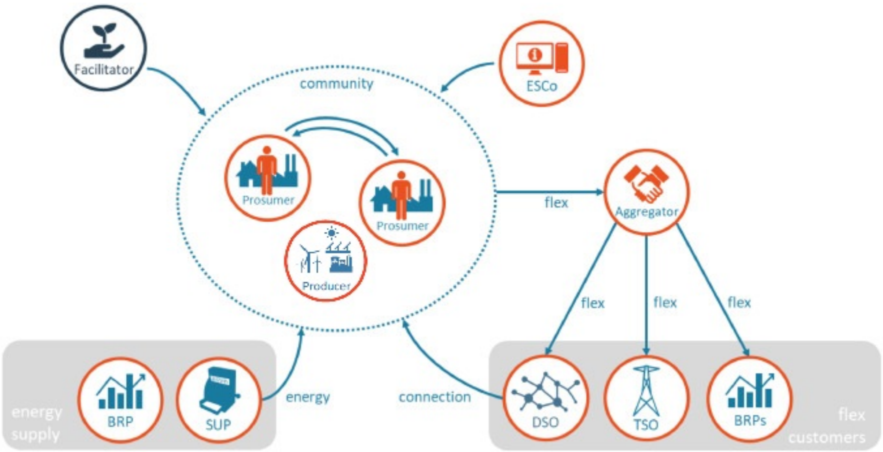


Figure 3.1: *Roles in the energy system, figure retrieved and adapted from [54].*

3.1.4 Services

The main services that can be performed by an energy community within the electric sector are detailed in the following. These activities do not depend on the roles the EC plays and, in general, they can be performed both in an integrated way (e.g ESCo fully integrated within the community) or interacting with external actors (e.g external ESCo). The advantages of integrating roles within the community is the reduction of the third parties dependency and costs, the drawback is the need of internal expertise end professional skills. According to [81], services can be divided in energy services and flexibility ones.

Energy Services

Energy services are described in the following:

- **Services to increase energy awareness**. They are the simplest ones and do not require investments in new assets. They could be the provision of energy diagno-

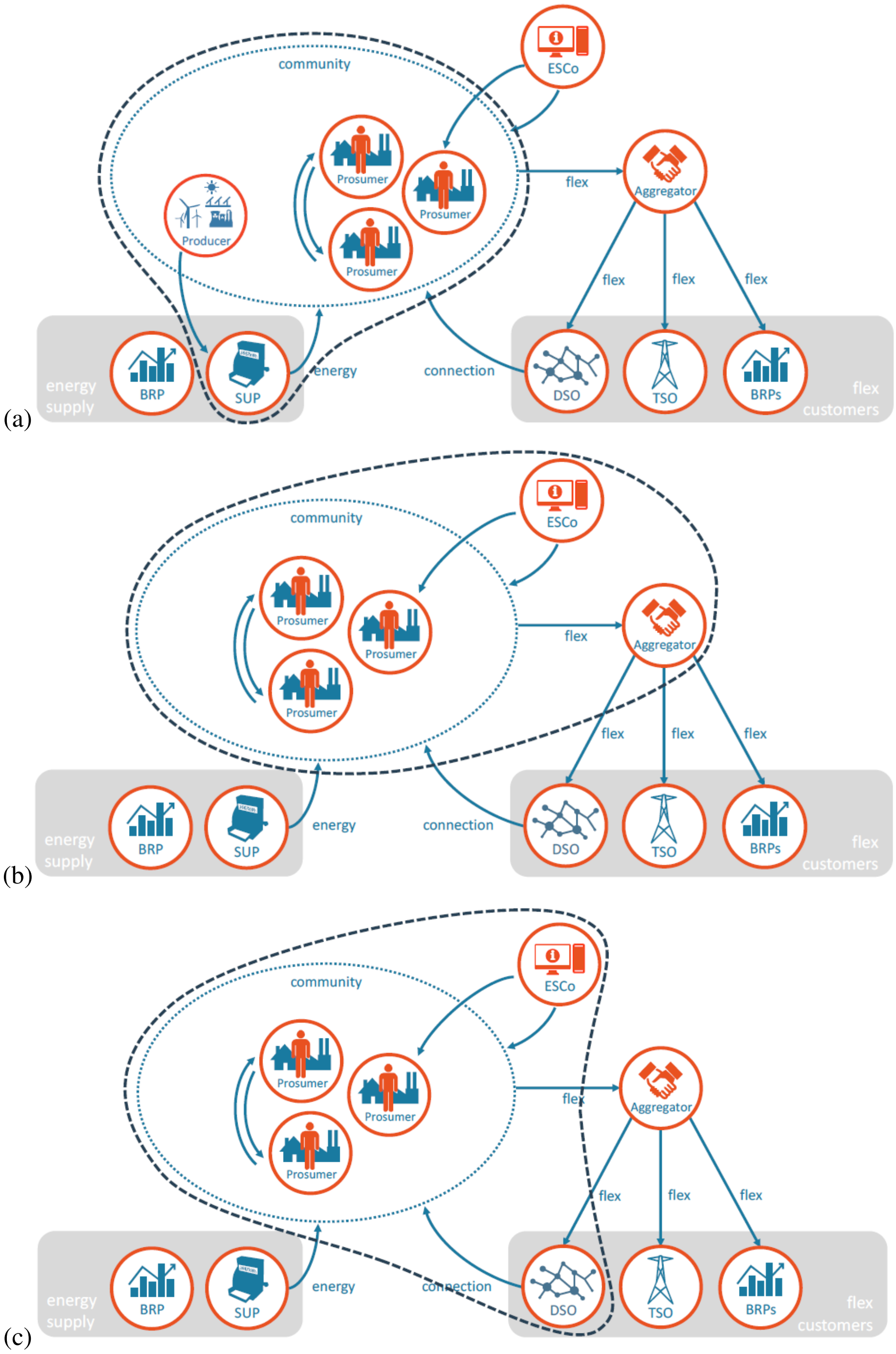


Figure 3.2: *Illustrations of the Energy Community that takes on the role of (a) both Producer and Supplier (b) both ESCo and Aggregator (c) both ESCo and DSO [54].*

sis, energy consumption monitoring or the organization of dedicated workshops and training programs to stimulate knowledge acquisition and exchange.

- **Joint purchase and maintenance of assets**. The community could facilitate the collective purchase of DERs or it could focus on the installation of shared generation assets.
- **Supply of (shared) energy**. Ones ECs become producers, they could sell their energy to centralized Suppliers/BRPs, via a Power Purchase Agreement (PPA) or they can supply the energy to their members or other costumers taking the role of suppliers.
- **Peer-to-Peer (P2P) supply**. An interesting opportunity for ECs could be the managing of the administrative exchange of energy between prosumers within the community. The P2P initiative can be managed by the supplier and some profit-based centralized suppliers currently offer P2P-services, handling the administrative exchange of energy between peers [82]. The initiative could also be managed in an internal way and separate from the administration of the Supplier/BRP. In this case it can be defined as shadow administration since it has no official role in the organization of the energy system and it is typically managed by the community itself (in the role of ESCo).

Flexibility Services

A further division can be made from implicit and explicit flexibility. Implicit flexibility is driven by variable costs defined by the supplier or the DSO. The EC, in the role of ESCo, defines the optimal management of the DERs given the constrains of each member of the community for minimizing the cost of the energy. This services includes self-balancing, peak shaving, time of usage optimization and emergency power supply. All this services could be managed from the perspective of the single users or the one of the entire community Explicit flexibility services are driven by an economic rewards. The EC, is the role of aggregator, can provide value to different parties:

- The Supplier and its Balance Responsible Party (BRP) aim to reduce sourcing costs, maximize revenue of generation and avoid imbalance charges. Flexibility can help a Supplier/BRP optimize its portfolio.
- The Distribution System Operator (DSO) is responsible for the installation and maintenance of distribution grids. A DSO can use flexibility, e.g. to defer or avoid grid reinforcement costs.
- The Transmission System Operator (TSO) is responsible for the installation and maintenance of the transmission grid and for system stability. It may also, depending on national regulation, have responsibility for ensuring generation adequacy. The TSO can use flexibility for any of these purposes.

They can be classified into wholesale services (Day-ahead optimization, Intraday optimization, Self-balancing and passive balancing, Generation optimization), constraint management services (Voltage control, Grid capacity management, Congestion management, Controlled islanding), balancing services (Frequency Containment Reserve, Automatic Frequency Restoration Reserve, Manual Frequency Restoration Reserve, Replacement Reserve) and adequacy services (capacity markets, capacity payments, strategic reserves, hedging). More details on each of these service can be found in [83]. In Figure 3.3 the energy and flexibility services described are illustrated.

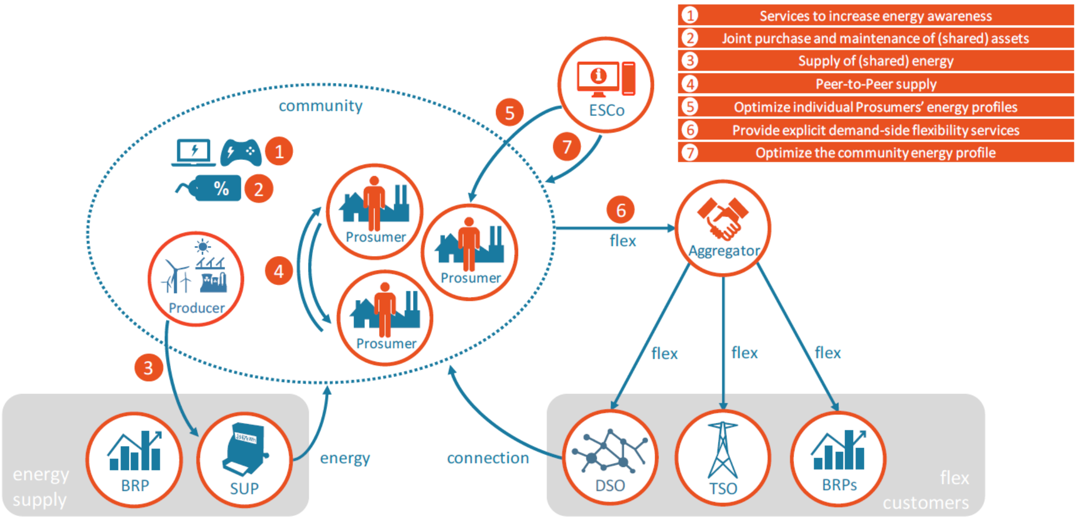


Figure 3.3: *Energy and flexibility services that an EC could provide.*

3.1.5 Interest of different actors

The stakeholders around an EC project are many and each one has its own private interests to take part/interact with the EC. At the same time, their participation could promote also system interests. In table 3.2 these interests are detailed for different actors.

3.1.6 Key issues

A review of keys issues and trends which are shaping the development of integrated community energy systems is proposed in [55]. An analytical framework is proposed where the issues are divided into four groups: technological, socio-economic, environmental and institutional. In table 3.3 the identified issues are reported.

3.2 European research projects

Considering the natural lack of interest from the private sector, the research activities in the field of energy communities is strongly driven by projects funded by public grants. In the following, some of the most important European projects of the last years are reported. The include universities, municipalities, private and public companies and they are characterised by the real life testing of ECs organization. These kinds of projects last on average 3 years and some of them are still open. It is interesting to notice how the focus of these projects was initially in the field on the social sciences (social acceptance, stakeholder engagement, legislative aspects...) while, in a second step, they

Table 3.2: *Interest of different actors in ECs projects (retrieved and adapted from [55]).*

	Actors	Private interests	System interests
Competitive parties	Households	Use of local, affordable and clean energy at a low cost	Sale surplus and purchase deficit energy
	Communities	Reduction in energy related costs, provision of local energy	Emission reductions, energy independence, energy supply security, resiliency
	Energy producers	Investment in local energy system (profit maximization)	Sale local generation
	Energy suppliers	Profit from deficit energy supply, portfolio optimization	Increase renewables in their portfolios, new roles and business models
	Energy service companies (ESCOs)	Profit from energy efficiency, operation and management of local generation	Role in energy efficiency improvement activities as well as operation and management of local generation
	Technology providers	Sell technologies to transform the existing energy landscape both production and consumption (e.g. circular economy)	Promotion of local generation as well as demand side management technologies
	Aggregators	Business model for generating profit, Maximize the value of flexibility in the markets (both with capacity and energy)	Role in making system more efficient
	Balance responsible parties	Portfolio optimization, balance energy procurement at lowest cost,	Provision of accurate scheduling to the system operator
Regulated parties	Transmission system operators (TSOs)	Maintain larger system balance of supply and demand at lowest cost to the consumers	Maintain larger system balance of supply and demand
	Distribution systems operators (DSOs)	Distribute energy to the neighborhood with safe, reliable and affordable grid	Avoid grid congestion, defer network investments, self-balancing energy islands in smart grids
	Government, policy makers and regulators	Ensure competition for affordable energy for end-users	Sustainable energy supply, transition to low-carbon energy system, energy security

Table 3.3: *Main issuses related to ECs according to [55].*

Technological
1. Intermittency of local RES generation and demand response
2. Energy efficiency
3. Storage
4. Local balancing of supply and demand
5. Local flexibility and impact on larger energy system
6. Load and grid defection
Socio-economic
1. Paradigm shift through community engagement
2. Economic incentives
3. Willingness to pay
4. Split-incentive problem
5. Energy poverty
6. Energy autonomy and security of supply
7. Initial costs and financing
Environmental
1. Environment and climate change
2. Emission
3. Waste
4. Spatial
Institutional
1. Trust, motivation, and continuity
2. Energy democracy
3. Ownership
4. Locality
5. Support schemes and targets
6. (Self-)governance
7. Regulatory
8. Institutional design
9. Roles and responsibilities

start moving towards technological aspects (energy management systems, flexibility services, EV charging...). Since they represent the state of the art of the research, many of the reference of the previous chapters are related to technical reports of these projects or to scientific publications that were published based on projects results.

3.2.1 RESCOOP 20-20-20

Goal	Foster social acceptance of RES by stakeholder engagement
Partners	12
Budget	2 M€
Duration	01/04/2012 to 31/03/2015

Table 3.4: *Overview of the REScoop 20-20-20 Project*

The project REScoop 20-20-20 [84] supported the start-up of 12 new energy cooperatives by means of a toolbox for starters and a network of mentors. It helped to improve social acceptance of electric generation from RES with a model of local cooperative citizen involvement. The overall goal of the project was to speed up the creation of RES projects and related cooperatives in various member States (Belgium, Italy, France, UK, Netherlands, Germany and Denmark). The project was articulated with the following three specific objectives: (i) Inventory existing REScoops and their RES projects in order to identify their added value in fostering RES in Europe; (ii) Developing and testing methodologies based on best practices (Business structures and financing models for new REScoops; (iii) Dissemination of cooperative RES approaches. The main results were:

- Develop and share methodologies based on best practices to create new citizens RES-projects: different business models, checklists, template contracts, financing and investment schemes.
- Support emerging cooperative RES-projects with a toolbox that integrates the learning of the more than 400 existing RES cooperatives and the involvement of at least 25 volunteer mentors, trained in best practice.
- Deliver recommendations to EU and national Governments on fiscal, legal and authorisation policies to increase the success rate of RES projects.
- Direct involvement of at least 6000 shareholders that leads to at least a 5% reduction in their electricity consumption and secure financial support to new RES initiatives collecting commitments for 100 M€ all over Europe.
- Creation of 12 new REScoops and projects, applying best practice and leveraging the network corresponding to at least 24 MW (average of 2MW per project) established thanks to the action support.

Furthermore, the project resulted in the creation of the European federation of citizen energy cooperatives, REScoop.eu. It was legally set up in 2013 as a Belgian not-for-profit association and it is still a growing network of 1500 cooperatives operating across Europe, representing over 1 million citizens. REScoop.eu provides a range of services to support citizens, businesses and local authorities that want to work on community energy. It has four objectives:

1. To represent the voice of citizens and energy cooperatives to European policy makers;
2. To support starting and established energy cooperatives and provide them with tools and contacts to help them grow and prosper;
3. To facilitate international exchanges and cooperation between energy cooperatives;
4. To promote the cooperative business model in the energy sector.

3.2.2 Community Power

COMMUNITY POWER for people's ownership of renewable energy	Goal	Enabling legislation to increase public acceptance for RES projects across Europe
	Partner	12
	Budget	1.6 M€
	Duration	15/04/2013 to 14/04/2016

Table 3.5: *Overview of the Community Power Project*

The goal of the Community Power project (CO-POWER) [85] was to speed up the development of community RES projects by creating a favourable legislative environment across Europe. The focus of the project were on the social and legislative aspects and the main results were:

- Analysis of public and private finance sources for community RES projects, and promotion of public-private financing schemes in 6 Central and Eastern European countries.
- A broad public coalition/network across Europe (at EU and national levels) supportive of enabling legislation for community RES projects is built up.
- Capacity building and informing of key EU level, national, regional and local policymakers, empowering them to put forward an enabling legislative framework in their respective countries and explore options for improvements in the EU framework.
- At least 7.000 - 12.000 citizens informed for joining energy community energy projects.

3.2.3 WISE Power

WISEPower	Goal	Fostering Social Acceptance for wind power
	Partner	14
	Budget	? M€
	Duration	01/05/2014 to 31/10/2016

Table 3.6: *Overview of the WISE Power Project*

WISE Power [86] was a European project about the social acceptance of wind energy, aiming at significantly improving local engagement and support for wind turbines while enhancing local community participation in the planning and implementation of wind energy projects. The project focused on 13 European countries, divided into three categories, according to the maturity of their local wind energy market. Among the output of the projects it is interesting to cite:

- Report on innovative financing models for wind farms.
- Status quo of social acceptance strategies and practices in the wind industry.
- Report on innovative financing models for wind projects, expected to be supportive of social acceptance.
- WE Engage - An online tool for onshore wind farm developers and industry stakeholders to engage with local communities on permitting and planning of wind sites. The online tool website aims to foster public support for onshore wind power through information and advice to communities, TSO, developers and local authorities.
- Social acceptance pathways containing concrete steps for community engagement, benefit sharing mechanisms and communication on local impacts or potential conflicting interests.

3.2.4 WiseGRID

Goal	Wide scale demonstration of Integrated Solutions and business models for European smart-GRID
Partner	21
Budget	17.6 M€
Duration	01/11/2016 to 30/04/2020

Table 3.7: *Overview of the WiseGRID Project*

WiseGRID project [87] integrated, demonstrated and validated advanced ICT services and systems in the energy distribution grid in order to provide secure, sustainable and flexible smart grids and give more power to the European energy consumer. WiseGRID's main objective was to provide a set of solutions and technologies to increase the smartness, stability and security of an open, consumer-centric European energy grid. The project combined an enhanced use of storage technologies, a highly increased share of RES and the integration of charging infrastructure to favour the large-scale deployment of electric vehicles. It placed citizens at the center of the transformation of the grid. On top of having a consumer-centric approach, the project delivered tools that facilitate the creation of a healthy, open market where not only 'traditional' utilities but also players such as electric cooperatives and SMEs can play an active role, contributing therefore effectively to a democratic energy transition.

The project was quite big and involving many aspects of the smart grids solutions, but a specific focus was on ECs. Indeed, some of the partners were energy cooperatives and among the technological solutions proposed there is one, named WiseCOOP, particularly focused on domestic and small businesses, with the purpose of supporting them in their roles of energy retailers, local communities and cooperatives. The main goal of the solution is helping consumers and prosumers to work together in order to achieve better energy deals while relieving them from administrative procedures and cumbersome research [88]. Among the main interesting solutions there are:

- Member profiling: clusters of consumers and prosumers with common energy usage patterns may be identified, allowing the aggregator to negotiate special terms (as for instance energy tariffs) particularly beneficial for those groups.
- Demand forecasting: by allowing the retailer to forecast the demand of its customers, optimized purchase of energy at the wholesale market is enabled.
- Implicit price-based DR towards modulating the overall demand of the group to achieve a common objective (e.g. maximize usage of renewable energy sources produced within the group).
- Tariff comparison: by offering members a tool for comparing their particular consumption with different available tariffs, those will have access to very valuable information to reduce their energy bills.

3.2.5 FLEXCoop

Goal	Democratizing energy markets through the introduction of innovative flexibility-based demand response tools and novel business and market models for energy cooperatives
Partner	13
Budget	4.0 M€
Duration	01/10/2017 to 31/01/2021

Table 3.8: *Overview of the FLEXCoop Project*

The FLEXCoop project was focused on the introduction of flexibility services for the energy cooperatives. Its purpose was to enables the realization of novel business models, allowing energy cooperatives to introduce themselves in energy markets under the role of an aggregator. To achieve this, it introduced an end-to-end Automated Demand Response Optimization Framework and it equipped cooperatives with innovative tools to exploit their microgrids and/or VPPs as balancing and ancillary assets toward grid stability and alleviation of network constraints [89]. Optimization in FLEXCoop applies to multiple levels. It spans local generation output, demand and storage flexibility, as well as the flexibility offered by EVs to facilitate maximum RES integration into the grid, avoidance of curtailment and satisfaction of balancing and ancillary grid needs. This is achieved via automated, human-centric demand response schemes with the participation of appropriately selected residential prosumers. To enhance prosumer acceptance, the FLEXCoop innovative services will feature non-intrusiveness, comfort and well-being preservation, non-violation of prosumer daily schedules as well as maximization of benefits through transparent and open participation in markets. It will also guarantee easy switching between DR service providers, vendor lock-in avoidance, customized DR service contracts and objective settlement and remuneration, thus establishing an energy democracy context and empowering prosumers to become active energy market players. FLEXCoop brings together a wide range of baseline technologies to build an open and interoperable DR optimization framework, including a fully-fledged tool suite for energy cooperatives (aggregators) and prosumers involved in the DR value chain, ensuring: (i) DR stakeholders empowerment and transformation into active market players, (ii) end-to-end interoperability between energy networks, energy management systems and devices and (iii) the realization of new business models for energy cooperatives.

Among the most interesting publications of the projects there are:

- Deliverable on "Models of DER Devices and associated Forecasting Algorithms" [90]. In this report, DER models are divided into demand, storage and generation. An approach for load and storage modelling is proposed, considering also the possibility of usage EVs as ESS (V2G). With respect to the generation, a forecasting literature review is proposed and a regression model for photovoltaic production based on numerical weather predictions is described.

- Deliverable on "Local Demand Manager Specifications and Intra-building Optimization Algorithms" [91]. It presents the whole demand response flexibility value chain and it details the algorithm of the Local Demand Manager. It is one of the module involved in the process and its task are: continuously gathering the potential flexibility that each device under its control can offer for the next 24 hours, receive DR requests communicated by the aggregator, dispatch the proper signals to the involved devices to provide the needed amount of flexibility.

- Deliverable on "FLEXCoop Global Demand Manager" [92]. The Global Demand Manager is responsible for dispatching automated control signals to Local Demand Managers with the objective of using the flexibility of the end-users, that are previously organized into clusters presenting similar behaviours. The clustering is based on individual household parameters, taking into account information related to the building infrastructure and DER device availability, the location, contracts with aggregator, etc. The main objective is to facilitate the management of the consumer demand and to provide the aggregator important information for the organization of demand response programs.

3.2.6 Compile

Goal	Integrating community power in energy islands
Partner	11
Budget	6.9 M€
Duration	01/11/2018 to 31/10/2022

Table 3.9: *Overview of the Compile Project*

COMPILE project [93] is funded under the Horizon 2020 program of the European Commission. The project is build around the concept of energy island. It defines an energy island as an area (e.g. isolated village, small city, urban district, rural area) either weakly connected to the grid or with a significant degree or potential of self-supply. In the context of the project, a weak connection means that the total rated power of connection lines or transformers is in the range of local energy system's peak load and/or the connections are not redundant, i.e. they don't comply with grid operation stability criteria in all operational states. The definition of an energy island is thus strictly technical, however, the project proposes a further division of the concept in local energy system and energy community. Local energy system presents the technical aspects, while the energy community includes the social aspects of the energy island which involve the engagement of citizens, enterprises and organisations, present on the area. The main aim of the project is to show the opportunities of energy islands for decarbonisation of energy supply, community building and creating environmental and socioeconomic benefits. Since this is a recently started and ongoing project, the European definition of RECs and CECs are already considered, and the goal of the project is to include these new configurations in the deployment, management and decarbonisation of local energy systems. The system services provided by local sources to the islanded system, implemented and evaluated in project are:

- Congestion management: local congestions which could occur in energy system due to increased local RES generation, increased consumption or outages of power system components (lines, transformers, production units) will be tackled by EC strategies for control of local energy storage (home and community batteries), demand response of appliances (including EV charging) and emergency control of local production according to the needs of power grid.
- Peak shaving: the peak of the demand can be reduced by shifting/redistributing some of the consumption to off-peak periods of the day. The reduction is achieved either by activation of local generation or by reduction of demand using smart demand response algorithms.
- Zero-load provision: if the local energy system strives for minimum dependence from the main grid, the operation is very similar to the islanded mode of operation (the entire consumption is covered by local generation), but still connected to the main grid.
- Power reserve provision: provision of reserve in case DSO would need additional power. Reserve could be provided by the implementation of demand response schemes (which result in a reduction of consumption on request of DSO), control of energy community's local storage and forced operation of production units.

In this regard, ECs are looking to tackle three major issues:

- To support the acceptance of local renewable production and energy services. The public dialogue process and the openness of the governance tool of the ECs are allowing local citizens to truly participate in the process of development of local sources, offering a concrete benefit to the decarbonization process. This allows for engagement of the local community in partnership with the developing actor (DSO, municipality, market actor or community energy project). The EC is support for a direct and transparent contact between the technical actors of the deployment and consumers which are the first impacted.

- To act as a pivot to mobilize local investment capacities toward the transition project, which is offering the opportunity to the development actor to find local partners and to lower its investment costs.
- Finally, the ECs are a way for local citizens and authorities to invest and produce local economic value. According to COMPILE, a locally financed renewable energy project is producing between 3 and 8 times the local economic output than a project financed by outside financing sources.

The approach of the COMPILE project is therefore an hybrid of the deployment of a decentralised technical management system for decentralised and decarbonized energy, centred around local citizens. The project is taking an integrated approach to the development of both technical and governance wise of an Energy Community (CEC or REC).

The project is expected to produce six tools: two of them are defined as Energy Community creation tools, while the other four are technical tools.

Energy Community tools

- COOLkit - It is an analysis dashboard and repository destined to support the EC leaders to understand and build their EC. The COOLkit is composed of several reports: Best Practice Guide, Financing Guide, Stakeholder Engagement Guide, Maturity Framework, Legislative Review, Technical Tools Implementation Guide and Stakeholder Guide.
- ValueTool - It serves as a decision support tool for EnCs and their members in the process of deployment of new production facilities or energy-related services. The tool assesses the benefits and potential risks related to planned investments and calculates economic and energy savings (return of investment) and environmental benefits derived from new installations.

Technical tools

- GridRule - It is a tool for the management of the local energy system. The tool enables the community managers (aggregators, microgrid operators, etc.) an operation and management of the local grid within network limits. It sets up the coordination of individual community members and enables the optimization of the whole community energy needs. GridRule also features various control strategies that optimize all the available flexibility in the network with a goal of maximizing the benefits of the community. These features include community battery management and community self-consumption optimization. One of the most important and challenging features is Community Island mode. This mode requires engineering, calculation and modifications to protection equipment. Another important feature is the development of ancillary service provision, which will be tested in cooperation with the local DSO in the pilot project sites.
- HomeRule - It is a Home Energy Management System for control and optimisation of energy consumption and production in residential and business buildings. It supports the connection with the GridRule tool to enable community-oriented

management of flexibility. The features includes advanced PV curtailment, voltage support, economic optimization and island mode.

- EVrule - It is a tool used for monitoring and control of the operation of EV charging infrastructure and to manage business processes related to EV charging.
- ComPilot - It is a technological solution for EC management, targeted to Aggregators of Final Customers, with functionalities to support them in different roles (energy retailers, local communities, cooperatives, etc.).

3.2.7 SocialRES

Goal	Fostering socially innovative and inclusive strategies for empowering citizens in the renewable energy market of the future
Partner	12
Budget	2.4 M€
Duration	01/05/2019 to 31/08/2022

Table 3.10: *Overview of the SocialRES Project*

Tha last three projects here presented are quite young, therefore few results have been presented so far. They are reported to highlight that important contribution could come from them in the future. SocialRES [94] in an ongoing project focusing on effective ways of increasing social innovation leading to greater social acceptability as well as more durable governance arrangements and socioeconomic benefits. Until now, few results have been presented, but it is interesting since an innovative P2P photovoltaic virtual platform will be developed as a pilot software application in off-line mode and will facilitate the understanding about existing barriers within current electricity markets and policies. [95]. Experience will be accumulated related to the main issues with the common access for energy trades between different actors on the market: prosumers, consumers, balancing responsible party and distributed photovoltaic generators.

3.2.8 COME RES

Goal	Community Energy for the uptake of RES in the electricity sector. Connecting long-term visions with short-term actions
Partner	15
Budget	3.0 M€
Duration	01/06/2020 to 28/02/2023

Table 3.11: *Overview of the COME RES Project*

COME RES [96] will focus on legal, socioeconomic, spatial and environmental features, detect the reasons for the slow development of RECs in some countries, establish stakeholder dialogues and develop regional action plans and business model proposals. The purpose of the project is to facilitate the market uptake of RES in the electricity sector and the development of RECs in nine EU countries. The project will include different socio-technological systems such as community photovoltaics, onshore wind, storage and integrated solutions. The project will analyse legal, socioeconomic, spatial and environmental features, detect the reasons for the slow development of RECs in some countries, establish stakeholder dialogues and develop regional action plans and business model proposals. Moreover, it will investigate good/best practice cases and develop a community platform.

3.2.9 REScoopVPP

RESCOOP VPP	Goal	Smart Building Ecosystem for Energy Communities
	Partner	11
	Budget	4.5 M€
	Duration	01/06/2020 to 31/05/2023

Table 3.12: *Overview of the REScoopVPP Project*

Among the ongoing project, REScoopVPP [97] is one of the most interesting from the technical point of view. The main aim of REScoopVPP is to set-up a community-driven virtual power plant that can actually provide flexibility services to the grid and contributes to a 100% share of renewable energy sources into the grid. The REScoopVPP project combines front-runner energy communities to create the most advanced community-driven smart building ecosystem for energy communities. The ecosystem consists of a Community-driven Flexibility Box (COFY-Box) acting as smart home controller, and a set of community tools to support energy services for aggregators, ESCO's, BRP's and suppliers of RES.

The COFY-box will be the first truly open and collaborative building controller, based on existing open source home automation technology with more than 1.400 integrations. The COFY-box will be affordable and easy to install. Community tools will enable energy communities to become real-time asset operators by employing demand and production forecasting algorithms, a dynamic pricing module for implicit DR and an OpenADR-based explicit DR solution.

[4] More and more energy communities are being established in Europe, and an estimated 98 million Europeans are expected to join them by 2050. The EU-funded REScoopVPP project will establish the most advanced community-driven smart building ecosystem for energy communities. This ecosystem consists of a community-driven flexibility box (COFY-Box) and tools to support energy services for aggregators, energy service companies, balance responsible parties and suppliers of renewable energy sources. The COFY-Box is based on existing open-source home automation technology with more than 1 600 integrations, resulting in it being the first entirely open, affordable and easy to install smart home energy controller. It will improve electric vehicles, photovoltaics and electric battery control, and focus on the intelligent integration of sustainable thermal storage and heating solutions. A peculiarity of the ecosystem is that it will be completely based on existing open source home automation technology. The COFY-box will be affordable and easy to install. Community tools will enable energy

---

[4] https://cordis.europa.eu/project/id/893240

communities to become real-time asset operators by employing demand and production forecasting algorithms, a dynamic pricing module for implicit DR and an explicit DR solution. To make sure that the ecosystem is viable, REScoopVPP will establish a dedicated legal entity that can bring solutions to the market and provide citizens with a European, community-driven alternative.

CHAPTER 4

Energy community modelling

In this chapter, a model capable to evaluate energy and economical exchanges of a REC is proposed. The aim of the model is the optimal planning of the REC, i.e. to optimize its portfolio in terms of installed generators and storage, based on users' consumption and local source availability. The community is composed of a group of prosumers, shared power plants and storage. In Figure 4.1 the community is depicted within the framework explained in Section 3.1.3. The model and methodology proposed constitute a tool that supports the facilitator in the planning of the community investments.

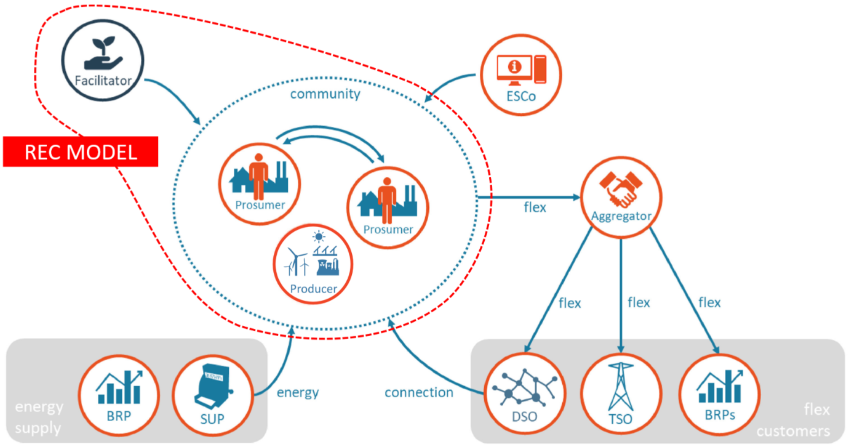


Figure 4.1: *The modelled REC, considered within the framework proposed in [54] (See Section 3.1.3 for more details).*

4.1 Modelling approaches for RECs

In order do deal with energy community modelling and optimal planning three main approaches have been identified in literature. In the first case, the energy community is considered in the form of a community microgrid, the problem is therefore the design of the optimal DER portfolio that meets the specific needs of the community. For the microgrid planning problem many solutions have been proposed in the last decades, in some cases commercial software are also available. Different authors have reviewed software tools to size off-grid power systems [98, 99]. Nowadays, HOMER [100] (a tool originally developed at NREL) is the most used software for the simulation and optimization of off-grid alone hybrid power systems. The design optimization model determines the configuration that minimises life-cycle costs for a particular site application. Another important software is RETScreen [101], a renewable energy decision support and capacity building tool by Natural Resources Canada. It can be used for energy efficiency, renewable energy and cogeneration project feasibility analysis as well as ongoing energy performance analysis. iHOGA by University of Zaragoza [102] is a software tool that exploits genetic algorithm for the multi or mono-objective optimization of hybrid power systems. PVsyst by PV syst SA [103] is a software for the study of stand-alone and grid-connected solar systems. It performs hourly simulation of the plant importing weather data form different sources as well as user-defined data. SAM by NREL [104] is techno-economic software model that makes performance and cost of energy estimation for grid-connected power systems. It runs system simulations over a one-year period, in time steps of 1 h, in order to emulate the performance of the system. It is worthwhile to mention that, among the financial models included in SAM, there are some that could be adapted to specific forms of energy communities (third party ownership, power generation with power purchase agreement, partnership flip or sale leaseback). Besides the commercial tools, others studies are proposing improvements for specific aspects, focusing on the community purposes. In [105] a method based on the Markov model and incorporating the interior-point algorithm is proposed for determining the sizes of PV and wind turbine generators in a community microgrid. An administration committee in this community microgrid conducts this planning with the purpose of reducing electricity expense while the temperature in each home is within the comfort zone. The cost of renewables and community welfare are optimized while the comfort zone of indoor temperature in all homes is maintained using air conditioning systems. [106] proposes a methodology that employs a techno-economic approach to optimize the design of a community DC microgrid by considering multiple criteria including size, cost, and availability. The author of this thesis collaborated to the development of a software package for the robust design of off-grid electric power systems in developing countries named PoliNRG (POLItecnico di Milano - Network Robust desiGn) [107]. The hallmark of the tool is the capability to incorporate the uncertainties on the load forecast into the design steps. It allows considering the uncertainties on daily basis by creating a set of equi-probable daily load curves. Therefore, it defines an area of solution instead of a single deterministic one. The most robust solution is computed as the weighted average of all the obtained optimum points inside the area. Other contributions based on the PoliNRG tool focus on specific aspects. In [108], a sensitivity analysis on a real-life study case is performed, in order to evaluate how each single parameter could affect the optimal sizing of each component of the microgrid (PV and ESS). While, in [11] and [109] the impact of considering different battery models into the tool is analysed. In the first paper, two modeling approaches (analytical and electrical) of lithium-ion battery are considered in the design process of the microgrid, while in the second a comparison between Li-ion and lead acid technologies is proposed.

In the second case, the energy communities are considered from the holistic perspective of the policy maker or the urban planner. Members and DERs are distributed on an wider area and are connected to the public distribution network. The availability of local energy sources and the impact of the community on the existing infrastructure are considered. [67] proposes a framework for establishing an EC in a city district. The aim is to quantify the advantages of optimizing the technology portfolio of ECs regarding cost and carbon emission reduction. The EC is modelled as a multi-energy system with the restriction of satisfying needs for electricity and heat of an energy system. The model is based on two open-source optimization models that have been adapted for this purpose [110]: the focus of the first sub-model is the optimal investment decisions on a high temporal level, the second sub-model address the optimal deployment of energy grids on a building level. The methods developed allow urban planners to analyze city districts of interest towards sustainability and costs. [68] investigates the potential of urban building clustering as a small-scale smart community solution. The participants cooperate by utilizing an Internet of Things (IoT)-based platform, in order to increase their energy self-sufficiency and to decrease the city's CO2 emissions, so that an optimum utilization of the energy generated by local renewables is achieved.

In the third case, the energy communities are considered as group of users, not necessarily within a microgrid, that invest in shared infrastructure (mostly on solar applications). This case is the most relevant for the purpose of this chapter, but it is also the less developed. In [111], the authors highlight that there are more than fifty commercial solar PV design and simulation tools, but only a few tools support, with limitations, the simulation, design, and analysis of community shared solar applications. The authors of [112] developed a probabilistic model for the definition of the optimal portfolio of a community solar. The objectives of the study include identifying the sources of uncertainties in PV valuation, developing a probabilistic model that incorporates the identified uncertainties into portfolios, and providing potential investors in community solar with realistic financial indicators. A set of optimized portfolios are considered: (i) portfolio with equal number of panels for each house (baseline portfolio), (ii) portfolio with maximum electricity output, (iii) portfolio with minimum risk, (iv) portfolio with highest risk-adjusted performance. In [111] two scenarios of a solar community composed by a set of consumption units are compared: in the first one, each unit is connected to a small PV system, in the second scenario, all units are connected to a large PV system. In this case, the community-scale PV system is connected to the community as a whole and distributed evenly among the individual end-users. The size and layout placement of the community shared solar energy system is identified by the optimisation engine. A limitation of these studies is that the entire community is considered as a whole unit, and the energy consumption, generation, and respective grid interaction measures are aggregated. This simplification has been motivated in [111] by referring to the novelty of community shared solar applications and the lack of knowledge on smart-metering infrastructure, as well as legal implications of such systems[1]. Nevertheless, nowadays the European countries have specific legal frameworks and, where the smart-metering infrastructure is ready, there is the need of introducing this aspect. Indeed, in the model presented in this thesis, a further step is proposed and the evaluation of the energy fluxes of each user is considered. In this way it is possible to consider the different economic value of self-consumed energy (i.e. produced and consumed by the same unit) and shared energy (i.e. produced and consumed within the REC, but in different locations.)

4.1.1 Introductory work on microgrid planning

The author actively contributed to the development of the tool PoliNRG, already introduced in the previous paragraphs, for the optimal microgrid planning. Therefore, the methodology behind the tool represented a reference for the development of the REC model presented in this thesis. Within PoliNRG, the operations of the specific off-grid power system are simulated for the entire lifetime of the microgrid. The simulation engine investigates different plant configurations considering the set of possible lifetime load profiles and the RES profiles.

In order to manage the microgrid robust design, a heuristic optimization method has been developed. This method is able to find the optimal solution according to the techno-economic criterion, simulating the microgrid operation in an iterative way, to test different combinations of components' sizes (PV and BESS). The optimal solution is the specific combination of components' sizes which have the minimum net present cost while fulfilling the desired level of loss of load probability. The heuristic optimization method is based on a two steps algorithm:

1. Definition of the searching space, i.e. the ranges of PV and BESS to be investigated.
2. Searching of the optimal combination within this searching space through an iterative process.

As regards the second step, a heuristic procedure based on the imperialistic competitive algorithm [113] is used to look for the optimal combination in agreement with the techno-economic criterion. The method employs an iterative process that progressively explore the searching space. Two parameters characterize the algorithm: the number of combinations of PV-BESS that have to be evaluated in each iteration, and the number of combinations that after each simulation of the lifetime operations are considered as the best ones.

The methodology of PoliNRG can not be applied to the case of ECs for two main reasons. The first one is that the load and the generators of REC are located in different places and there is the need to distinguish between shared energy and self-consumed one. The second reason is that the heuristic procedure adopted in PoliNRG for the research of the optimum portfolio has been tested only in a two dimensional research space. In the case of RECs, the number of independent variables is equal to the number of possible distributed generators and storage. Considering the increased complexity of the problem, the REC model proposed in this thesis has been based on a MILP approach.

---

[1] The article was published in 2018.

4.2 Overall structure of the proposed REC model

The energy community is supposed to be composed by a set of users and a set of generators. Each passive user is connected to the grid by mean of a specific Point Of Delivery (POD), while generators can be connected to a dedicated POD as well as to one of the POD of the passive users. Regardless of the connection points, it is assumed that the REC owns generators and storage within the community. The assumption is in line with [67]. Given this configuration, the energy consumed by each user can be categorised in three different ways (Figure 4.2):

- Self-consumed - It is produced and consumed under the same POD;
- Shared - It is produced by a generator of the community and it is consumed by users of the community connected to different PODs;
- Bought - It is bought from the market if the production of the REC's generators is not enough to satisfy the request of passive users.

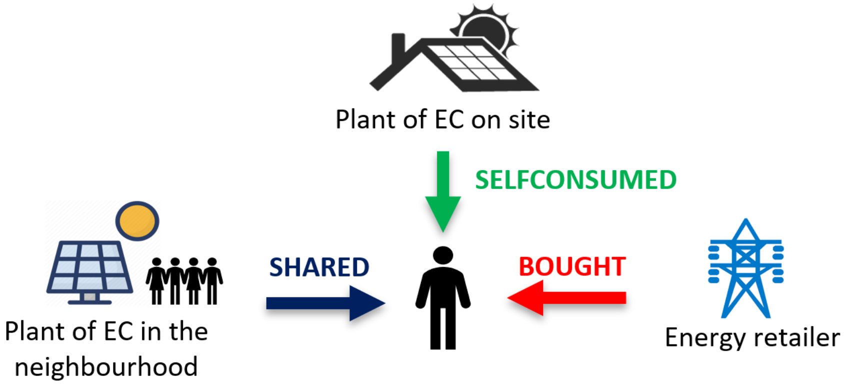


Figure 4.2: *Possible origin of the energy consumed by the REC's members.*

The methodology considers a base case in which there are no generators owned by the community and the overall energy is bought from the market. Starting from this, it is possible to consider costs, revenues and savings obtained with the installation of a community portfolio of generators and Energy Storage System (ESS). Self-consumed energy generates savings that are the sum of two contributions:

1. Saving from the energy that was originally bought and, after the installation of the REC's generators, is produced with the community's plants;
2. Saving from the tariff components that are not due thanks to a minor usage of the grid. This term is called in some technical documents Self-Consumption Saving Index (SCSI) [114].

Also the shared energy can generate the same types of savings, but in this case the second term is called Shared Energy Saving Index (SESI) and it is lower than SCSI. This is justified considering a cost-reflective nature of the tariff: energy bought from the market (potentially) uses the entire energy system of a country, energy locally shared minimize the usage of the transmission infrastructure but it still uses the distribution network, finally, energy self-consumed does not use neither transmission network nor the distribution one.

The cited savings are related to the (theoretically) cost-reflective structure of the electricity tariff. In addition to these, the model considers the revenues that can be obtained from economical incentives. Indeed, given the high importance of energy sharing in the REC configuration, a possible way to promote the deployment of the energy communities is to give and economical incentive based on shared energy (e.g see the Italian case presented in section 2.2.2). Finally, the energy produced but not consumed can be sold on the market, generating additional revenues.

It is clear that the values of the savings, incentive and revenues depend on the tariff regulation in place, on the presence of incentives and the market conditions. It is possible, adapting these values, to apply the model to different countries and scenarios. The energy balances are evaluated hourly to quantify the energy produced, self-consumed, shared, bought and sold from the single users' and the community's perspectives. The installation of new generators for the community is evaluated, and the relative economical revenues provide different incomes for the community. Since the benefits are mainly given by the energy shared and self-consumed, there will be an optimal choice for the type and size of the power plants, given the local availability. Operational cost of the generators are considered, and also some administration cost are taken into account. The complete model of the renewable energy community and the investment in new power plants is detailed in the following paragraphs.

4.3 Proposed REC model

Mathematically, the REC model has been based on the following set of parameters, variables and constraints.

4.3.1 Sets

- M: Members of the community (element i);
- G: Available generators (element j);
- T: Time steps within each single year for which the energy balances are computed (element t);
- Y: Years in the expected lifetime for which the yearly balance is repeated, and the economical flows are evaluated (element y).

4.3.2 Parameters

- $\hat{E}_i^{load}(t)$: Reference yearly load profile for user i [kWh];
- $e_j(t, y)$: Energy produced by plant j in the time step t normalized for the rated power [kWh/kW_{rated}];
- Rel_{ij}: Relationship between users and generators. 1: user i and generator j are under the same POD. 0: user i and generator j are under different PODs;

- $\hat{PE}^{\rightarrow market}(t)$: Reference yearly price profile for the energy sold to the market [€$/kWh$];
- $\hat{PE}^{\leftarrow market}(t)$: Reference yearly price profile for the energy bought from the market [€$/kWh$];
- P_j^{max}: Maximum rated power for generator j [kW_{rated}];
- $Capex_j$: Investment cost for generator j [€$/kW_{rated}$];
- $Opex_j$: Operational cost for generator j [€$/kW_{rated}/year$];
- ESS_{cap}^{max}: Maximum capacity of the ESS [kWh];
- EPR: Minimum Energy to Power Ratio [h][2];
- SOC_{min}: Minimun state of charge of the ESS;
- $Cycles_{max}$: Maximum number of cycle for the ESS;
- $Capex_{ESS}$: Investment cost of the ESS [€$/kWh_{rated}$] ;
- $Opex_{ESS}$: Operational cost of the ESS [€$/kWh_{rated}$];
- Rep_{ESS}: Replacement cost of the ESS [€$/kWh_{rated}$];
- EC_{cost}: Administrative cost for the energy community [€$/year$];
- η_{CH}: Charge efficiency;
- η_{DIS}: Discharge efficiency;
- Inc: Incentive on shared energy [€$/kWh$];
- EL: Expected life of the investments [$year$];
- DR: Discount rate or return that could be earned in alternative investments [$\%$];
- $SESI$: Shared Energy Saving Index. Saving achieved thanks to energy sharing [€$/kWh$];
- $SCSI$: Self-Consumption Saving Index. Saving achieved thanks to self-consumption [€$/kWh$];
- $load_{trend}$: Yearly growth of the load [$\%/year$];
- $price_{trend}$: Yearly growth of the market price [$\%/year$];
- $\%_{ded}$: Percentage of the investment expense that can be deduced from taxes;
- $year_{ded}$: Number of years in which the deduction has to be split.

---

[2] The power limit of the ESS can be expressed in term of its capacity by mean of the EPR. This index is defined as the capacity over the maximum power of the ESS. Physically, it is the minimum time necessary to completely charge or discharge the ESS.

4.3.3 Variables

- P_j: Rated power of generator j $[kW]$;
- ESS_{cap}: Capacity of the centralized energy storage system $[kWh]$;
- $E_i^{load}(t,y)$: Energy consumed by member i for each year y $[kWh]$
- $E_i^{prod}(t,y)$: Energy produced by the sum of generators located under the same POD of user i $[kWh]$;
- $E_i^{selfcons}(t,y)$: Energy self-consumed by user i $[kWh]$;
- $E_i^{surplus}(t,y)$: Energy surplus of user i $[kWh]$;
- $E_i^{deficit}(t,y)$: Energy deficit of user i $[kWh]$;
- $E_{ec}^{off}(t,y)$: Energy offered from the members of the community that have a surplus $[kWh]$;
- $E_{ec}^{req}(t,y)$: Energy required from the members of the community that have a deficit $[kWh]$;
- $E_{ec}^{sharedRT}(t,y)$: Energy shared in real time within the community $[kWh]$;
- $E_{ec}^{shared}(t,y)$: Energy shared within the REC considering also energy provided by the ESS $[kWh]$;
- $E_{ec}^{\leftarrow market}(t,y)$: Energy bought from the market $[kWh]$;
- $E_{ec}^{\rightarrow market}(t,y)$: Energy sold to the market $[kWh]$;
- $E_{ec}^{stored}(t,y)$: Energy stored in the ESS at time t (initial instant of the time window) $[kWh]$;
- $E_{ec}^{\leftarrow ESS}(t,y)$: Energy withdrawn from the ESS $[kWh]$;
- $E_{ec}^{\rightarrow ESS}(t,y)$: Energy injected into the ESS $[kWh]$;
- $PE^{\rightarrow market}(t,y)$: Price of the energy sold to the market for each year y $[€/kWh]$;
- $PE^{\leftarrow market}(t,y)$: Price of the energy bought from the market for each year y $[€/kWh]$;
- $Inv(y)$: Total investment cost [€];
- $Cost(y)$: Total operational cost [€];
- $Cost_{ESSrep}(y)$: Equivalent cost for the energy storage replacement [€];
- $Sav(y)$: Saving obtained self-consuming/sharing energy [€];
- $Rev(y)$: Revenues obtained selling the surplus to the market or by mean of the incentives [€];
- $Fin_{inc}(y)$: Financial incentives for the community [€].

4.3.4 Constraints: single users energy balances

The energy consumed by each user i in the expected lifetime is evaluated based on the load growth trend.

$$E_i^{load}(t, y) = \hat{E}_i^{load}(t) \cdot (1 + (y - 1) \cdot load_{trend}) \tag{4.1}$$

The energy produced by the generators in the availability of user i (i.e. located under the same POD) is computed as:

$$E_i^{prod}(t, y) = \sum_{j \in G} e_j(t, y) \cdot P_j \cdot Rel_{ij} \tag{4.2}$$

where P_j is limited by the maximum rated power for generator j.

$$P_j \leq P_j^{max} \tag{4.3}$$

Hour by hour, the energy that is self-consumed by user i is the minimum between its load and the energy produced by the generators in its availability.

$$E_i^{selfcons}(t, y) = min(E_i^{prod}(t, y), E_i^{load}(t, y)) \tag{4.4}$$

Therefore, the energy surplus for user i is the difference between the energy produced and the energy self-consumed.

$$E_i^{surplus}(t, y) = E_i^{prod}(t, y) - E_i^{selfcons}(t, y) \tag{4.5}$$

On the other hand, the energy deficit for user i is the difference between the load and the energy self-consumed.

$$E_i^{deficit}(t, y) = E_i^{load}(t, y) - E_i^{selfcons}(t, y) \tag{4.6}$$

In some conditions it may be forbidden to self-consume energy produced by community plants[3]. In this case, it could not be possible to self-consume the energy produced and eq. 4.4 is substituted with:

$$E_i^{selfcons}(t, y) = 0 \; \forall t \; \forall y \tag{4.7}$$

As a consequence, eq. 4.5 and eq. 4.6 become:

$$E_i^{surplus}(t, y) = E_i^{prod}(t, y) \tag{4.8}$$

$$E_i^{deficit}(t, y) = E_i^{load}(t, y) \tag{4.9}$$

---

[3] Allow members' self-consumption could increase the revenue of the community (given that SCSI is higher that SESI), but at the same time it requires a more complex way to redistribute the economical benefits, that may be unfairly concentrated on the users that self-consume the energy produced by the REC's generators.

4.3.5 Constraints: energy community energy balance

The amount of energy that is offered to the energy community from the members that have a surplus at time t can be evaluated as:

$$E_{ec}^{off}(t,y) = \sum_{i}^{N} E_i^{surplus}(t,y) \tag{4.10}$$

The amount of energy that is requested to the energy community from the members that have a deficit at time t can be evaluated as:

$$E_{ec}^{req}(t,y) = \sum_{i}^{N} E_i^{deficit}(t,y) \tag{4.11}$$

In general, these two values are different and it is not possible for the community to manage all the energy required and offered by the users at each time step.

The amount of energy the community can collect and redistribute in the same hour is equal to the minimum for each instant between the energy offered to the community and the energy request to the community. We define this quantity as energy shared in real time.

$$E_{ec}^{sharedRT}(t,y) = \min(E_{ec}^{off}(t,y), E_{ec}^{req}(t,y)) \tag{4.12}$$

Energy Storage System

In the case the community does not have an energy storage system, the energy offered to the community but not requested by other users is sold to the market.

$$E_{ec}^{\rightarrow market}(t,y) = E_{ec}^{off}(t,y) - E_{ec}^{sharedRT}(t,y) \tag{4.13}$$

The energy requested by community members, not provided from other users, is bought from the market.

$$E_{ec}^{\leftarrow market}(t,y) = E_{ec}^{req}(t,y) - E_{ec}^{sharedRT}(t,y) \tag{4.14}$$

The shared energy is equal to energy shared in real time.

$$E_{ec}^{shared}(t,y) = E_{ec}^{sharedRT}(t,y) \tag{4.15}$$

In the case a centralized Energy Storage System (ESS) is considered, the amount of energy managed by the community can increase because the system can store the surplus of energy instead of selling it. Other than the energy shared in real time, a more general definition of shared energy can be specified as the energy consumed by the users coming from the community generation or from the ESS. The model of the ESS is technologically neutral and, depending on the value assigned to the parameters, can represent different types of storage (e.g. electrochemical, hydroelectric, compressed air, etc.).

The maximum capacity of the ESS is:

$$ESS_{cap} \leq ESS_{cap}^{max} \tag{4.16}$$

The maximum charging power for the energy storage system depends on the Energy to Power Ratio. The maximum energy that can be stored at time step t is:

$$E_{ec}^{\rightarrow ESS}(t,y) \leq \frac{ESS_{cap}}{EPR} \cdot 1h \tag{4.17}$$

The maximum energy that can be withdrawn from the the ESS at time step t:

$$E_{ec}^{\leftarrow ESS}(t,y) \leq \frac{ESS_{cap}}{EPR} \cdot 1h \tag{4.18}$$

The amount of energy stored into the system is defined with the following constraints:

$$E_{ec}^{stored}(t,y) = \begin{cases} E_{ec}^{stored}(t-1,y) + E_{ec}^{\rightarrow ESS}(t,y) \cdot \eta_{CH} - \frac{E_{ec}^{\leftarrow ESS}(t,y)}{\eta_{DIS}} & \text{if } t > 1 \\ E_{ec}^{stored}(8760,y) + E_{ec}^{\rightarrow ESS}(8760,y) \cdot \eta_{CH} - \frac{E_{ec}^{\leftarrow ESS}(8760,y)}{\eta_{DIS}} & \text{if } t = 1 \end{cases} \tag{4.19}$$

In order to not increase the computational cost, the model of the ESS considers only SOC and power limitations, while other elements (e.g aging factors and the capacity reduction over time) are not considered. The energy stored within the battery has to respect SOC limits.

$$E_{ec}^{stored}(t,y) \leq ESS_{cap} \tag{4.20}$$

$$E_{ec}^{stored}(t,y) \geq ESS_{cap} \cdot SOC_{min} \tag{4.21}$$

The energy sold to the market is the energy offered to the community that is not shared in real time and not stored.

$$E_{ec}^{\rightarrow market}(t,y) = E_{ec}^{\leftarrow off}(t,y) - E_{ec}^{sharedRT}(t,y) - E_{ec}^{\rightarrow ESS}(t,y) \tag{4.22}$$

The energy bought from the market is the energy requested by the community members not provided from other users in real time nor from the storage system.

$$E_{ec}^{\leftarrow market}(t,y) = E_{ec}^{req}(t,y) - E_{ec}^{sharedRT}(t,y) - E_{ec}^{\leftarrow ESS}(t,y) \tag{4.23}$$

The energy that is evaluated as shared is equal to the energy shared in real time plus the extra energy provided from the storage.

$$E_{ec}^{shared}(t,y) = E_{ec}^{sharedRT}(t,y) + E_{ec}^{\leftarrow ESS}(t,y) \tag{4.24}$$

4.3.6 Constraints: cash flow evaluation

The investment is equal to:

$$Inv = \sum_{j \in G} P_j \cdot Capex_j + ESS_{cap} \cdot Capex_{ESS} \tag{4.25}$$

For each year y the net cash flow is evaluated as:

$$CF(y) = Sav(y) + Rev(y) + Fin_{inc}(y) - Cost(y) \tag{4.26}$$

The net present value of the investment is then calculated as:

$$NPV = -Inv + \sum_{y=1}^{EL} \frac{CF(y)}{(1 + DR)^y} \tag{4.27}$$

The savings for each year y are the sum of the instantaneous savings due to self-consumption of each member i and the saving due to shared energy in the considered year.

$$\begin{split} Sav(y) = \sum_{t \in y} \Bigg(\sum_{i \in M} \Big(E_i^{selfcons}(t) \cdot (PE^{\leftarrow market}(t,y) + SCSI) \Big) \\ + E_{ec}^{shared}(t) \cdot (PE^{\leftarrow market}(t,y) + SESI) \Bigg) \end{split} \tag{4.28}$$

The revenues at year y come from the energy sold to the market in each time step or from the incentive.

$$Rev(y) = \sum_{t \in y} \big(E_{ec}^{\rightarrow market}(t) \cdot PE^{\rightarrow market}(t,y) + E_{ec}^{shared}(t) \cdot Inc \big) \tag{4.29}$$

The market price profiles used in Eq. 4.28 and Eq. 4.29 are evaluated for the entire lifetime depending on the expected growth or decrease.

$$PE^{\leftarrow market}(t,y) = \hat{PE}^{\leftarrow market}(t) \cdot (1 + (y-1) \cdot price_{trend}) \tag{4.30}$$

$$PE^{\rightarrow market}(t,y) = \hat{PE}^{\rightarrow market}(t) \cdot (1 + (y-1) \cdot price_{trend}) \tag{4.31}$$

In some particular cases of the Italian context there is the possibility to deduct a part of the investments in photovoltaic power plants from the taxes of the years following the investment. This financial incentive can be treated as a yearly revenue from year 1 to $year_{ded}$ and can be evaluated as:

$$Fin_{inc}(y) = \begin{cases} \frac{\%_{ded} \cdot Inv}{year_{ded}} & \text{if } 1 \leq y \leq year_{ded} \\ 0 & \text{if } y > year_{ded} \end{cases} \tag{4.32}$$

The total cost at year y is:

$$Cost(y) = \sum_{j \in G} (P_j \cdot Opex_j) + ESS_{cap} \cdot Opex_{ESS} + Rep_{ESS}(y) + EC_{cost} \tag{4.33}$$

where the replacement cost of the battery is computed with the following equation:

$$Cost_{ESSrep}(y) = \frac{\sum_t \left(E_{ec}^{\rightarrow ESS}(t,y) \cdot \eta_{CH} + \frac{E_{ec}^{\leftarrow ESS}(t,y)}{\eta_{DIS}} \right)/2}{Cycles_{max} \cdot (1 - SOC_{min})} \cdot Rep_{ESS} \tag{4.34}$$

where the numerator accounts for the number of equivalent cycles the ESS executes in year y (it is divided by 2 to consider the roundtrip definition of the cycle), and the denominator accounts for the maximum number of cycles the ESS could perform before its replacement. In general, the effect of battery degradation is twofold: it decreases the ESS performances, and it requires to replace the battery after some years. The proposed model does not account for the worsening of the performances. It means that the efficiencies η_{CH} and η_{DIS} are constant and the useful range of state of charge $(1 - SOC_{min})$ does not face any reduction. Nonetheless, the model accounts for the cost of replacement of the ESS. Specifically, for each year y, the cost of replacement is allocated proportionally to the number of equivalent cycles performed in that year. In this way, instead of assigning the entire cost of replacement to the single year in which the ESS is replaced, it is distributed on the useful life. The methodology is aligned with the one adopted in Homer [100] for computing the battery wear cost.

4.3.7 Blocks of years

The evaluation of more than one year is useful to take into account the variation of load, production and prices over time. Nevertheless, it increases the computational effort required to evaluate the variables of the model. For this reason, a simplified approach is used to represent blocks of years y_{bk} with common characteristics, instead of single years y with unique values. To apply these change, all the variables that are function of y are converted in function of y_{bk}. The expected lifetime EL (i.e. the number of yearly energy balances to be computed) becomes EL_{bk}. The ratio EL/EL_{bk} has to be an integer number, and it represents the number of years for each considered block.

The load profiles of each users (Eq. 4.1) has to be updated as follow:

$$E_i^{load}(t, y_{bk}) = \hat{E}_i^{load}(t) \cdot (1 + (y_{bk} - 1) \cdot load_{trend}^{bk}) \tag{4.35}$$

where $load_{trend}^{bk}$ is computed in order to keep the same overall consumption over the entire lifetime. It can be demonstrated that this happens when:

$$load_{trend}^{bk} = load_{trend} \cdot \frac{EL - 1}{EL_{bk} - 1} \tag{4.36}$$

The same approach is adopted to define the value of the market prices as defined in Eq. 4.30 and Eq. 4.31 according to their growing trend. The price trend as to be updaded as:

$$price_{trend}^{bk} = price_{trend} \cdot \frac{EL - 1}{EL_{bk} - 1} \tag{4.37}$$

Finally, the evaluation of the Net Present Value (NPV) of the investment has to be updated as:

$$NPV = -Inv + \sum_{y_{bk}=1}^{EL_{bk}} \left(CF(y_{bk}) \cdot \sum_{y \in y_{bk}} \frac{1}{(1+DR)^y} \right) \tag{4.38}$$

4.3.8 Optimization

The optimization provides the community with the indication of the generators and storage to install to maximise the economical value of the investment. To achieve this, the maximisation of the net present value of the investment is the selected objective function. In this way, the overall cash flow of the energy community is evaluated.

4.4 Software implementation

To create a tool that is as reusable as possible, the optimization procedure has been implemented in a software architecture that is reported in Figure 4.3. The core of the software is the model of the energy community written in Pyomo, a Python-based, open-source optimization modelling language, and the used solver is Gurobi. The model inputs are divided into two categories. The first ones are specific to the case study under consideration, which must be included in a predefined excel file. These are related to the number of users and characteristics of each one, the energy sources availability in the area and the economic variables for the financial evaluation. The latter are inputs that can be considered common to several case studies and that have been previously entered into a MongoDB database. The following annual profiles with hourly time step are integrated into the database.

- Load profiles. The dataset has been created with load profiles of different type of users. Some profiles comes from real measurements while others have been generated with the tools LoadProGen [115].
- Production profiles of the available energy sources. Each possible generator of the community has a specific profile, normalized by its rated power. Each profile could be inserted into the database, but standard profiles are provided. For PV generators there is no need to manually add the profile. When the software identifies a PV among the inputs of the case study, it automatically calls a public API provided by PVgis [116] and the production profile for the specific coordinates, tilt and orientation is downloaded. The profiles are then stored also in the local database to avoid repeating API call in case of multiple executions. Polycrystalline silicon are chosen as PV technology and system losses were set at the reference value of 14% and a fixed, free-standing mounting position was chosen.
- Market profiles of the price of the energy on the wholesale market.

4.5 Test cases

In order to validate the model developed, a reference case study has been built, simulating a small scale REC formed by a local group of domestic users. The model is used to evaluate the economic feasibility of forming a REC in two different scenarios: considering only shared energy or including also self-consumption.

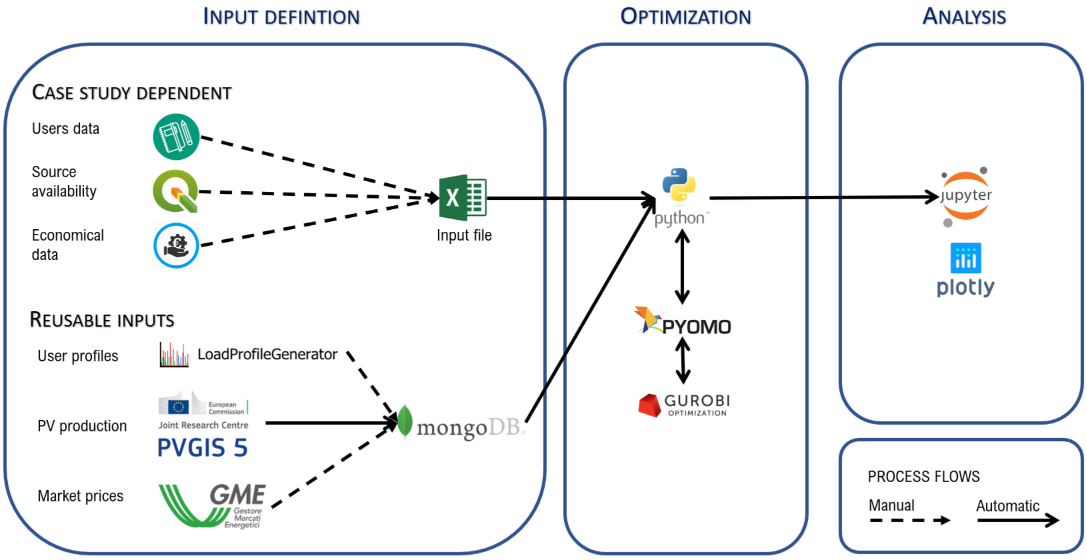


Figure 4.3: *Software implementation of the REC optimization procedure.*

4.5.1 Users consumption

In the case study, a group of ten households is considered. They have been created taking into account the data about the average structures of the Italian family, taken by the yearly report about family and population of the Italian institute for statistics (ISTAT) [117]. The statistic identified 30% of Italian households consisting in single people, another 30% of household made by a couple and the remaining 40% of families with one or more children. The electrical loads have been selected among the ones modelled using the tool named Load Profile Generator (LPG) [115]. LPG provides the electric, heat and water consumption in households, which comprises different kinds of devices that create the demand. The households are populated by individuals, whose traits, such as habits or professions, are customisable. LPG performs a behavioural simulation of the individuals inside the households, replicating their daily routines and devices utilization, to create annual electric curves. The default consumption curves take into account national holidays, vacations and different locations in Germany. In order to have electric curves compatible with Italy, model's parameters have been modified using the data available in the database of the Odyssee-Mure, a European project financed by the European Commission that collects data about energy consumption and energy efficiency from European national energy agencies [118]. In particular, the appliances have been changed to a Mediterranean Country, with the introduction of air-conditioning and gas heating instead of electric heating. The average energy consumption per m2 in dwellings has been shifted to Italian standards and the space heating has been adapted to the Italian climate. Lastly, public holidays and school vacations have been contextualized to the Italian calendar. The users' typologies and annual demands are summarized in Table 4.1.

Table 4.1: *Typology of the users and annual demand.*

ID_user	Typology	Annual Load [kWh]
User 1	Working couple, no kids	4370
User 2	Working couple with one kid	3530
User 3	Single with work	1817
User 4	Student	2201
User 5	Senior couple	3021
User 6	Single with one kid	1089
User 7	Senior single	2712
User 8	Working couple with two kids	3346
User 9	Working couple with three kids	4257
User 10	Couple with kid, one parent at home	4560

4.5.2 Source availability

The REC have the possibility to install some PV capacity on the top of the users' roofs. Each roof is characterised by specific inclination and orientation, that influences the electricity production from the panels. Table 4.2 summarizes the main features of the households for the case study, such as their geographical coordinates and the slope, orientation and maximum capacity of their PV system depends on the characteristics of their roofs. The slope of the PV modules is the angle between the horizontal plane and the PV module, and the azimuth (orientation) of PV modules is the orientation of the PV system with respect to the South in which 180 is North, -90 is East, 0 is South and 90 is West. The average investment cost for domestic PV systems between 2 and 10 kW settles around 1,550 €/kW (including VAT) with observed thresholds of 1,330 and 1,740 €/kW, according to the joint statistics for Italy by GSE, RSE and IEA [18]. On the other hand, maintenance costs for domestic PV systems are more dependant on the contract stipulated with the contracting company that installs the PV, so a clear statistic was not available by national agencies. Anyways, a JRC report sets the maintenance costs equal to 2% of the investment costs [19]. Considering these information, the capex of each PV are assumed 1550 €/kW and the opex are assumed 31 €/kW/year.

Table 4.2: *Potential generator availability for the energy community.*

ID_gen	ID_user	latitude	longitude	PV slope	PV orientation	Pmax [kW]
PV_1	User 1	45.699019	9.001100	10	East	5.0
PV_2	User 2	45.698533	9.000239	10	West	5.0
PV_3	User 3	45.698966	9.000496	10	North	3.0
PV_4	User 4	45.698456	9.001077	10	South	10.0
PV_5	User 5	45.698818	9.000378	35	South	10.0
PV_6	User 6	45.698445	9.001062	35	North	3.0
PV_7	User 7	45.698497	9.000415	35	East	5.0
PV_8	User 8	45.698633	9.000952	35	West	5.0
PV_9	User 9	45.698818	9.000099	35	South	10.0
PV_10	User 10	45.698680	9.000319	10	West	10.0

4.5.3 Other parameters

The lifetime of the investment is supposed to be equal to 20 years, the actualization factor is equal to 4%. Tax deduction is considered for 50% of the investment cost, during the first 10 years of operation [119]. The incentive on shared energy SE_{inc} is based on the actual value for collective self-consumption in the Italian transitional regime (see Section 2.2.2). Self-consumption saving index $SCSI$ is based on the value indicated in [114]to which are summed excise and 10% VAT. Shared energy saving index may depend on the tariff structure of the connected users, but it must be lower than $SCSI$. The administrative cost are considered negligible for the initiative (i.e. the low number of users allows a basic management, that can be done by volunteers). The load is expected to grow in the next years due to the impact of the electrification trend in the domestic sector (mainly for mobility and heating) [120]. The price of the energy is expected to decrease, according to the trend of the last ten years[4] on the Italian Day-Ahead Market [121]. The possibility to install an energy storage system up to 200 kWh is considered. In Table 4.3 the values of the economical parameters are detailed, while in Table 4.4 the values used to detail the battery model are reported. They refer to an electrochemical storage, based on lithium-ion cells.

Table 4.3: *Economical data.*

Name	Value	Unit	Description
SE_{inc}	100	[€/MWh]	Incentive on shared energy
$SCSI$	80	[€/MWh]	Self-consumption saving index
$SESI$	40	[€/MWh]	Shared energy saving index
$Cost_{adm}$	0	[€/user/year]	Administrative cost of the REC
$load_{trend}$	+2%	[%/year]	Yearly growth of the load profiles
$price_{trend}$	-2%	[%/year]	Yearly growth of the price profiles

Table 4.4: *Storage data.*

Name	Value	Unit	Description
$Cost_{ESS}$	200	[€/kWh]	Storage investment
Rep_{ESS}	100	[€/kWh]	Storage replacement cost
ESS_{cap}^{max}	200	[kWh]	Max storage size
EPR	2	[h]	Energy to power ratio
η_{CH}	0.95	[-]	Storage eta CH
η_{DIS}	0.95	[-]	Storage eta DIS
SOC_{min}	0.2	[-]	Minimum state of charge
$Cycle_{max}$	5000	[-]	Max cycles

Scenarios

Since the SCSI is higher than SESI, two different scenarios have been evaluated, each one correspond to a different strategy of the REC. In the first one, the power plants of the REC are used only to share energy and self-consumption is not considered (scenario

---

[4] The trend has been computed based on data from 2009 to 2019, considering that 2020 market results were strongly impacted by the effect of the pandemic.

"Sharing only"). This means that the power produced by the set of generators of the community can be summed, indeed there are no differences in managing the energy of the different plants. Actually, it is exactly like having a single generator, but divided into smaller ones. This solution is easy to manage, but the REC is not taking advantage from the higher saving achievable with self-consumption. In the second scenario, each user connected to the POD of a generator of the REC can self-consume the energy produced by the generator (scenario "Self-consumption priority"). The surplus of the single user is shared with the other members of the community. This allows to take advantage from the most convenient tariff for self-consumed energy. The drawback of this option is that the single members are taking advantage from the energy produced with the shared power plants and therefore the REC has to consider the option of redistributing the benefit also to other members. Since another strategy that the REC could consider is to evaluate the installation of a battery energy storage system, a total of four scenarios are evaluated:

1. Scenario 1 - Sharing only, no BESS;
2. Scenario 2 - Sharing only with centralized BESS;
3. Scenario 3 - Self-consumption priority, no BESS;
4. Scenario 4 - Self-consumption priority with centralized BESS.

4.5.4 Results

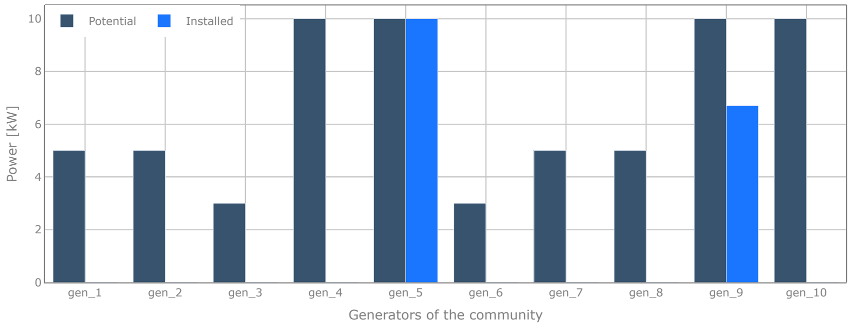
The optimization of the community led to the PV and BESS capacities summarized in Table 4.6 and Figure 4.4.

Name	Scenario 1	Scenario 2	Scenario 3	Scenario 4
PV_1 [kW]	0	0	2.13	2.20
PV_2 [kW]	0	0	0.47	0.65
PV_3 [kW]	0	0	0.27	0.26
PV_4 [kW]	0	3.99	0.76	1.09
PV_5 [kW]	10.00	10.0	6.37	10.0
PV_6 [kW]	0	0	0.00	0
PV_7 [kW]	0	0	1.19	0.84
PV_8 [kW]	0	0	0.44	0.49
PV_9 [kW]	6.70	10.0	5.64	10.0
PV_10 [kW]	0	0	1.53	1.86
ESS [kWh]	0	63.0	0	64.5

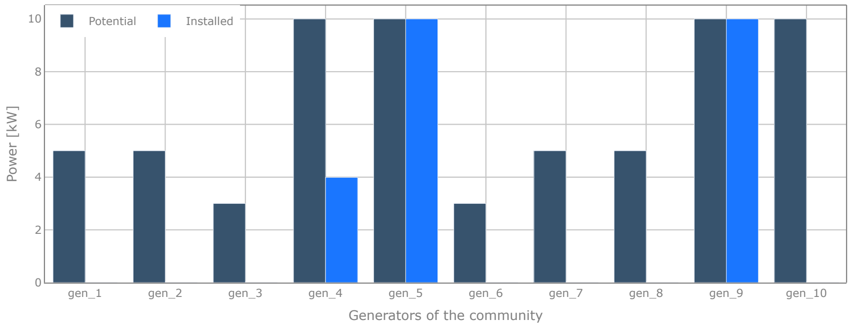
Table 4.5: *Optimal portfolio for each considered scenario.*

Scenarios without ESS

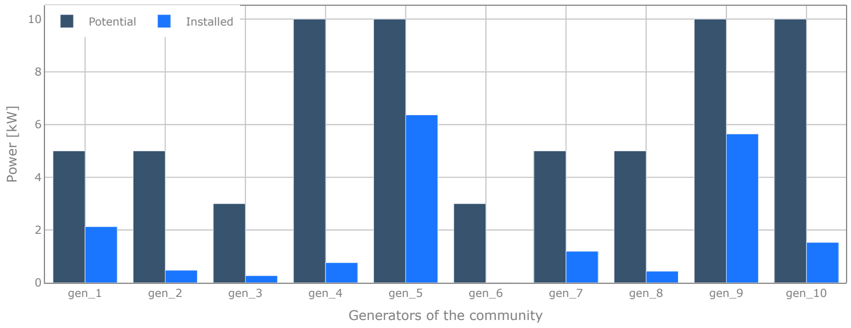
For a better analysis of the results, a comparison between the scenarios without ESS is proposed (Scenario 1 and Scenario 3). When only shared-consumption is considered (Scenarios 1) the optimal solution includes two centralized generators: PV_5 (10 kW) and PV_9 (6.7 KW). In the case of PV_5, the optimal power is equal to the entire availability and the energy source is completely exploited. The average size of the



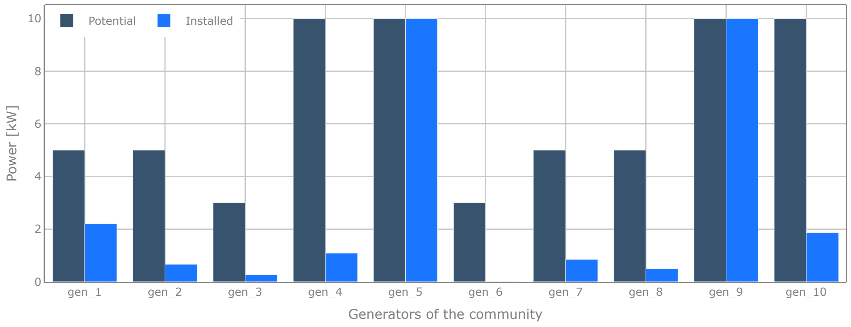
(a) Scenario 1



(b) Scenario 2



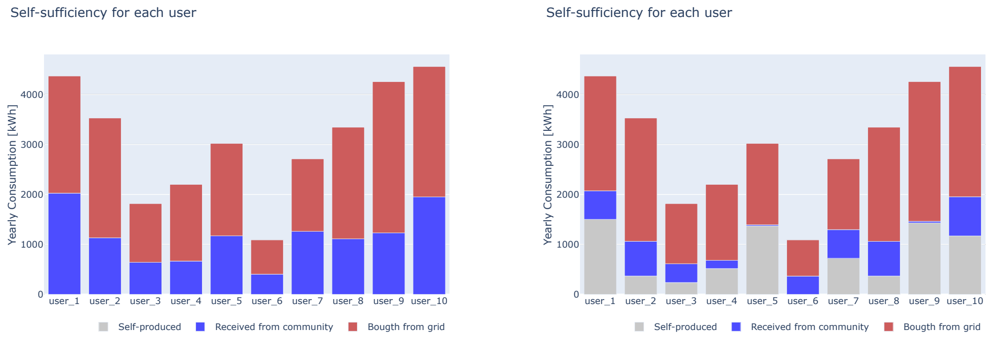
(c) Scenario 3



(d) Scenario 4

Figure 4.4: *PV sizing of the optimal REC portfolio for different scenarios.*

generators is 8.35 kW and the total installed power is 16.7 kW. The energy produced by the community plants and shared with the community members covers 37.5% of the REC's consumption, while the 62.5% of the energy is bought from the market. On the other hand, when self-consumption is considered (Scenario 3) the optimal portfolio includes a larger number of small PV power plants. The average size of the generators is 1.88 kW and the aggregated size of the portfolio is higher 18.8 kW (+12% with respect to Scenario 1). The only energy source not included in the optimal portfolio is PV_6, and this can be easily explained considering that the load of the user 6 is the lowest (1,080 kWh/year) and the rooftop surface availability is the worst (North oriented with high slope). All the other rooftops are included in the optimal solution, even if the rated power never reaches the limits of the maximum power availability. In this case, the energy self-consumed is 24.9% of the total energy request of the community, but an additional portion of the load (13.8%) is covered with shared energy. The total self-sufficiency of the community is therefore 38.7%, a little bit higher than Scenario 1. The origin of the energy consumed by each user is shown in Figure 4.5.



(a) Shared only (Scenario 1)

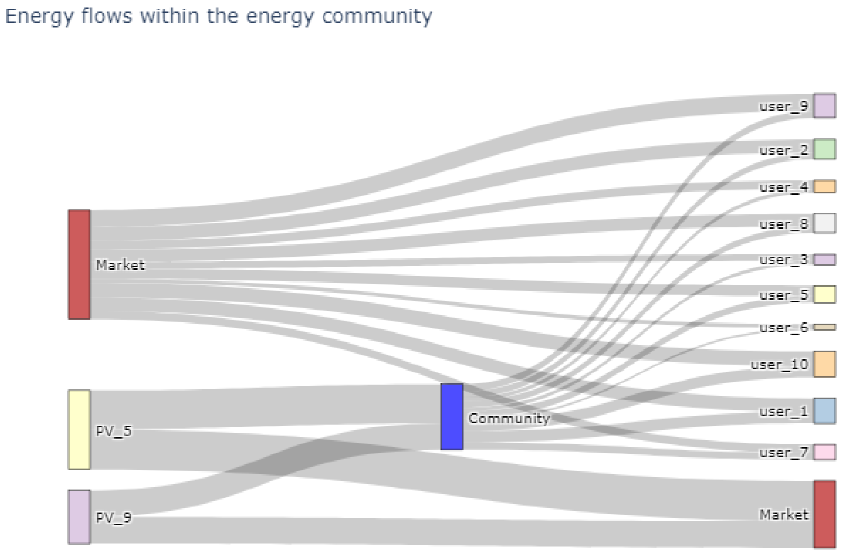
(b) Self-consumption priority (Scenario 3)

Figure 4.5: *Origin of the energy consumed by each member of the REC.*

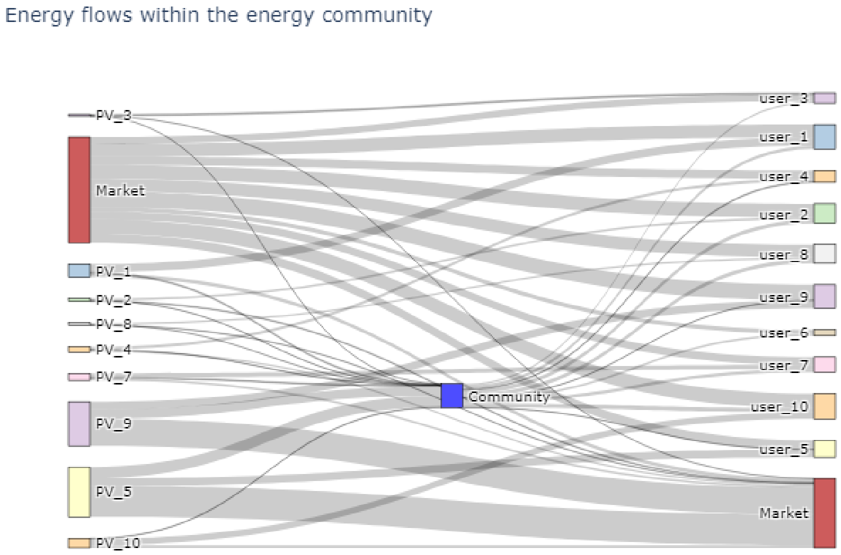
In Figure 4.6 the energy exchanges for Scenario 1 and Scenario 3 are depicted in two sankey diagrams. On the left side of each graph, the sources of the energy are represented: they can be power plants of the community or the market (as a seller). On the right side there are the final users of the energy produced, they can be community members or the market (as a buyer). In the middle there is the energy community, that creates the link between generators and loads of the community, enabling the sharing of energy among the community members. With respect to Scenario 1, the energy produced by the generators has two possibilities: to be shared by mean of the community (if others community's members require it) or to be sold to the market (if the members of the REC do not require it). In Scenario 3, an additional option is present: the energy produced by a REC's generator can directly feed the load of a user, if this user is located under the same POD of the power plant (self-consumption).

Scenarios with ESS

Scenario 2 and Scenario 4 consider the possibility to include an energy storage system in the portfolio of the energy community. The optimal portfolio of Scenario 2 is



(a) Scenario 1 - The energy produced by each generator can be (i) given to the community for sharing (ii) sold to the market.



(b) Scenario 3 - The energy produced by each generator can be (i) given to the community for sharing (ii) sold to the market, (iii) self-consumed.

Figure 4.6: *Sankey diagram with the energy exchanges of the community.*

comparable with the one of Scenario 1, since both consider only energy sharing. In the case with the energy storage system, its optimal size results to be 63.0 kWh. Given the possibility to store the energy produced, the generation portfolio is larger and composed by three generators instead of two. The average size of the generators is 8.00 kW and the total installed power is 24.0 kW (+43.7%). In this way, the percentage of energy consumed that comes from REC's generators becomes equal to 77.9% and the dependency from external suppliers is reduced to 22.1% of the total need.

Economic performances

From the economical side, the optimal solution of Scenario 1 requires an initial investment of 25,890 €, providing a NPV of 15,738 €. For the Scenario 3, the initial investment is 29,134 €(+12.5%) but also the NVP rises to 18,793 €(+19.4%). The best performances of Scenario 3 with respect to Scenario 1 are confirmed also by the Profitability Index (PI) that is equal to 1.65 in the first case and 1.61 in the second one[5]. This allows to say that a REC's portfolio optimized considering also self-consumption can represent for the community a better investment. The same trend is confirmed also comparing the corresponding cases in which the ESS in included. The usage of an ESS can increase the NPV of the investment, but it requires an high initial investment and therefore the profitability index of the investment decreases when adding the ESS.

Name	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Investment	25,890 €	49,784 €	29,134 €	55,351 €
Net present value	15,738 €	25,452 €	18,793 €	29,122 €
Profitability index	1.61	1.51	1.65	1.53

Table 4.6: *Investment evaluation for each considered scenario.*

4.5.5 Computational time

The computational time for the four cases evaluated are reported in Table 4.7. It can be noticed that the entire execution has been divided into 12 steps and, in this way it is possible to understand which step is the more demanding from the computation point of view. It is trivial to say that the solving step is the more demanding but it is interesting to notice that the scenarios in which self-consumption is considered require a time 6 times higher than the same scenarios without self-consumption. Moreover, it is possible to see that some steps require a negligible time in some scenarios while are more important in the others. Specifically, the definition of the constraints for self-consumption (step 6) is negligible in scenarios 1 and 2, while it is important in scenarios 3 and 4. The total requested time strongly depends on the requirements asked to the solver in terms of relative MIP optimality gap. The time shown in Table 4.7 are related to specific executions with a relaxed value equal to 0.01. If setting more demanding values the computational time easily increase to hours or even days, but the optimal solution does not change from the practical perspective.

The impact of considering blocks of years in the model has also been evaluated, comparing it with the case in which each year is considered separately. The analysis

---

[5] The PI is calculated as the ratio between the NPV and the initial amount invested in the project. A higher PI means that a project will be considered more attractive.

Step		Scenario 1	Scenario 2	Scenario 3	Scenario 4
1	Loading input	1 sec	0 sec	0 sec	0 sec
2	Sets definition	0 sec	0 sec	0 sec	0 sec
3	Parameters definition	1 sec	2 sec	1 sec	2 sec
4	Variables definition	2 sec	1 sec	2 sec	2 sec
5	Constraints production	12 sec	11 sec	11 sec	11 sec
6	Constraints self-consumption	1 sec	1 sec	19 sec	19 sec
7	Constraints energy sharing	1 sec	1 sec	1 sec	1 sec
8	Constraints ESS	1 sec	3 sec	2 sec	4 sec
9	Constraints cash flow	0 sec	1 sec	1 sec	1 sec
10	Solver call	38 sec	52 sec	241 sec	340 sec
11	Results handling	4 sec	4 sec	2 sec	2 sec

Table 4.7: *Computational time for the four scenarios evaluated.*

have been carried out changing the number of years of each block for values equal to 1, 2, 5 and 10 (all the values that allow an integer division of the lifetime of the investment have been considered, excluding 4 because it does not allow to properly consider the tax deduction that is valid for 10 years).

In Table 4.8 the results of the comparison are proposed in term of optimal PV size, optimal ESS size, net present value and computational time. It can be noticed that reducing the model to blocks of years introduces some variations in the results, due to the approximation introduced in the actualization of the monetary flows (Eq. 4.38). The maximum error in the results is -2.58% and is related to the battery size in Scenario 2. On the other hand, the definition of the blocks of years drastically reduces the computational time (the reduction is higher than 90% in all the scenarios). Given that the reduction of the computational time is achieved at the cost of an approximation in the results, depending on the application, this approximation can be considered acceptable or not. For the considered case study, given the intrinsic uncertainty of the power profiles and considering that commercial equipment have standard and not continuous sizes, the results obtained with two blocks of 10 years can be considered acceptable.

4.6 Summary

This chapter has addressed the problem of modelling an energy community with the purpose of the optimal planning of the community's DERs portfolio. A model has been presented to evaluate energy exchanges among the community members and the external market. The model is capable to optimize the REC portfolio, defining the solution that maximise the NPV of the investment. A theoretical case study has been introduced to test the model. Two different strategies have been considered for the energy community: evaluating all the energy as shared or specifically accounts for the self-consumed one, and including or not an energy storage system. The results show that optimizing the portfolio considering self-consumption can increase the value of the investment, while the usage of ESS increases the NPV but decreases the PI due to the high initial investment. When considering the self-consumption, the computational cost increases more than six times.

Table 4.8: *Impact of reducing the model to blocks of years on the computation time and optimal solution.*

Scenario 1	**Number of years per block**			
	1	**2**	**5**	**10**
Total PV size	16.79 kW (-)	16.78 kW (-0.03%)	16.76 kW (-0.17%)	16.70 kW (-0.49%)
Total ESS size	0 kWh (-)	0 kWh (-)	0 kWh (-)	0 kWh (-)
Net Present Value	15,829 € (-)	15,825 € (-0.03%)	15,807 € (-0.14%)	15,738 € (-0.57%)
Computational time	722 sec (-)	329 sec (-54.4%)	147 sec (-79.6%)	59 sec (-91.8%)

Scenario 2	**Number of years per block**			
	1	**2**	**5**	**10**
Total PV size	24.20 kW (-)	24.20 kW (-0.00%)	24.13 kW (-0.32%)	24.00 kW (-0.89%)
Total ESS size	64.67 kWh (-)	64.52 kWh (-0.24%)	63.92 kWh (-1.16%)	63.00 kWh (-2.58%)
Net Present Value	25,743 € (-)	25,727 € (-0.06%)	25,664 € (-0.30%)	25,452 € (-1.13%)
Computational time	753 sec (-)	729 sec (-6.9%)	178 sec (-77.3%)	76 sec (-90.3%)

Scenario 3	**Number of years per block**			
	1	**2**	**5**	**10**
Total PV size	18.72 kW (-)	18.73 kW (0.07%)	18.77 kW (0.26%)	18.80 kW (0.42%)
Total ESS size	0 kWh (-)	0 kWh (-)	0 kWh (-)	0 kWh (-)
Net Present Value	18,937 € (-)	18,929 € (-0.04%)	18,896 € (-0.22%)	18,794 € (-0.76%)
Computational time	5468 sec (-)	1979 sec (-63.8%)	784 sec (-85.7%)	280 sec (-95.9%)

Scenario 4	**Number of years per block**			
	1	**2**	**5**	**10**
Total PV size	27.29 kW (-)	27.30 kW (0.04%)	27.34 kW (0.17%)	27.39 kW (0.36%)
Total ESS size	65.50 kWh (-)	66.44 kWh (-0.09%)	65.23 kWh (-0.41%)	64.50 kWh (-1.52%)
Net Present Value	29,418 € (-)	29,401 € (-0.06%)	29,334 € (-0.29%)	29,122 € (-1.01%)
Computational time	6052 sec (-)	2523 sec (-58.3%)	674 sec (-88.9%)	382 sec (-93.7%)

CHAPTER 5

Benefit sharing within a REC

The model presented in Chapter 4 is capable to define an overall cash flow, in which costs and revenues are considered as they were monetary flows of a single entity. In real life, this economical balance is not referred to a single entity, since many actors are involved in a community project (different users and at least one producer). It is thus essential to investigate whether the return on investment of each stakeholder justifies its participation in the community. As stated by [122], the ability of energy communities to share gains amongst their members is key for their long-term sustainability, because if an EC fails to fairly distribute benefits to all participants some members may find it more beneficial to opt out and create another community. As a matter of fact, an investment that can be theoretically profitable when considering the cumulative profits, can be halted by insufficient returns from individual participants. Taking this challenge into consideration, the game theory is an effective tool to address the interactive nature of energy sharing, since it provides *general mathematical techniques for analyzing situations in which two or more individuals make decisions that will influence one another's welfare* [123]. In this chapter, a methodology based on the Shapley value is proposed to redistribute the benefits obtained by a REC.

5.1 Element from the game theory

The game, that can also be referred as conflict or interaction, describes any situation in which the decision-making processes of the players, i.e. the game participants, are interrelated. The players are said to be rational, as their decisions are guided solely by the desire to complete their own objectives, that are assumed to be the maximization of their expected payoff, mathematically described by an utility function. The players are also said to be intelligent, and it is assumed that any player is aware about the rules of the game and can think of consistent assumptions to make his decisions. The game theory is generally divided into two classes defining the level of constraint of the agreements taken among the players. Cooperative games analyse situations in which commitments are fully binding and enforceable. On the other hand, in non-cooperative (or strategic) games there is no obligation to fulfil such commitments.

5.1.1 Non-cooperative game

In non-cooperative games the players are independent and choose their strategy, for the maximization of their utility function, with no communication or exchange of information with the other players. The outcome of the decisions will lead to conflicting interests in reaching the desired objectives. A classical representation of static non-cooperative games is given by a set of players N, a set of possible actions $(A_i)_{i \in N}$ and the utility functions of the players $(u_i)_{i \in N}$. The player has to select an appropriate action in the set $a_i \in A_i$ so that its utility function will be maximised. Nevertheless, the utility function does not only depend on the individual action of the player a_i, but also on the array of actions of the other $N \backslash \{i\}$ players. One important solution in non-cooperative games is the Nash equilibrium, a stable state in which the players cannot improve their utility function by changing their action a_i^*, if the other players $N \backslash \{i\}$ keep the same array of decisions a_{-i}^*.

Non-cooperative game theory is often used to model those situations in microgrids, or small power systems, in which users act individually and aim to optimize their own benefit. In [124] a framework to regulate the percentage of domestic users owning a storage device is presented. The problem is modelled as a non-cooperative game in which players act to minimise their costs. A Nash equilibrium that maximises social welfare is found as the number of battery owners with respect to the considered population. The authors of [125] provide a methodology to enhance the stability and the efficiency of a microgrid using an algorithm based on non-cooperative game theory. A Nash equilibrium is found as a solution of this dynamic game, that optimises the power regulation of the load and the sources within the system. Moreover, it is studied how loads and sources can react by adjusting their power to the actions of the other players. Some specific declinations of non-cooperative game theory are also considered in literature, in order to better analyze some particular situations. As an example, [126] studies an isolated microgrid with users benefiting of PV electricity generation and batteries. The system is analyzed using two concepts from non-cooperative game theory: the Potluck problem and an auction game. The interaction between consumers and producers is modelled as a Potluck problem, a dynamic non-cooperative problem in which players have no communication but act rationally. The problem is known in literature for not possessing a Nash equilibrium. As game theory predicts, due to the rational thinking of the players, the system oscillates between a state in which there is excess demand or excess production. As a consequence, a non-rational thinking is adopted for the users to find an equilibrium in which the system can work. An auction game is then implemented to simulate the internal market under different conditions of market clearing strategies. For every condition a different Nash equilibrium is found. Another example of non-cooperative game is reported in [127], where a mechanism to encourage users in a smart grid to actively participate in energy trading with a central power station is proposed. The system is modelled as a single-leader multiple-follower Stackelberg game (a theory first developed in economics in which a leader has the advantage of a first move and the follower plays the best response to optimize its utility) in which the aggregator is the leader that sets the internal price of energy within the microgrid and the users of such microgrid have to decide the amount of energy to sell in response to the determined price. The objective of the aggregator is to set a price that incentivises active users to sell electricity during peak hours in order to meet the demand of the microgrid, while maximizing the overall benefit (generalized Nash equilibrium).

5.1.2 Cooperative game

Cooperative (or coalitional) games are characterized by the possibility of communication between the players. In particular, the players decide to form coalitions between each other in order to improve their payoff from the game. This alliance represent an agreement that binds the players to act collectively. Cooperative games comprehend two categories of games. Nash bargaining deals with the analysis of the possible conditions and terms that players stipulate in order to form coalitions. Nash bargaining is used to find if a payoff for the players exists, whose value exceeds the one of the so-called disagreement point, that is the value that the players receive if the negotiation does not go through. On the other hand, coalition games study the architecture of formed coalitions and the interaction between the players. Another possible division of cooperative games is based on the nature of the utility function. In games with Transferable Utility (TU) the utility function assumes a numerical (monetary) value that can be distributed among the players of the coalition following a fairness rule. The payoff of each player is represented by the share of the coalition's utility received.

The coalitional game is uniquely defined by the pair $(N; v(S))$, where N denotes again the set of players and $v(S)$ is the value of the coalition $S \in N$. The payoff x_i of the player $i \in S$, part of the coalition, is determined by an allocation criterion. This allocation should be fair and accepted from all the players, that otherwise would prefer to leave the coalition.

The core

The core is a classical solution of the stability of a canonical game and delineates a space of solutions (i.e. payoffs) x for the members of the grand coalition N, for which no player can receive any greater payoff in any other subset of the grand coalition $S \in N$. Indeed, it could happen that, given a payoff vector, a subset of actors would prefer to form a smaller coalition instead to form the gran coalition. In mathematical terms, a payoff vector x is in the core of a coalitional game $(N; v(s))$ if and only if:

$$\forall S \subseteq N, \sum_{i \in S} x_i \geq v(S) \tag{5.1}$$

The Shapley value

All things considered, a solution based on the core may comprehend many possible values for each player and this payoff may not reflect the most fair way to allocate the grand coalition's value. In order to fairly allocate the coalition's value among the players of the game, the Shapley value takes into account the added value that each player brings to the coalition. In other words, it reflects the most fair payoff for the players in the grand coalition, taking into account the marginal contribution of each player. Shapley value ϕ for user i is expressed as:

$$\phi_i(v) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!\,(n-|S|-1)!}{n!} (v(S \cup \{i\}) - v(S)) \tag{5.2}$$

in which the marginal contribution $(v(S \cup \{i\}) - v(S))$ of the player i in the coalition S is weighted on the factor $\frac{|S|!\,(n-|S|-1)!}{n!}$ that takes into account the possible orders in which player i can join the coalition S. The Shapley value definition is bounded to four axioms:

1. Pareto efficiency: $\sum_{i \in N} \phi_i(v) = v(N)$, the total value of the grand coalition is redistributed among the players.
2. Symmetry: if $v(S \cup i) = v(S \cup j)$ then $\phi_i(v) = \phi_j(v)$, if two players contribute equally to the coalition, they receive the same payoff.
3. Additivity: being v and u value functions of two games, it holds $\phi_i(v+u) = \phi_i(u+v) = \phi_i(v) + \phi_i(u)$
4. Null player: if $v(S) = v(S \cup i)$ then $\phi_i(v) = 0$, a player that does not contribute to the coalition, receives no payoff.

One of the major drawbacks of the Shapley value is its computational burden as the number of players inside the coalition increases. It is not possible to evaluate the Shapley value for a set of hundreds of users like it could be the one of an energy community. Furthermore, it has to be noted that the Shapley value does not necessary lies in the core.

When considering academic literature in the domain of cooperative games, Nash bargaining is employed to provide incentives to individual users to share their excess energy. In [128] a Nash bargaining problem is set up to stimulate two users to share an energy storage device. The Nash bargaining solution is used to determine a fair compensation that a user should receive, if the other user has discharged the battery that he had first charged. In a similar fashion, in [129] the authors design an incentive mechanism based on Nash bargaining to develop energy trading between interconnected microgrids. The Nash bargaining solution finds a price of electricity at which the microgrids can trade electricity that minimises the individual costs of electricity demand. As all the microgrids act as rational layers with the objective of minimizing their cost, the Nash bargaining solution also delineates the subset of microgrids willing to participate in active energy trading. On the other hand, coalition formation game theory can analyse which size of micro-grid is more convenient for the participants. As an example, the purpose of [130] is to form coalitions of microgrids comprising energy producers and energy buyers whose objective is to optimize the payoff of each participant. Users' costs are reduced by trading the power within the distribution and avoiding much power flowing through the macro station and the subsequent power losses. An algorithm based on coalition formation game theory is set up, that creates coalitions within a selected area bringing together in the same coalition buyers and producers whose production and demand curves are as similar as possible and whose distance does not create too many power losses. The algorithm iterates the creation of coalitions until the game becomes stable, so no user has an advantage to leave its coalition. Within canonical coalitional games, the Shapley value proves to be the most effective method applied in the literature to fairly divide the benefit resulted by forming a microgrid in which energy is shared. [131] relates to a community microgrid in which active users, equipped also with a storage system, can share their excess energy. In the paper, different methods are used to allocate the energy bill among the community participants. When the problem is modelled as a cooperative game, allocating the costs with Shapley value, the users receive a more fair treatment with respect to other P2P trading mechanisms such as bill sharing, mid-market rate and supply demand ratio. [132] introduces instead a payment calculation scheme to compensate the users of a joint microgrid based on the Shapley value. In particular, the energy producers within the microgrid are fairly compensated taking into account the difference between the Shapley values and the generation costs of each technology. The authors in [133] optimize the energy fluxes in an energy community in order to minimise the overall costs of the system. Some participants are provided with a renewable energy source, some participants with a storage systems. A coalitional game framework is used to model the energy trading inside the community. Shapley value is then used to fairly distribute the savings among the participants.

5.2 Energy community as a coalitional game

Based on the classification presented in the previous section, the REC modelled in Chapter 4 can be seen as a cooperative game. Indeed, the community members decide to form a coalition to improve their payoff and define agreements that bind them to act collectively. From the literature review on coalitional game, a similar case has not been identified. Even if similar contexts are considered, small differences (as the ownership of the equipment) completely change the rules of the game. However, the review shows that the Shapley value is a common approach for pay-off distribution in many cooperative games. Therefore, it has been chosen for the presented application.

In the cooperative game of the REC, the players are the producers (i.e. the financers of the generation plants) and the consumers. The economical value generated hour by hour depends on the presence and the interaction between load and production, in particular on the quantities of energy produced and shared[1]. The players can decide to take part to the community or not. Both producers and consumers want to take advantage from the participation to the community. Producers can be generically considered as external actors that can invest in the installation of new generators and wants to get a return from the investment. In real applications, they can be external financers or the community itself (with the financial participation of the community members). In any case, even if external and internal financers could require different rates of return, it is important to notice that they are both expecting a positive return of the investment. From the methodological side, who is the financier does not impact. On the other hand, when considering consumers, they have a certain contractual power as they are necessary to generate the profit (mainly based on the incentive for shared energy). As a consequence, they can require an appropriate return for their participation in the energy

---

[1] Self-consumed energy is not considered in this step.

community. The objective of studying this game is to find a stable and fair allocation rule that gives an adequate payoff to the players, so that each one is encouraged to take part to the EC.

The game

The game is defined as follows:

- N is the set of players $\{Gen_1, Gen_2, ..., Gen_{N_G}, User_1, User_2, ..., User_{N_U}\}$. Where N_G and N_U are respectively the number of generators and passive users participating to the energy community.
- The possible actions for each player are to take part to the community or not[2].
- $v : 2^N \to \mathbb{R}$ associates with each coalition $S \subseteq N$ a real-valued payoff $v(S)$ that the coalition's members can distribute among themselves. The value generated by coalition S at hour t is defined as:

  $$v_t(S) = E_{ec}^{\to market}(t) \cdot PE^{\to market}(t) + E_{ec}^{shared}(t) \cdot (SEsi + PE^{\leftarrow market}(t) + Inc) \tag{5.3}$$

  Where the energy sold to the market $E_{ec}^{\to market}(t)$ and the energy shared $E_{ec}^{shared}(t)$ depend on the members of the coalitions S and are obtained from Equations 4.22 and 4.24. The presence of each player in the community affects the quantity of energy produced and shared, and consequently the economical value produced. The value should be redistributed among the players depending on their contribution. For convenience, the value function could be evaluated yearly, keeping the results immediately comparable with the cash flow analysis. The yearly value $v(S)$ is simply the summation over time of $v_t(S)$.

  $$v(S) = \sum_{t \in y} v_t(S) \tag{5.4}$$

Stability and fairness

The study of the coalition stability, that is the confirmation that everybody wants to form the gran coalition instead of smaller ones, is trivial. The reason is that the rules of the game state that the participation to the energy community has to be open and voluntary. This means that, even if some coalition could be preferred from a subset of players, they are not allowed to exclude others from the coalition. From their side, all the users want to take part to the community, since they can only gain from this participation. From the producers side, since the optimal portfolio for the community as a whole has already been evaluated in the optimization phase, the community will constrain its generation portfolio to that one. In other words, it is not the single investor that decides which generator is more profitable, but is the community that defines the set of generators that have to be installed. The choice of the producer is to invest or not in that specific portfolio. Given this consideration, the study of the game is reduced to the research of a fair way of dividing the grand coalition's payment among its members.

---

[2] In the planning phase, users consumption are not considered flexible. In real operation, the same game could become dynamic, since users could apply demand response schema to maximise shared energy and, consequently, their payoff.

Value distribution

When dealing with fairness, two issues are of particular importance. The first concerns the division of the value between consumers and producers. It is important for those who invest in community facilities to know that they are getting a fair return for their financial intervention. At the same time, value should be distributed among consumers according to their contribution to value generation, because not everyone contributes in the same way. The contribution of a passive user will be zero if his energy demand occurs at a time when the total load already exceeds the current production. On the contrary, a user will produce a greater value if he consumes the energy produced by the facilities of the community when there are no other users who require it. The calculation of the Shapley value can solve both issues. For the application into this field, a two levels payoff distribution is proposed. In the first level the payoff is distributed with the Shapley value between producers and groups of consumers. The second level of distribution concerns the division among each single consumer within each group with a proportional distribution.

The distribution based on group of consumers (instead of considering each consumer individually) introduces an approximation, since the marginal contribution of the group can be different from the sum of marginal contributions of each single user. Nevertheless, this can be accepted in order to preserve the computational feasibility.

To demonstrate the acceptability of the assumption a test case has been developed based on the following hypothesis. A REC is supposed to be composed by a generator and a set of 100 consumers. The simplified income of the REC are given by the value of the energy produced, considered equal to 0.05 €/kWh, and the incentive on the shared energy, estimated equal to 0.10 €/kWh. These values are aligned with the average price on the Italian market in 2019 (52.3 €/MWh, according to GME statistics [121]) and the incentives defined for collective self-consumption and energy communities (100-110 €/MWh, see Section 2.2.2). The value of the produced energy is obtained even if there the energy is not shared (i.e. there is no load), while the incentive is obtained only with the contribution of consumers. The hourly balance of the REC is evaluated considering a constant production of 150 kW and a variable consumption in the range 0-300 kW. This consumption is divided among the members of the community with a random selection based on a constant distribution. Theoretically, the Shapley value should be evaluated for each one of the members of the community, but this requires a computational effort that make its evaluation unfeasible. Therefore, users are aggregated with the k-means algorithm into different clusters according to their similar behaviour, and the Shapley value is computed for these groups. The higher the number of clusters, the closer the resulting Shapley values will be to the theoretical one. In order to identify the impact of the number of clusters, the evaluation has been repeated varying it from 1 to 15. In Figure 5.1, the revenues obtained by the REC when varying the consumed energy in depicted in blue. If the load is equal to zero, the unique income is given by the value of the energy produced and sold. In this case, the Shapley value division assigns to the producer the entire revenue (red line), since the marginal contribution of the consumers is null. If the members of the community have an energy request higher than zero but lower than the energy produced, the REC receives an incentive proportional to the shared energy. In this case, the marginal contribution of passive users is not negligible and therefore they receive a payoff (green line). When the energy request is higher than the produced, the total revenues of the community does not increase, since the shared energy is limited to the produced one. When the consumption increases, the payoff of the generator continue to increase, while the payoff of the consumers starts to decrease slowly. The reason is that the surplus of consumption creates an abundance of load, therefore the marginal contribution of each passive user is reduced. With respect to the number of clusters, it can be noticed that it impacts only when the energy request is higher than the produced. Considering only one cluster of passive users gives it a strong contractual power: to obtain revenues from the energy sharing, this single cluster is strictly required. This does not correspond to the reality, in which single members act individually. Therefore an higher number of clusters has to be considered. When the number of clusters increases, the importance of the each single cluster decreases since it becomes easily replaceable with others. In Figure 5.2, the error obtained clustering users in different groups is depicted. The relative percentages are referred to the case with 15 clusters, given that it is the solution more close to the ideal case of computing Shapley value to each single user. It can be noticed that the biggest variations in the payoff distribution are obtained considering few clusters, and that these variations increase with the energy request (when the load is equal to the production, 150 kW, the difference is null). This means that the usage of a suitable number of clusters becomes more and more important when the load is higher than the production.

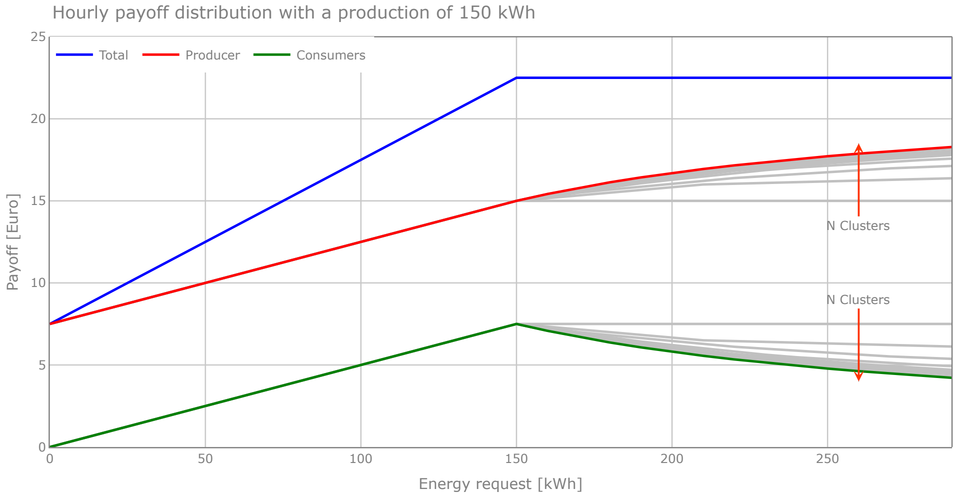


Figure 5.1: *Results of the payoff distribution between producer and cluster of consumers.*

5.3 Application to an Italian REC

The model of REC and the methodology for benefits sharing have been applied to a real case study base on the Italian experimental phase (see Section 2.2.2), to test them on a practical usage and to evaluate their potential. The case study is related the low voltage grid of Chiou, a fraction of the village Porossan (710 m), in the municipality of Aosta (Figure 5.3). Given the great presence of renewable energy sources and the mountainous morphology of the area, Valle d'Aosta Region has always been a producer of renewable energy. The Distribution System Operator (DSO) of Porossan is the Electric Cooperative of Gignod (CEG), a pioneer in the field of energy communities [1]. Policy

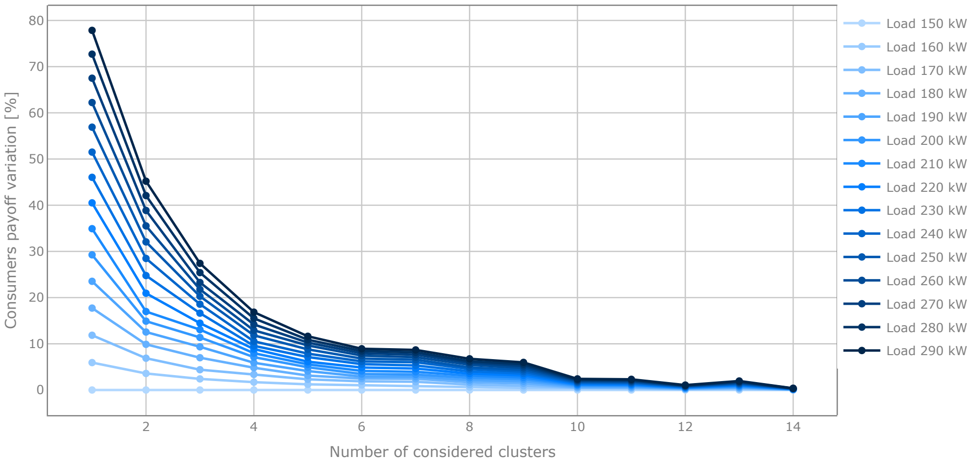


Figure 5.2: *Impact of the number of clusters on the total payoff assigned to consumes. Percentages are referred to the case with 15 clusters.*

makers in the area are particularly willing to improve the environmental sustainability; in [13] it is reported a study devoted to identify the optimal portfolio for maximising local self-sufficiency.

Figure 5.3: *The village of Porossan and its location in Italy. The red circle indicates the area feeder by the MV/LV substation Chiou.*

5.3.1 Users consumption

The power profile of each user (active and passive) under the MV/LV substation has been obtained from real measurements collected by the DSO. The selected LV network has already some PV power plants connected, but for the goal of this application they have been removed in order to consider a more generic greenfield project. In Porossan there are two MV/LV substations: Chapelle and Chiou. The nominal power of each transformer is 250 kVA. The power profile of the transformer in the substations is available from the local DSO. Their data have been elaborated assuming realistic assumptions, as detailed in the following.

To evaluate the feasibility of a REC in the area feeded by Chiou, the number of users connected and their consumption needs to be known. The information about number and type of users connected is obtained from public dataset (ISTAT). Specifically, in Porossan there are 245 buildings, some of them are divided in more than one internal unit, for a total number of 324 units. We suppose that each unit has its own POD. According to the Italian regulation, LV users can be of three different types: domestic (that can be resident or not resident), for "other usages" and for public lighting.

The number of families living in Porossan according to ISTAT data is 247, for a total number of 565 people. The number of people in each family is reported in Table 5.1. Since we are supposing that the grid of Chiou feeds 40% of the village of Porossan, the number of families is then adapted to this quote. Each family has its own POD of residential type *Domestico residente*. The consumption of each type of family is supposed to increase with the number of people in the family, with the following formula:

$$Consumption = 500 + 600 \cdot N_{members} \; [kWh/year] \tag{5.5}$$

The proposed formula is based on the general indication of the Italian Authority that assumes a consumption of 2.700 kWh for a typical family with 3-4 members. The equation has a constant term to approximate the non-linear correlation that actually exists with the number of users. The yearly consumption for each type of family is reported in Table 5.1. Giving this hypothesis, the mean yearly consumption results to be 1862 kWh. This value is comparable with the average value for domestic residential users for the entire Valle d'Aosta Region (2018 kWh/year according to DSO data).

From ISTAT data, we also know that 38 bulding units in Porossan are for not domestic usages, it means they are used for economic activities, business and other services. From the electrical point of view they are all labelled as other usages (*Altri usi*). Keeping the hypothesis that 40% of the load is under Chiou substation, we consider 16 users of this type. We suppose that the users of this type have an yearly consumption equal to 1356 kWh, that is the average value in the entire Valle d'Aosta Region.

The units that are nor residential nor for other usages are domestic users not resident (*Domestico non residente*). These are not related to people living in the area and, giving the tourist interest of the place, they could be holiday houses. According to the hypothesis that 40% of Porossan's users are under the grid of Chiou, we obtain that there are 15 users of this type. We suppose that yearly consumption for LV domestic but non residential users is equal to the mean value for the Valle d'Aosta Region, that is equal to 642 kWh.

Finally, we suppose also that the total consumption for public lighting is equal to 2000 kWh/year. The total consumption of the LV grid results to be equal to 217.2 MWh/year.

Users power profiles

To compute energy balances, a specific hourly profile has to be assigned to each type of users. The hourly power transit in the substation is measured by the DSO and reported in Figure 5.4. It is clear that many PV power plants are installed and, especially in spring and summer, there is an important inverse flow from the LV to the MV level. This reverse flow appears for 20.0% of the hours of the year. Indeed, 18 PV power plants are connected to the LV feeders, for a rated power of 80.6 kWp. The average size of each plant is 4.48 kWp.

To evaluate the profile of load consumption, it is necessary to quantify the effect of local generators. Not all of these plants are monitored, so the total production from the PV generators has been estimated. A standard PV production profile is computed

Table 5.1: *Number and consumption of users in the energy community grouped by types.*

Type of user	Number	Load [MhW/year] User	Total
1 person resident	32	1.1	35.2
2 people resident	32	1.7	54.4
3 people resident	19	2.3	43.7
4 people resident	11	2.9	31.9
5 people resident	3	3.5	10.5
6 people resident	2	4.1	8.2
Not resident	15	0.642	9.6
Other usages	16	1.356	21.7
Public lighting	1	2.0	2.0
Total	131		217.2

from the production profile of the monitored plant, and it is multiplied by the total rated power of the 18 plants. The standard profile is computed, hour by hour, as the 90th percentile of the measured profiles. This choice is due the fact that the measurement available are for the injected powers and not for the produced ones. Evaluating the standard profile in this way avoids to consider values that are particularly low due to high self-consumption. The obtained profile is depicted in Figure 5.5. The number of yearly equivalent hours for such profile is 1072 (the value is reasonable considering that for the optimal oriented panels in the same location, the tool PVgis [134] indicates a number of equivalent hours equal to 1210).

The total load profile due to LV users has been evaluated as the difference between the transit in the substation and the local production. The profile obtained is shown in Figure 5.6. Simple machine learning techniques based on regression trees (specifically, random forest) has been used to remove outliers. It is interesting to notice that, the total consumption of the area has been estimated equal to 215.5 MWh. This value is quite close to the value obtained from the mean consumption for each category of users as detailed in Table 5.1 (217 MWh).

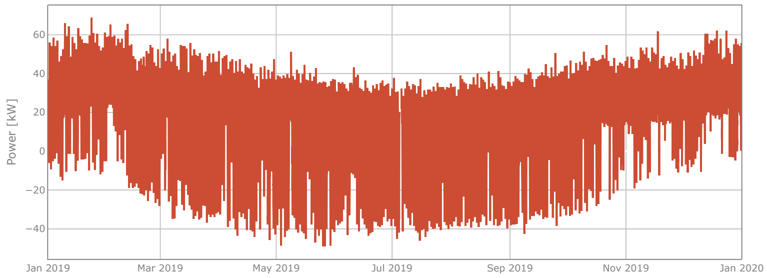


Figure 5.4: *Power transit in the MV/LV transformer of Chiou.*

Once the total load profile has been obtained, it has been divided among the LV users, according to their estimated yearly consumption and hypotheses about the hourly distribution. In total, 9 different power profiles have been defined, clustered into the following groups:

- *Profile for public lighting*. There is only one user to which this profile is assigned.

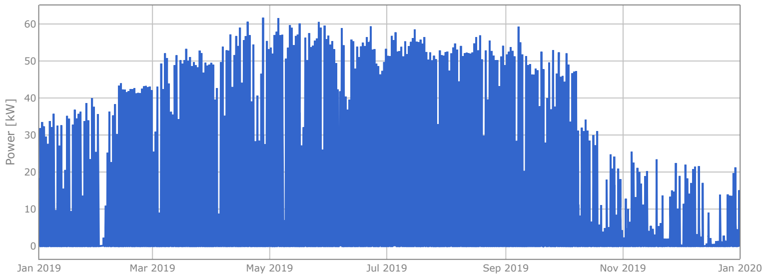


Figure 5.5: *Power production of plants connected to LV grid of Chiou.*

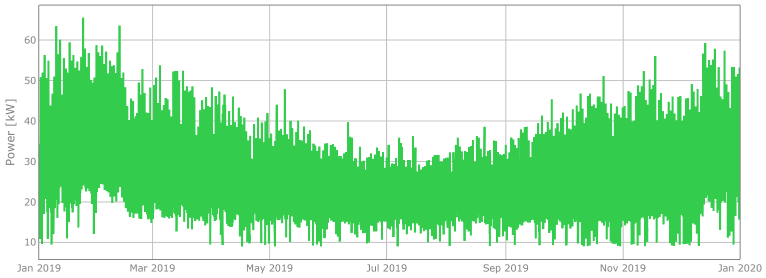


Figure 5.6: *Estimated power consumption of LV users of Chiou.*

The yearly energy consumption has been spread over the hours of darkness, supposing the public lighting work in an ON/OFF mode.

- *Profile for other usages*. 16 users have been defined. We suppose that these users are mainly offices, small artisans and commercial activities. The profile has been created supposing energy consumption in the working hours of the year. Also in this case, an ON/OFF mode is considered, with energy consumption concentrated in the peak time windows of the Italian tariff schema (*Fascia 1*: form 8 a.m. to 7 p.m. from Monday to Friday, national holidays excluded).

- *Profile for not residential usage*. 15 users have been defined. The profile for public lighting and other usages is subtracted to the power transit in primary substation and the resulting profile is the total consumption of domestic users. This is divided between residential and not residential users. The consumption of non residential users is supposed to the be concentrated on weekends.

- *Profiles for residential usage*. The remaining part of the consumption profile is distributed among 6 types of families, according to the number of family members and proportional to their consumption.

5.3.2 Sources availability

With respect to the generation side, two technologies have been investigated: photovoltaic and hydroelectric. More in detail, we consider the possibility to install a single hydro power plant and several PV power plants. The main data about the availability of these sources are reported in Table 5.2.

Theoretically, each rooftop could host a PV plant, nevertheless it is trivial to exclude some of them due to their particular shape, orientation and shadows. For this reason, the number of considered rooftops in the optimization has been reduced to 20. This represents the number of surfaces for which the installation of a PV plant is supposed to be reasonable. The area and the orientation of the surfaces have been evaluated with GIS software, while the slopes have been defined with realistic values from 10° to 40°. The installation cost for each plant is considered different, going from the lowest value equal to 1,400 €/kW to the highest value equal to 2,000 €/kW.

The production profiles for each of these plants are automatically requested via API to the PVgis tool *Performance of grid-connected PV* [134], in order to properly take into account the shadows from high horizon. Since the location of all the surfaces is almost the same, this type of shadows does not introduce big differences among the plants, and each power profile is mainly characterised by the orientation and the slope of the single surface. The profile is requested to PVgis for a PV plant with a rated power of 1 kW based on crystalline silicon cells, and the sum of the system losses is set to 14%. In Figure 5.7 the profiles obtained for each of the 20 surfaces are reported for four days. From this zoom, it is possible to see the effect of the different orientation on the daily production profiles. The heatmap in Figure 5.8 reports the average profile with time divided into two axis: the day of the year and the hour of the day. In this way, it is easy to see the daily and seasonal trends. This specific profile is not used in the model, but it is useful to see the seasonal behavior of this type of generators. Moreover, this average profile has been used to verify that the energy content of the profiles generated by PVgis is comparable with the average profile obtained from the DSO measurements.

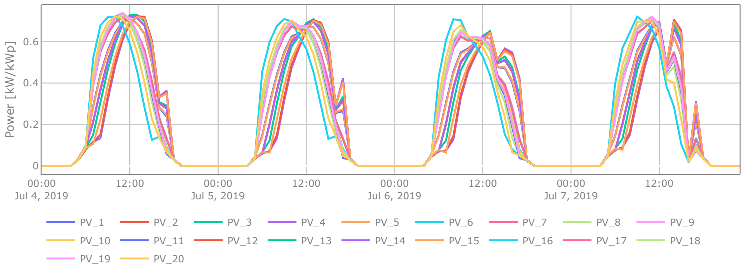


Figure 5.7: *Daily differences among PV power profiles.*

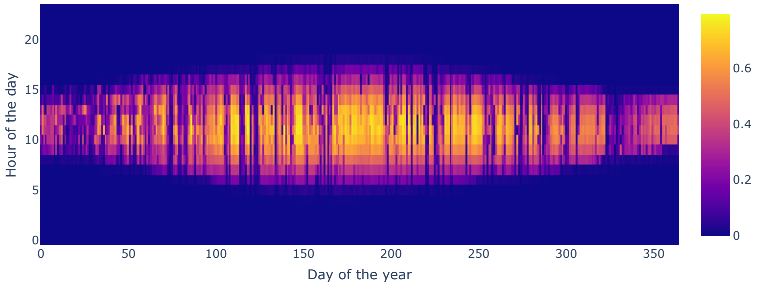


Figure 5.8: *Heatmap of the average normalized photovoltaic power production.*

The production profile of the hydroelectric power plant is a standard profile, built from the production profiles of similar power plants in the area. Since the maximum allowed size of a generator connected to the Italian LV network is 200 kW, only power plants with a nominal power lower than 200 kW are used to build the standard profile. In the area under evaluation, there are 6 monitored hydroelectric power plants with the following rated power: 40 kW, 6.4 kW, 72 kW, 45 kW, 45 kW. Looking to their production profiles, it is clear there is a common path defined by the seasonal water availability. In Figure 5.9 the standard production profile of the hydroelectric power plant is depicted compared with the five measured profiles of the real plants currently in place. They are all normalized by their maximum power and the reference profile is obtained as the median value for each hour of the year. It is also shown in Figure 5.10, where it is possible to see the seasonal trend and the absence of a daily trend. The number of the equivalent working hours per year for the profile obtained is equal to 4,205.

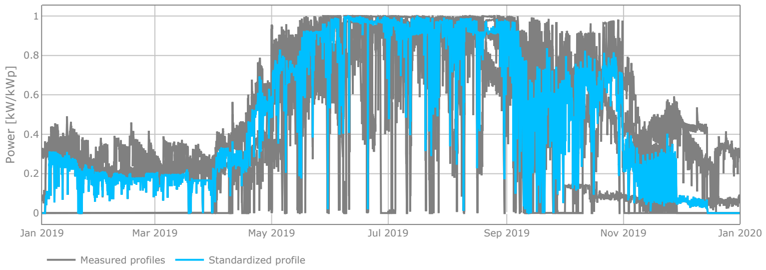


Figure 5.9: *Standardized hydroelectric production profiles (light blue) represented over the five measured profiles on which is based (gray).*

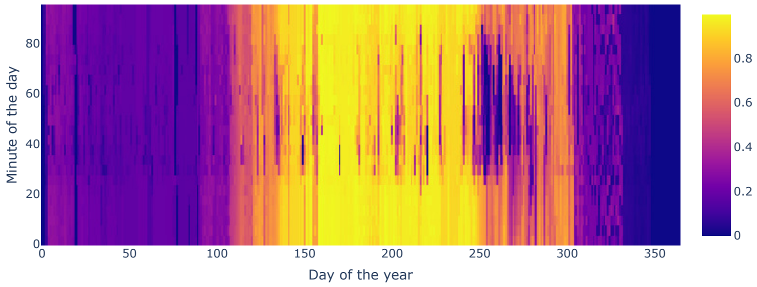


Figure 5.10: *Heatmap of the standardized hydroelectric power profiles.*

5.3.3 Economical data

The lifetime of the investment is supposed to be equal to 20 years, the actualization factor is equal to 4%. Tax deduction is not considered, and all the energy produced and consumed by the REC's member is considered as shared energy (no self-consumption). The possibility to install an energy storage system up to 200 kWh is considered. In Table 5.3 the values of the economical parameters are detailed, while in Table 5.4 the values used to detail the battery model are reported. They refer to an electrochemical storage, based on lithium-ion cells.

Table 5.2: *Potential generator availability for the energy community.*

ID_gen	ID_user	Pmax [kW]	Cost [€/kW]	Yearly O&M [€/kW]	Area [m^2]	Orientation [°]	Slope [°]	Lon [°]	Lat [°]
PV_1	user_24	5	1400	40	60	49	10	7.330	45.756
PV_2	user_32	3	1400	40	30	50	20	7.329	45.757
PV_3	user_22	13	1400	40	158	45	30	7.329	45.757
PV_4	user_84	5	1400	40	55	61	40	7.329	45.756
PV_5	user_82	6	1400	40	73	57	10	7.329	45.757
PV_6	user_98	7	1600	40	82	-24	20	7.329	45.756
PV_7	user_81	2	1600	40	25	-19	30	7.329	45.756
PV_8	user_56	12	1600	40	139	-20	40	7.329	45.756
PV_9	user_9	7	1600	40	82	-30	10	7.330	45.756
PV_10	user_7	6	1600	40	76	-27	20	7.330	45.756
PV_11	user_116	10	1800	40	120	-23	30	7.329	45.756
PV_12	user_1	8	1800	40	101	57	40	7.330	45.756
PV_13	user_124	7	1800	40	87	-36	10	7.330	45.755
PV_14	user_60	3	1800	40	36	53	20	7.329	45.755
PV_15	user_120	14	1800	40	165	68	30	7.331	45.755
PV_16	user_26	6	2000	40	69	-60	40	7.331	45.755
PV_17	user_10	4	2000	40	42	-38	10	7.332	45.755
PV_18	user_105	7	2000	40	80	-34	20	7.331	45.755
PV_19	user_49	5	2000	40	60	-18	30	7.329	45.756
PV_20	user_43	4	2000	40	50	-36	40	7.329	45.755
Hydro	user_132	20	4000	40	——— *Specific profile for Hydro* ———				

Table 5.3: *Economical data.*

Name	Value	Unit	Description
$Cost_{adm}$	5	[€/user/year]	Administrative cost of the REC
SE_{inc}	110	[€/MWh]	Incentive on shared energy
$SCsi$	80	[€/MWh]	Self-Consumption saving index
$SEsi$	8.22	[€/MWh]	Shared Energy saving index
$load_{trend}$	+2%	[%/year]	Yearly growth of the load profiles
$price_{trend}$	-2%	[%/year]	Yearly growth of the price profiles

Table 5.4: *Storage data.*

Name	Value	Unit	Description
$Cost_{ESS}$	400	[€/kWh]	Storage investment
Rep_{ESS}	200	[€/kWh]	Storage replacement cost
$O\,\&\,M_{ESS}$	10	[€/kWh]	Operation and maintenance
ESS_{cap}^{max}	200	[kWh]	Max storage size
EPR	2	[h]	Energy to power ratio
η_{CH}	0.95	[-]	Storage eta CH
η_{DIS}	0.95	[-]	Storage eta DIS
SOC_{min}	0.2	[-]	Minimum state of charge
$Cycle_{max}$	5000	[-]	Max cycles

5.3.4 Results

Solving the model presented in Section 4.2, the optimal energy community configuration has been calculated. It is based on 2 PV power plants and 1 hydroelectric plant. In Figure 5.11 the optimal power is compared with the theoretically available one. This production portfolio includes 14.4 kWp of photovoltaic generators and 20 kW of hydroelectric. With this configuration, the energy community is expected to produce on average 102.2 MWh/year, sharing 95.2% of it among the members (97.4 MWh/year) and selling the other 4.8% to the market (4.9 MWh/year). Thanks to the incentive on shared energy, and considering the actualization of these values, shared energy provides an average income equal to 7230.5 €/year, while producing savings for 3397 €/year. The energy sold to the market contributes with 173.7 €/year to the yearly income. The results is that the incentive of shared energy contributes to 66.9% of the total revenues over the lifetime of the investment (Figure 5.12), the second driver for the investment is the saving due to the not bought energy (31.5%). The smallest part of the income is due to the energy not shared within the community but sold to the market. Considering that this is not the main goal of the energy community, it contributes only for 1.61% of the total. The net present value of the investment is equal to 85'866 €. The profitability index is equal to 1.84 and the payback time is less than 9 years. It is interesting to notice that the energy storage system does not result in the optimal solution, due to the high cost of investment.

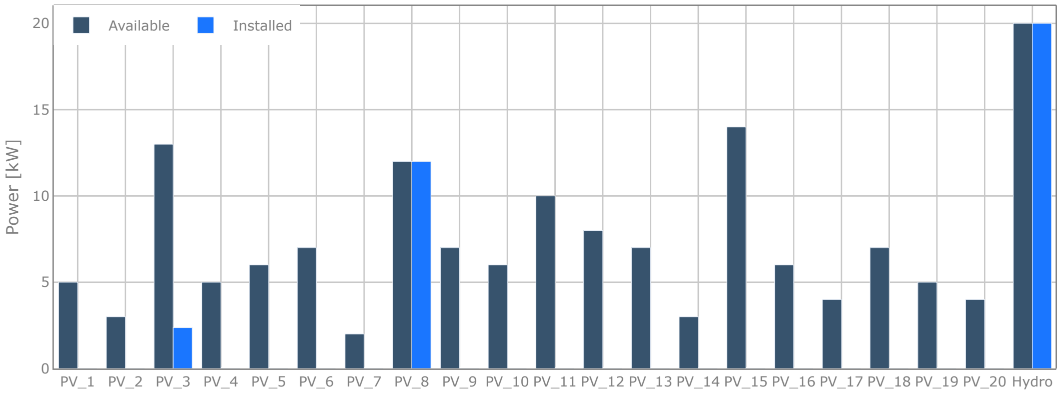


Figure 5.11: *Maximum size of each generator based on the sources availability and optimal capacity of generator.*

5.3.5 Value Distribution

The Shapley value has been evaluated considering the producers and the group of consumers as actors as proposed in Section 5.2. In this case, the clusters of users correspond to the types identified in Table 5.1. The producers receive only a part of the profit of the investment, since part of it goes to the consumers. In Figure 5.13 (a), the global value of the investment for the community is depicted in blue, while the cash flow of the producers is shown in red. It is possible to see that the initial investment of the community is exactly the investment of the producers, but then the community obtains higher profits that are only partially shared with the producers. This means the

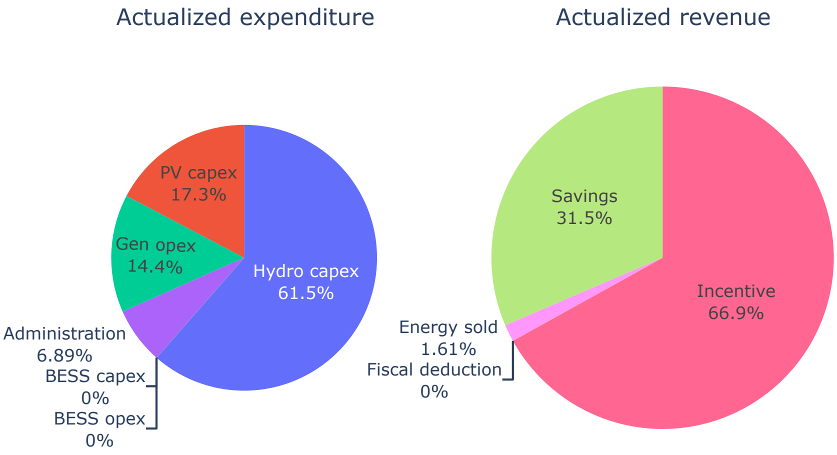
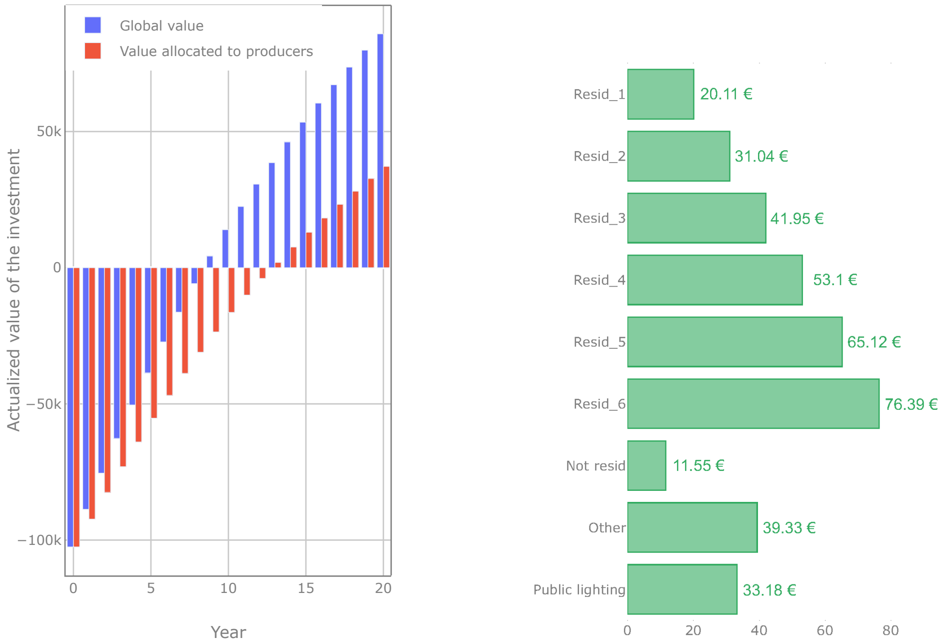


Figure 5.12: *Cash flow contributions.*

payback time is higher than the one that could be achieved allocating to the producers the entire value generated by the community (+44.4%). In a similar way, the net present value of the investment for the producers is lower than the global one achieved by the community (37,204€, −56.7%), with a profitability index equal to 1.36 (−0.48). The difference between the value of the community and the value allocated to the producers is distributed to the consumers. The distribution amongst the group of users is obtained via the Shapley value, then it is divided proportionally between the number of users within the group. In Figure 5.13 (b), the yearly revenue obtained by each consumer that is taking part to the community is depicted. The revenues depend on the amount of energy consumed but also on the way to consume it and, on average, each user achieves a saving of 32.1 € per year. It is important to notice that users can obtain this value without any economical effort (not considering the yearly contribution to cover administrative expenses, set in this case to 5 €). This is aligned with one of the primary purposes of the energy community as characterised in the aforementioned REC definition; that is "to provide economic or social community benefits for its shareholders or members or for the local areas where it operates". Furthermore, this could be a way to fight energy poverty "assessing the possibility to enable participation by households that might otherwise not be able to participate, including vulnerable consumers and tenants" [22].

5.4 Summary

In this chapter the problem of benefits sharing in a REC has been addressed. Game theory algorithms have been identified as a suitable approach for this purpose, therefore



(a) Investment cash flows obtained by the producers.

(b) Yearly revenue obtained by each consumer.

Figure 5.13: *Results of applying redistribution rules on the investors and members of the REC.*

some elements from the cooperative and non-cooperative game theory have been presented, together with examples of application in some energy sharing situations. The REC model proposed in Chapter 4 has been formalized as a cooperative game, and the problem of benefits sharing has been faced. A two steps distribution rule, based on the Shapley value among clusters followed by a proportional allocation, has been proposed. The methodology has been applied to a real-life case study based on the Italian scenario.

CHAPTER 6

Energy communities impact on the distribution network

In this chapter, a methodology for the evaluation of the impact that ECs could have on the MV distribution network is presented. In order to take into account the different configurations and scenarios EC could have, a stochastic approach has been designed. From the perspective of the DSO, the procedure could be useful to evaluate if the creation of new ECs (i.e. the installation of new generators and ESS, sized and controlled to feed subset of the local load) could have an impact on the operating of the network. If it has an impact, it is fundamental to evaluate if it is a positive or a negative one, and which are the ECs' characteristics that affect this results. The proposed methodology is applied to two case studies based on real MV networks.

6.1 Literature overview

Energy communities may have a key role in the decentralisation of the energy system and in the exploiting of local renewable energy, nevertheless they may also pose certain challenges for the energy system [122]. They could impact on quantity and prices of the energy and ancillary services markets, and on the operation of transmission and distribution networks. In this chapter the impact that an EC could have on the planning and operation of the distribution network is evaluated. According to the Joint Research Centre of the European Commission "at the distribution network level, energy communities may improve quality of service (by reducing network losses) and reduce or postpone network investments (by increasing hosting capacity and improving flexibility)" [122]. In principle, it is possible to agree with this observation, nonetheless it has to be verified and a metric is required to quantify this theoretical benefits. To evaluate this aspects, the impact of the distributed generation (DG) on the distribution grid could be adopted as a proxy, obviously the main elements that differentiate the generators of an EC from the classical DG has to be considered.

6.1.1 Distributed generation and hosting capacity

A distributed generator "is an electric power source connected directly to the distribution network or on the customer site of the meter" [135]. The DG is becoming more and more important for the modern electrical system. In the last decade, the production from DG has seen an important growth and, considering the contribution that the DG could have in the decarbonization of the energy system, this increase will not end soon (see the European energy strategy detailed in Chapter 2). In Italy, the production from small DG (<1 MW) has increased more than 10 times from 2008 to 2018[1] [136]. Despite all the environmental, economical and social merits of the DG, it has an important impact on the operation of the electrical grids and therefore it requires a strong research activity. Increasing penetration of DG, by changing the characteristic of passive grids to active ones, could cause some issues both in normal operation mode (such as bidirectional power flow, voltage rise, overloading) and in fault condition (protection coordination and unwanted islanding). In normal operation mode, the important and interesting discussion is related to the amount of DG that can be connected to the distribution grid without violating the technical constraints. Different research activities based on statistical, deterministic and heuristic approaches have been done in order to ensure that, with a given amount of DG connected to the distribution grid, the electrical network is still working within the admitted operational ranges [137]. The capacity of the grid to host new generators in commonly known as Hosting Capacity (HC) and different algorithms for the HC evaluation have been proposed. According to [138], the common steps for the HC evaluation are the following: 1) a performance indicator is selected (e.g. voltage or current amplitude); 2) an acceptable limit for the indicator is defined; 3) the indicator is evaluated as a function of new generation; 4) the highest amount of generation for which the acceptable limit for the indicator is not violated is the HC. The HC concept is graphically explained in Figure 6.1. The Figure is retrieved from [139], but similar representations are common in the literature on hosting capacity [137, 138, 140].

Among the approaches used in the HC evaluation problem, it is possible to identify at least two classifications: a nodal HC evaluation or a global (grid-scale) approach, moreover algorithms could be based on deterministic or stochastic models. With respect to the approach adopted, HC quantification could significantly change. Nodal HC could be formulated as an objective function maximizing the active power injected by DG in a specific bus of the network. In order to evaluate it, DG power injections into a specific bus of the grid could be increased iteratively until the selected constraints are violated. This method is defined as an iterative procedure, in which at each loop a power flow calculation is performed: if the technical limit is respected, DG active injections are increased. We refer to global HC as the maximum amount of capacity that can be connected to the whole grid with more than one generator. Examples of the evaluation of the Hosting Capacity can be found in literature, both for the nodal Hosting Capacity [141], and for the global one [142–144]. When considering deterministic approaches, all the information about the grid, the load and the generators are known

---

[1] From 2.5 TWh to 30 TWh

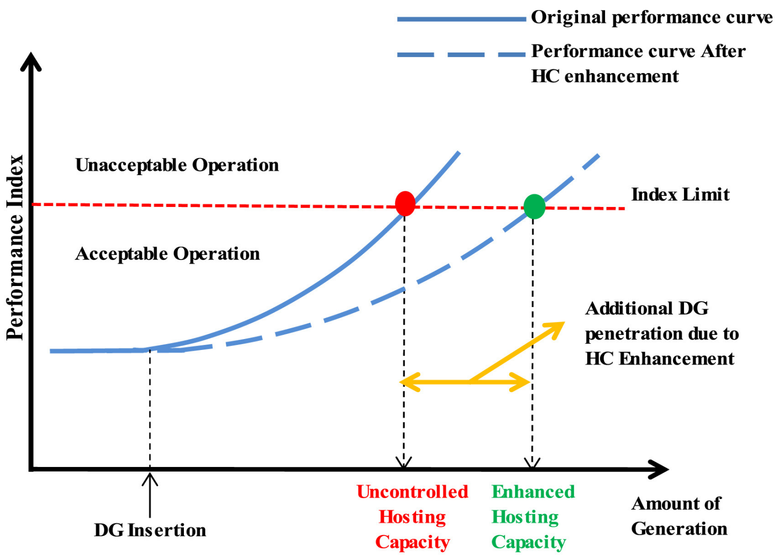


Figure 6.1: *HC concept and the effect of its enhancement, retrieved from [139].*

in a deterministic way. The only missing information is the capacity of the generator, which is the variable to be optimized. In this case, the problem has a unique set of input and also the optimal solution will be unique and well defined. According to this approach, many studies are devoted to finding the optimal technology, size, and placement of DGs in power systems that can maximize the Hosting Capacity [145, 146]. On the other hand, with the probabilistic approach, different combinations of input are considered. Each set of input is defined introducing the variability that characterizes the loads and the production and an optimal solution can be found for each set of input. Probabilistic approaches can be developed with different levels of variability depending on the number of variables that are considered stochastic: a stochastic behavior can be considered for the load while the position of generators and their production profiles are assumed deterministic [141]; the position of generators can be defined but their production profiles can change according to a probability distribution [142, 147]; both the position and the production profiles of generators can be considered stochastic, while the load profiles are supposed deterministic [143, 144]; finally, DG's position can change stochastically, while their production is deterministic [148]. In Italy, studies to evaluate the nodal HC in MV and LV grids have been also commissioned by the National Energy Authority. Such studies had been based on an extended sample of the Italian distribution system (the database was detailed in about 5% of the Italian MV distribution grid, and 1% of the LV one) [149, 150].

This thesis work does not focus on the fault conditions, but for the sake of completeness, it is worth to cite [151], where a review of the issue of DG from the protection perspective is proposed. As remarked by the authors, "traditional distribution networks are generally radial by design and the protection strategies that are in use assume single-source in-feed and radial current flows", but the integration of DGs transforms the distribution network into a multi-source system allowing two-way power flows. In addition, the variability of the DG production to the system have the effect of producing variable fault levels and currents, further compromising the protection coordination.

Therefore, the classical protection strategies has to be changed and specific researches are devoted to define new suitable strategies.

6.1.2 Characteristics of ECs

The knowledge of the DG effects on the distribution networks and the concept of HC are fundamental to understand the impact that the ECs could have on the distribution systems. As already introduced, activating an EC could be simplified as the deployment of one or more generators on the distribution network, driving to an increase of the penetration of the dispersed generation. Nonetheless, there are some characteristics that are typical of the EC, therefore the study of the hosting capacity differs in some ways. The main differences between the classical DG and new generation from EC are reported in Table 6.1. The first element that differentiate these forms of generation is the purpose that drive its installation. The spread of DG has two main economical drivers: in one case the purpose of the installation is the internal usage of the energy produced (self-consumption), in the other case is to sell the entire production, often for the presence of incentive for the renewable energy production (e.g. Feed-in tariff mechanism). The main differences of the generators installed in an EC's perspective is that they are sized and controlled in order to maximise self-consumption and energy sharing. The goal is similar to the one of the simple self-consumption logic, this allows to avoid generation oversizing, nevertheless some complications occur and the impact on the distribution network is different. The positions of the users, loads and generators on the grid can obviously be different. This means that a generator or a storage can be controlled in order to maximize the self-consumption of the energy community, but since the energy balance of the energy community is commercial and its it blind from the point of view of the network, it could also be in contrast with the optimal electrical balance of the feeder on which it is connected. The last difference concerns the reason for installing an ESS. For DG dedicated to energy production and sale (i.e not coupled with a load), the installation of an ESS may have different interests. Theoretically, it could be used for energy arbitrage, production-shifting or for providing ancillary services. On the other hand, in case the DG is dedicated to an EC, ESS can be an effective solution to maximise self-consumption. ESSs are not a novelty in the framework of self-consumption, and they are always more common for private usage. The peculiarity for ECs applications is that the quote of self-consumed energy is evaluated on the set of distributed consumers.

Table 6.1: *Main differences between classical DG and new generation from ECs.*

	Classical DG		Energy community
Purpose	Self-consumption	Sell energy	Energy sharing
Generation portfolio	Optimized for single user's consumption	Driven by market request and presence of incentives	Optimized for EC members' aggregated consumption
ESS	Behind the meter application (intra-POD balancing)	Not useful	Collective storage (inter-PODs balancing)

6.1.3 P2P trading

Given that energy sharing and P2P markets have some similarities, actually they are two options for a consumer-centric energy system, it is worth to mentioning that some researches focus on the effect of P2P trading on the distribution network. The authors of [152] notice that a major challenge to implementing P2P energy trading is ensuring that network constraints are not violated during the energy exchange. Therefore, they propose a methodology based on sensitivity analysis to assess the impact of P2P transactions on the network fluxes and to guarantee an exchange of energy that does not violate network constraints. In [153], a mechanism to estimate the losses associated with P2P transactions is proposed. A non-P2P case is considered, in this case the excess generation of the prosumers are sold to the grid at feed-in tariff rate, then for the same network topology a P2P case is considered, in order to investigate the consequence of P2P trading on the network losses. Similarly, in [154] the authors build a distributed P2P trading model, investigating the impact of distribution network losses on P2P trading. Moreover, they consider that the DSO can charge participants the costs for network losses. In [155], the impact of P2P energy trading on short-term planning and operation of the distribution network is investigated. The objective function of planning is to minimize the overall cost for both of the customers and the utility. Even if these studies are based on the concept of P2P trading and not on energy sharing, they provide some interesting contribution, that can result interesting also in the case of energy sharing within an EC.

6.2 Proposed methodology

For the evaluation of the impact of an EC on the distribution network a stochastic methodology based on Monte Carlo simulations has been proposed. The EC model considered is based on the possibility for users located on the same MV network to constitute an EC and share energy within the area using the public distribution network. The EC would install a DER portfolio based on its preferences and this will have impact on the operation of the grid. The portfolio is composed of one or more generators based on different energy sources and, possibly, a centralized ESS.

The following sets of elements are used for modelling the problem.

- U_{Area}^{LV}: Low voltage passive users fed by the MV grid (through a MV/LV substation);
- U_{Area}^{MV}: Medium voltage passive users connected to the MV grid;
- G_{Area}: Generators connected to the MV grid;
- U_{EC}^{LV}: Low voltage passive users, members of the EC;
- U_{EC}^{MV}: Medium voltage passive users, members of the EC;
- G_{EC}: Generators of the EC connected to the MV grid.

The evaluation of the impact is based on four main steps, that are here briefly introduced and analysed in the detail in the following sections.

- **Loads**. The EC's members are a subset of the passive users of the area. They can be both MV users directly connected to the considered network, or LV users fed through MV/LV transformers.

$$\begin{cases} U_{EC}^{LV} \subset U_{Area}^{LV} \\ U_{EC}^{MV} \subset U_{Area}^{MV} \end{cases} \tag{6.1}$$

- **Generators**. The EC installs a set of new generators G_{EC} according to an optimal generation portfolio that is sized on the energy needs of the members and bounded to the local source availability. The definition of the EC's generation portfolio is optimized according to specific objective functions that could be, as examples, the minimization of the exchanges of the EC with external actors or the maximisation of the economic value of the investment (as seen in Chapter 4). The generators connected to the MV network will be the sum of the ones already connected in the base case, and the ones resulting from the EC portfolio optimization.

$$G = G_{Area} \cup G_{EC} \tag{6.2}$$

- **Energy storage system**. An energy storage system ESS_{EC} can be installed to maximise the energy shared within the EC and to reduce the exchanges with other actors that are not members of the EC[2].
- **Electrical analysis**. The energy flows are evaluated on the MV grid for an yearly duration with hourly time steps. The topological limits of the network are the primary substation, with the HV/MV transformer and the MV secondary substations in which MV users and low voltage grids are connected.

To each of the four elements introduced in the previous list corresponds a different step of the proposed methodology. The flowchart of the entire procedure is shown in Figure 6.2 and each step is described in the following.

6.2.1 Energy community loads

1. The set of LV users that participate to the community is defined. In most of the practical cases, it is not necessary to model each single LV user when considering MV networks. The number of LV users is high enough so that the scale effects cover the behaviors of individuals. Given this, considering each LV user could be an expensive and over-detailed representation. Therefore, the meaning of participation to the EC is transposed from the single LV user to the entire low voltage grid connected to each secondary substation. Consequently, the probability for the low voltage networks to take part to the energy community is defined, and the set of secondary substations that participate to the EC is computed. The total power profile of the LV users of the community $EC_{load}^{LV}(t)$ is evaluated as:

$$EC_{load}^{LV}(t) = \sum_{i \in U_{EC}^{LV}} load_i(t) \tag{6.3}$$

---

[2] The shared energy is defined, as for the previous chapters, as the minimum value between production and consumption in the same hour.

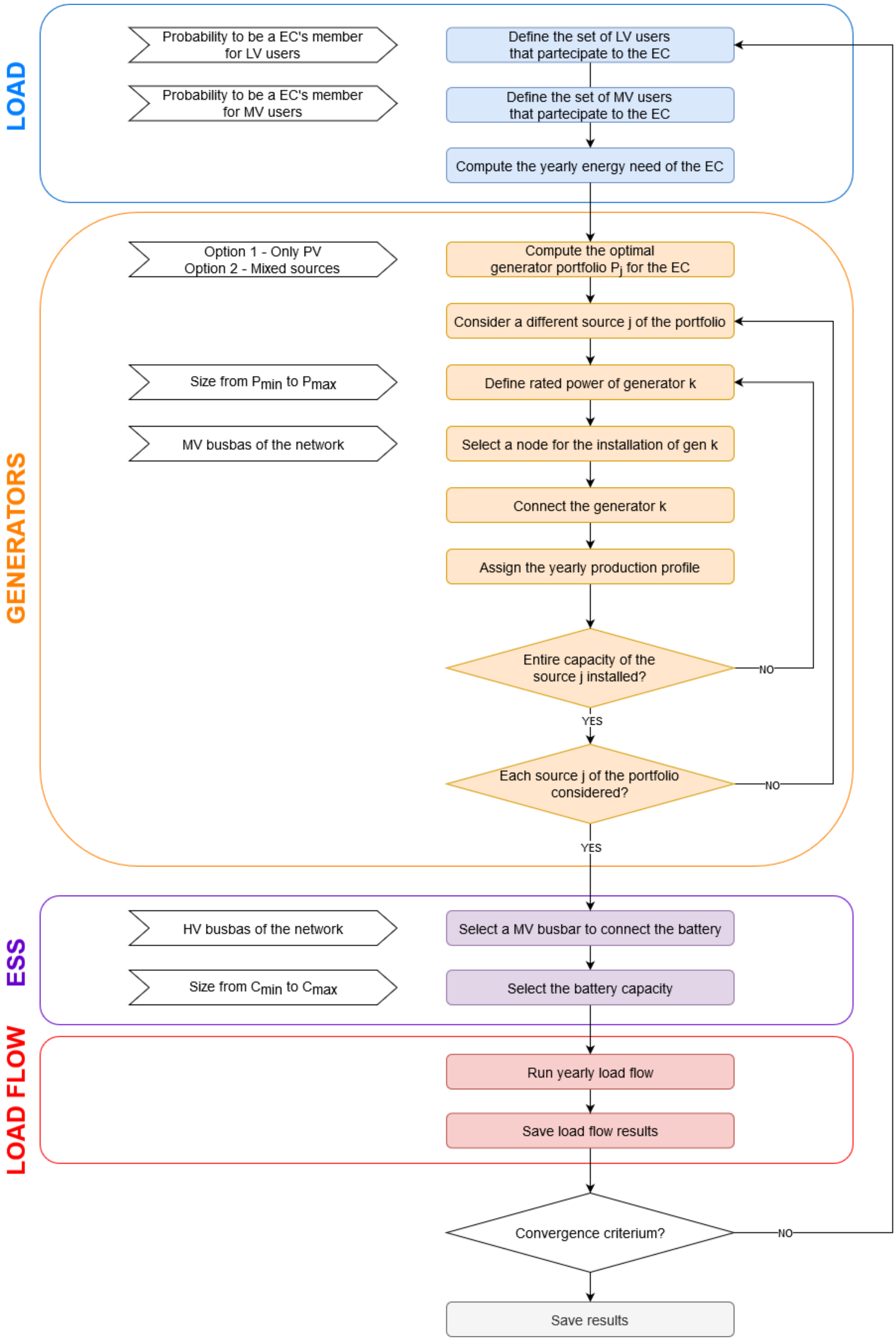


Figure 6.2: *Flowchart of the Monte Carlo procedure*

where $load_i(t)$ is the power profile of the user i and U_{EC}^{LV} is the set of LV users within the EC. It is defined from the entire set of LV users of the area, considering for each user u_i the probability $Prob_{LV}$ to participate to the EC.

$$\begin{cases} u_i \in U_{EC}^{LV} & \text{if } x_i \leq Prob_{LV} \\ u_i \notin U_{EC}^{LV} & \text{if } x_i > Prob_{LV} \end{cases} \text{where} \begin{cases} x_i = random(0,100) \\ Prob_{LV} \in (0,100) \end{cases} \tag{6.4}$$

2. The set of MV users is defined in a similar way. In this case there are no simplifications and all the passive MV users are considered singularly. The subset of MV users that are members of the EC is defined based on the probability to take part to the energy community $Prob_{MV}$. The total power profile of the MV users of the community $EC_{load}^{MV}(t)$ is evaluated as:

$$EC_{load}^{MV}(t) = \sum_{i \in U_{EC}^{MV}} load_i(t) \tag{6.5}$$

   where $load_i(t)$ is the power profile of the user i and U_{EC}^{MV} is the set of MV users within the EC. It is defined from the entire set of MV users of the area, considering for each user u_i the probability $Prob_{MV}$ to participate to the EC.

$$\begin{cases} u_i \in U_{EC}^{MV} & \text{if } x_i \leq Prob_{MV} \\ u_i \notin U_{EC}^{MV} & \text{if } x_i > Prob_{MV} \end{cases} \text{where} \begin{cases} x_i = random(0,100) \\ Prob_{MV} \in (0,100) \end{cases} \tag{6.6}$$

3. The overall load profile of the community $EC_{load}(t)$ is computed as the sum of the loads of LV and MV users. It will be used in the next step to size the EC's generation portfolio.

$$EC_{load}(t) = EC_{load}^{LV}(t) + EC_{load}^{MV}(t) \tag{6.7}$$

   The yearly energy request of the EC is computed in order to have a relative penetration of the EC with respect to the overall local load. The EC's penetration ($EC_{penetration}$) is computed as the ratio between the yearly energy request of the EC and the yearly energy request of the entire set of users connected to the MV network.

$$EC_{penetration} = \frac{\sum_t EC_{load}(t)}{\sum_t Area_{load}(t)} \cdot 100 \tag{6.8}$$

   where

$$Area_{load}(t) = \sum_{i \in U_{Area}^{LV}} load_i(t) + \sum_{i \in U_{Area}^{MV}} load_i(t) \tag{6.9}$$

6.2.2 Energy community generators

1. The optimal generation portfolio for the EC is evaluated according to a predefined objective function. This optimization is a key element of the procedure since it reflects the behaviour and the preferences of the EC. This is one of the two steps in which the difference between the generic distributed generation and the energy community emerges (the second one in the usage of an energy storage system).

The objective function can be based on energy balances, such that the EC can try to reduce the interchanges with the other actors, but it can also be based on others variables such as economical or environmental. If properly modelled, this optimization allows to answer the question "what kind of energy communities will spread if their members aim to reach a specific target?". The result of the optimization is a vector that contains the optimal rated power P for each considered source j. The installation of the optimal portfolio brings to a production profile equal to $EC_{gen}(t)$, given by the sum of the energy produced by each generator. The same normalized production profile $prod_j(t)$ is considered for each source j, in this way the total production can be evaluated as:

$$EC_{gen}(t) = \sum_{j \in Types} prod_j(t) \cdot P_j \tag{6.10}$$

where:

- $Types$ is the set of different sources considered (e.g. PV, Hydroelectric, Wind, Biomass...);
- $prod_j(t)$ is the normalized production profile for each source j;
- P_j is the overall rated power for the generators of type j.

Two strategies based on the energy balance of the EC have been implemented.

Strategy 1

With the first strategy, the EC produces the same amount of energy consumed by its members during the year, but it is not interested in the contemporaneity between production and consumption. The generation portfolio is sized in order have a net-zero balance over the year, with the installation of photovoltaic power plants.

$$\sum_{t \in year} EC_{load}(t) = \sum_{t \in year} EC_{gen}(t) \tag{6.11}$$

Strategy 2

With the second strategy, the EC is interested in minimizing the energy exchanged with external actors. In this way it wants to reduce the dependency from external suppliers, but at the same time to avoid to inject energy into the grid when it is not required by the community members. In this scenario, the objective function that has been adopted is the minimization of the energy exchanges. To achieve an higher contemporaneity between loads and production, also sources different from PV are evaluated.

$$EC_{exchanges} = \sum_{t \in year} |EC_{load}(t) - EC_{gen}(t)| \tag{6.12}$$

The limited source availability is considered by mean of a specific set of constrains that limits the installed power P_j to the maximum available P_j^{max}.

$$P_j \leq P_j^{max} \tag{6.13}$$

2. The total rated capacity indicated in the optimal portfolio is divided into a set a generators G_{EC} that are then connected to different nodes of the grid. Each source j is considered separately and the size of the generators is selected from a uniform distribution probability, from a minimum of 200 kW to a maximum of 10 MW. These limits are defined in order to consider the entire range of generator sizes that, according to the Italian Authority [156], could be connected to the MV network. Then, each generator k is connected to a node that is selected with a constant probability from the set of the MV nodes of the grid[3]. The hourly production profile for each generator is obtained multiplying the normalized profile defined for the source j for the rated power of the generator. Other generators are added in the same way, until the total capacity for that source is installed. The sum of the rated power of the generators that exploit source j is equal to the optimal overall rated power defined in the portfolio.

$$P_j = \sum_{k \in G_{EC}^j} RP_k \tag{6.14}$$

where RP_k is the rated power of generator k and G_{EC}^j is the subset of generators of the community that exploit the source j.

6.2.3 Energy storage system

1. An energy storage system is considered in order to maximise the energy shared within the EC and reduce the exchanges with others market actors. A centralized storage is considered in the primary substation. This means that it contributes to reducing the usage of the transmission network, but it does not affect the energy flows on the local MV network. The nominal capacity of the energy storage system ESS_{cap} can be defined in the optimization phase, or it can be randomly selected from a distribution probability function.

2. The control logic of the ESS charges the storage when there is a surplus of energy (EC's production higher than EC's energy requests) and discharges it when there is a deficit. The power request to the ESS P_{ESS} is consequently defined as the difference between the energy community request EC_{load} and production EC_{gen}. Positive values mean that the storage is behaving as a generator, while negative values mean it is behaving as a load.

$$P_{ESS}(t) = EC_{load}(t) - EC_{gen}(t) \tag{6.15}$$

The state of charge is updated considering the power exchange, according with the following formula:

$$SOC(t+1) = SOC(t) - \frac{P_{ESS}(t)}{ESS_{cap}} \cdot 100 \tag{6.16}$$

The model of the ESS has constrains that limit minimum and maximum State Of Charge (SOC).

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \;\; \forall t \in \text{year} \tag{6.17}$$

---

[3] The probability distribution functions could be refined as presented in [13]

Where SOC_{min} and SOC_{max} are the minimum and the maximum SOC in which the ESS is allowed to operate. If these bounds are reached, the $P_{ESS}(t)$ saturates in order to not overpass the SOC limits at time $t+1$. Another constrain is defined in order to consider the limitation of the maximum power exchange of the ESS.

$$\begin{cases} P_{ESS}(t) \leq P^{dis}_{max} & \forall\, t \text{ s.t. } P_{ESS}(t) > 0 \\ -P_{ESS}(t) \leq P^{ch}_{max} & \forall\, t \text{ s.t. } P_{ESS}(t) < 0 \end{cases} \tag{6.18}$$

Where P^{dis}_{max} is the maximum discharging power and P^{ch}_{max} is the maximum charging power of the ESS. As for the previous constrain, the power exchanged by the ESS saturates when these bounds are reached.

6.2.4 Quasi-dynamic load flow

1. The yearly operation of the network is simulated and the power flows are computed for each hour of the year. Given the presence of time dependent variables related to the ESS, it is necessary to execute the quasi dynamic analysis in chronological order and parallel calculation is not possible.

6.2.5 Convergence criterion.

Monte Carlo iterations are stopped when the convergence criterion is reached. The proposed criterion in based on the results of the quasi-dynamic load flow evaluation, specifically on the grid losses. A double check is required: the convergence is reached when both the mean value and the standard deviation of the losses are stable within a tolerance limit. After each iteration i, the mean value of the grid losses $\mu_{Loss}(i)$ and their standard deviation $\sigma_{Loss}(i)$ are evaluated considering all the previous iterations. Starting from the second iteration, the difference between the most updated values and the ones resulted from the previous iteration are computed. These differences are evaluated in percentage as detailed in Equations 6.19 and 6.20.

$$\Delta\mu_{Loss}(i) = \frac{\mu_{Loss}(i) - \mu_{Loss}(i-1)}{\mu_{Loss}(i-1)} \cdot 100 \tag{6.19}$$

$$\Delta\sigma_{Loss}(i) = \frac{\sigma_{Loss}(i) - \sigma_{Loss}(i-1)}{\sigma_{Loss}(i-1)} \cdot 100 \tag{6.20}$$

The convergence is reached when these variations are smaller than a limits ϵ for a number of consecutive iterations N_{conv}.

6.2.6 Result processing

For each EC configuration (i.e. for each Monte Carlo iteration) a set of variables is stored. The aim is to identify the correlations between the penetration level of the EC and a set of performance indexes. These variables are divided in three categories that correspond to the community itself, to the local area in which the EC is supposed to develop and to the MV distribution grid to which EC's loads and generators are connected.

Variables related to the community

- N_{LV} Number of LV users (the number of elements of U_{EC}^{LV})
- E_{LV} Yearly energy request from LV users [MWh]

$$E_{LV} = \sum_t EC_{load}^{LV}(t) \tag{6.21}$$

- N_{MV} Number of MV users (the number of elements of U_{EC}^{MV})
- E_{MV} Yearly energy request from MV users [MWh]

$$E_{MV} = \sum_t EC_{load}^{MV}(t) \tag{6.22}$$

- N_j Number of generators exploiting the energy source j
- E_j The yearly energy produced from each type of source considered j [MWh]
- P_j The overall rated power for each type of source considered j [MW]
- RP_j The rated power of the single generator of type j [MW]
- ESS_{cap} ESS capacity [MWh]
- $EC_{surplus}$ Energy community yearly surplus [MWh]
- $EC_{deficit}$ Energy community yearly deficit [MWh]

  Moreover, the information about users and generators are grouped also for feeder f:
- N_{LV}^f Number of LV users on feeder f
- E_{LV}^f Yearly energy request from LV users on feeder f [MWh]
- N_{MV}^f Number of MV users on feeder f
- E_{MV}^f Yearly energy request from MV users on feeder f [MWh]
- N_{gen}^f Number of generators for each source j located on feeder f
- E_{gen}^f Yearly energy production for each source j on feeder f [MWh]

Variables related to the area

- $Area_{load}$ Yearly energy request from the area [MWh]
- $Area_{gen}$ Yearly energy production in the area [MWh]
- $Area_{import}$ Yearly energy import of the area [MWh]
- $Area_{export}$ Yearly energy export from the area [MWh]

Variables related to the network

- Yearly Losses [MWh/year]
- Number of overloaded branches
- Maximum loading of the branch elements [%]
- Maximum voltage of the grid nodes [p.u.]

6.3 Software implementation

The methodology proposed has been implemented in a software framework based on two different modules: DIgSILENT PowerFactory for the electrical simulations and Python for automatizing the process. This framework exploits the synergic relationship that can be established between PowerFactory and Python libraries thanks to the Python API provided with PowerFactory. The integration among the two environments allows to get the best performances from each one. In the developed framework, Python is the main environment, while PowerFactory is called in engine mode (i.e. it is used in background). The usage is not sequential since the interaction between the environments is continuous. In the following, the main tasks of each of the two tools are listed.

Python

- Stochastic definition of the EC members;
- Optimization of the EC's portfolio (Pyomo library and solver Gurobi);
- Stochastic definition of the generators characteristics;
- Read/write operations on the network database within DIgSILENT PowerFactory;
- Statistical analysis and visualization.

DIgSILENT PowerFactory

- Hosting network model database;
- Execution of the quasi-dynamic simulations;
- Control logic of the ESS;
- Visualization of GIS model;
- Visualization of electrical schemes.

6.3.1 Network modelling

To enable the communication between the two modules, the network model has to be already present into the PowerFactory database. An automatic procedure based on a set of Python scripts have been coded in order to create a PowerFactory model of the grid that can be easily interfaced with the Monte Carlo procedure.

6.4 Selection of the test grids

Two real distribution networks have been selected and modelled in PowerFactory environment in order to apply the defined procedure. A criterion for the choice of the networks has been the need for evaluating both rural context and urban ones. In general, in the rural context there is higher source availability but lower loads, while in the urban one the concentration of loads is higher but the energy source are scarce. The model of the networks are based on the dataset of the DSO. The power flows on the grids in the base scenario (i.e. without energy communities) are evaluated for each hour of the year, based on real measurement collected in 2019. Specifically, all the MV users profiles come from real measurements, while MV/LV substations profiles have been obtained with the following procedure. Given the yearly power profile in primary substation and the power profile related to all the MV users, the power profile that represents the sum of the power in all the secondary substations is obtained as difference between them. This profile is then scaled on each secondary substation proportionally to the ratio between the energy absorbed in the reference year by the substation under investigation and the total energy correlated to MV/LV substations [13]. The main characteristics of the test grids are detailed in the following paragraphs.

6.4.1 Test grid 1 - Urban MV network

The first grid considered is the grid of the city of Aosta (Figure 6.3). The grid extends mainly in the city center, even if few lines reach the southern rural periphery of the town, composed of small mountain villages. In the primary substation there are two HV/MV transformers, with a rated power of 25 MVA. It is characterized by a large number of feeders (17) with an average length of 8 km. The most of the lines is made by cables (78.4%) while overhead lines are a smaller part of the total length (21.6%). The yearly energy requested by secondary substations (i.e. low voltage users) is 95.7 GWh, while the yearly energy requested by MV users is 58.6 GWh. This load can be only partially satisfied with local production (29.6%), since the injection into the MV grid are only 45.6 GWh. This cause a local deficit of 108.7 GWh per year. On the other hand, energy produced locally is entirely consumed within the MV network and there is no energy surplus. In Figure 6.5 (a) the hourly profile of the power injections and requests are shown. It can be noticed that the request is, hour by hour, higher than the injection. This generates the surplus and deficit profiles of Figure 6.6 (a). As already said, energy surplus never occurs, while there is always an energy deficit. It has to be noticed the peculiar shape of the injections, that has a lower production from June to October. This is due to an important Combined Heat and Power (CHP) generator that feed the district heating of the city that is switched off during summer. Looking to this graph, it is clear that there is a deficit of energy that could be easily reduced installing new generation units. Finally, Figure 6.7 (a) represents, by mean of a Venn diagram, the main self-sufficiency indicators for the network. The hourly withdrawal are represented with the set on the left, while the energy injections are represented with the set on the right. Their intersection represents the energy that, hour by hour, is inject and withdrawn locally. The part of withdrawal set not in the intersection represents the deficit of energy, while the part of injections set not in the intersection represents the surplus of energy. It is trivial that, for test grid 1, the injections set is completely included in the withdrawal one and there is no surplus. Executing the quasi-dynamic simulation of the network for the base case scenario, the losses and the maximum loading of the grid branches have been evaluated. Power profiles over one year with a hourly granularity have been evaluated. The yearly losses result equal to 1,770 MWh. This number included the losses of the transformers in the primary substation and the losses on the lines. The transformer losses are equal to 1,029 MWh, while the line losses are 741 MWh. The line losses per km of line are 5.43 MWh. The maximum loading of each branch is reported in Figure 6.8. It is possible to see that only two elements reach a maximum loading particularly high (higher than 70%). These are due to the already cited CHP.

This generator has an electrical power of 7 MW and it is connected to the red busbar of the primary substation. The line that connects the CHP generator to the primary substation is a dedicated connection sized for the maximum power of the generator, therefore it is normally operated around 70-75% of the nominal capacity. The second element that is much more loaded than the other is the red transformer in the primary substation (the one to which the CHP generator is connected). In this case, so high values are exceptions that occur in winter, when the CHP is off. Indeed, most of the winter loads are connected to the red busbar, since the CHP is producing at the nominal power for most of the time, and energy flowing in the red transformer are limited. It happens that, for few hours, the CHP generator is off for some reasons (maintenance, faults...) and all the load connected to the red transformer is fed from the HV side, increasing the loading of the transformer. All the other branches of the system have a maximum loading lower than 47%, with an average value of 14.3%.

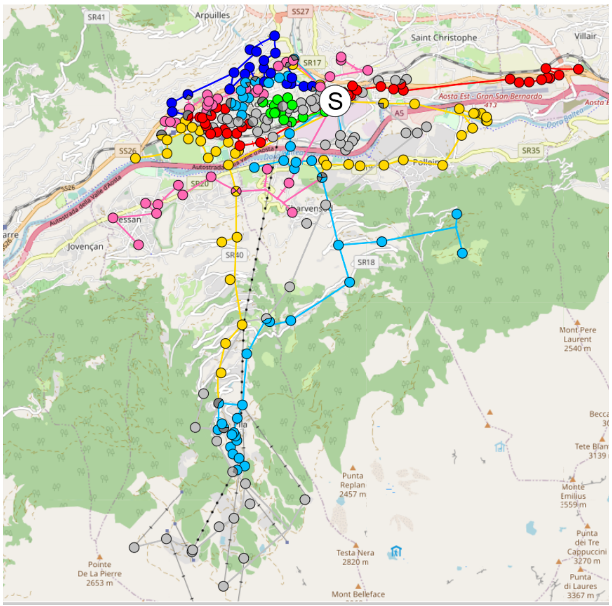


Figure 6.3: *Geographic view of the medium voltage test grid 1 (city of Aosta). It is possible to notice the high density typical of urban areas and the existence of a single primary substation.*

6.4.2 Test grid 2 - Rural MV network

The second grid considered is the one of the valley of Cogne. In this case the topology is not a radial standard one. The feeders that connect the valley of Cogne with the HV network start in the primary substation named Villeneuve, located at the entrance of the valley, and they terminate in the MV/MV substation in the village of Cogne. In Figure 6.4, it is possible to see the primary substation of Villeneuve on the top left of the map, and the village of Cogne on the lower right. From here, three smaller feeders depart and connect the users in the upper part of the valley. For this reason, the network is characterized by longer feeders (+61% with respect to test grid 1), and the presence of overhead lines is more important than for test grid 1 (49.3% instead of 29.5%). Another big difference is the low presence of MV loads (1.0 GWh/year) and the high presence of MV active users (12.2 GWh/year). This cause a surplus of energy that produce a reverse power flow in the primary substation, i.e. in some periods, the system is injecting energy into the HV transmission grid. This is due to an important presence of hydroelectric power plants, whose production is concentrated in the summer months, as clearly shown in Figure 6.6 (b). Because of this overproduction concentrated in a short period, only 70.6% of the energy injected into the MV network is consumed locally. In this way, the area have a surplus of energy in summer, but still have a deficit during the rest of the year. This situation is depicted in the Venn diagram in Figure 6.7 (b). In the electrical model of the primary substation of Villeneuve, only the HV/MV transformer to which the feeders of Cogne are connected is represented. The quasi-dynamic simulation shows that the yearly losses are 312 MWh. The losses due to transformers are 144 MWh, while the ones due to the distribution lines are 168 MWh. The losses per km of line are 2.61 MWh/km, a lower value with respect to the ones of Aosta. Also in this case, it is possible to identify two elements that are more loaded than others (but in any case lower that 50%). The first one is a long overhead line 2.8 km at the entrance of the valley (maximum loading 42%), the second one is the MV/MV transformer in the substation of Cogne (maximum loading 47.7%). It is interesting to notice that these values occur both in summer and in winter since the maximum direct and reverse flows are similar. The maximum loading of the other elements of the grid is limited to 33%. A comparison between the test grids is reported in Table 6.2.

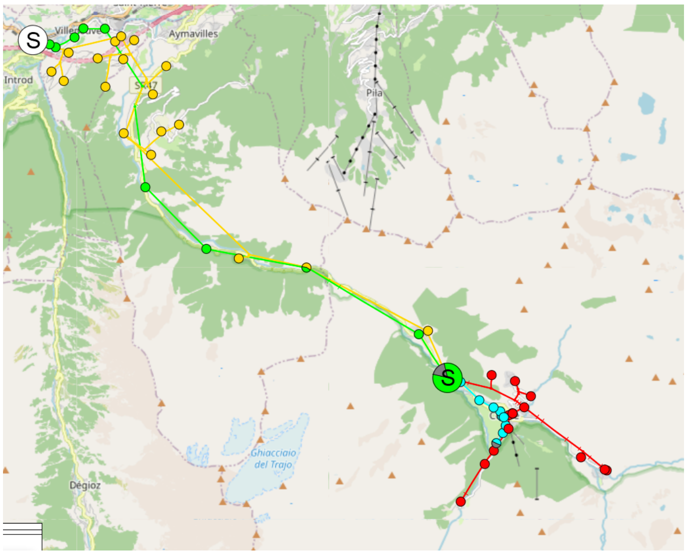
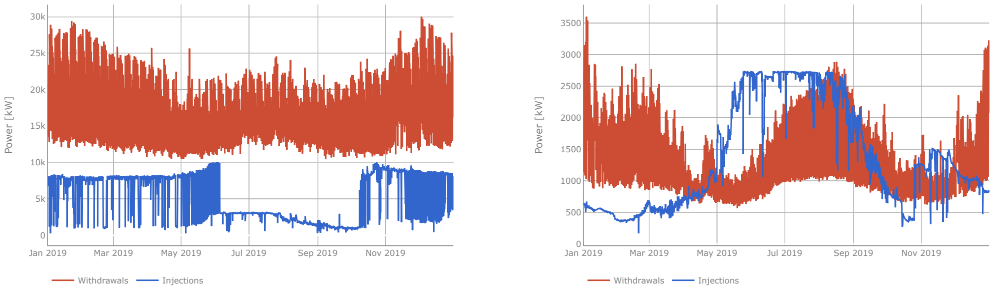


Figure 6.4: *Geographic view of the medium voltage test grid 2 (valley of Cogne). It is possible to notice the low density typical of rural areas and the existence of the primary substation and the MV/MV one.*

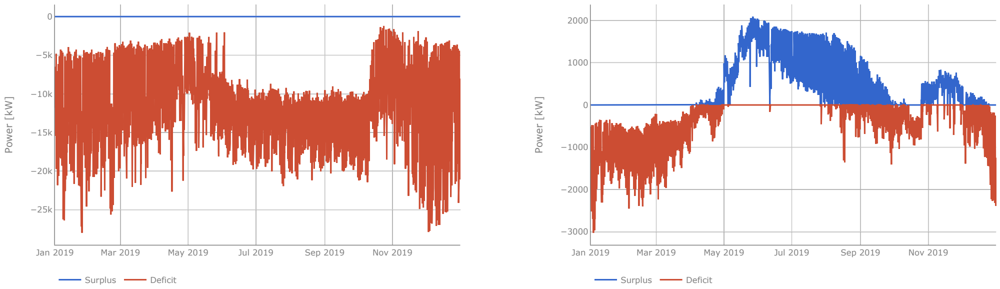
6.5 Strategies and boundaries for portfolio optimization

As explained in Section 6.2.2, the optimal generation portfolio is defined according to the objective function of the EC. It is reasonable that ECs will take their decision based on economical objective functions. Nevertheless, in the Italian scenario the development of ECs on a MV network scale has not yet been defined (see 2.2.2), therefore this kind on objective function has not been implemented. Nonetheless, to analyse the



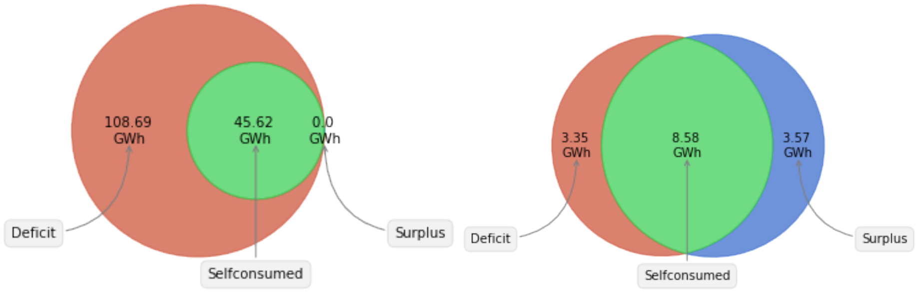
(a) Aosta (b) Cogne

Figure 6.5: *Hourly injections (blue) and withdrawals (red) for the test grids.*



(a) Aosta (b) Cogne

Figure 6.6: *Hourly surplus (blue) and deficit (red) for the test grids.*



(a) Aosta (b) Cogne

Figure 6.7: *Self-sufficiency status for the test grids.*

Table 6.2: *Comparison between the two test grids.*

	Test grid 1	**Test grid 2**
Grid name	Aosta	Cogne
Grid type	Urban	Rural
Number of feeders	17	5
Total line length	136.4 km	64.3 km
- Cable	- 106.9 km (78.4%)	- 32.6 km (50.7%)
- Overhead line	- 29.5 km (21.6%)	- 31.7 km (49.3%)
Mean feeder length	8.0 km	12.9 km
Number of secondary substations	225	45
Number of LV users	27768	3717
Yearly LV users request	95.7 GWh	11.0 GWh
Average yearly request per LV user	3447 kWh	2951 kWh
Number of MV users	70	11
- Passive	- 59	- 6
- Active	- 11	- 5
Yearly MV users request	58.6 GWh	1.0 GWh
Yearly MV users injections	45.6 GWh	12.2 GWh
Deficit	108.7 GWh	3.4 GWh
Energy produced and consumed locally	45.6 GWh	8.6 GWh
Surplus	0 GWh	3.6 GWh
Locally produced energy (% of local consumption)	29.6%	71.6%
Locally consumed energy (% of local production)	100%	70.6%
Losses	1,770 MWh	312 MWh
Losses trafo	1,029 MWh	144 MWh
Losses lines	741 MWh	168 MWh
Losses lines/km	5.43 MWh/km	2.61 MWh/km
Loading max (max)	76.6 %	47.7 %
Loading max (avg)	14.3 %	8.50 %
Maximum voltage (max)	1.005 p.u.	1.039 p.u.
Minimum voltage (min)	0.950 p.u.	0.964 p.u.

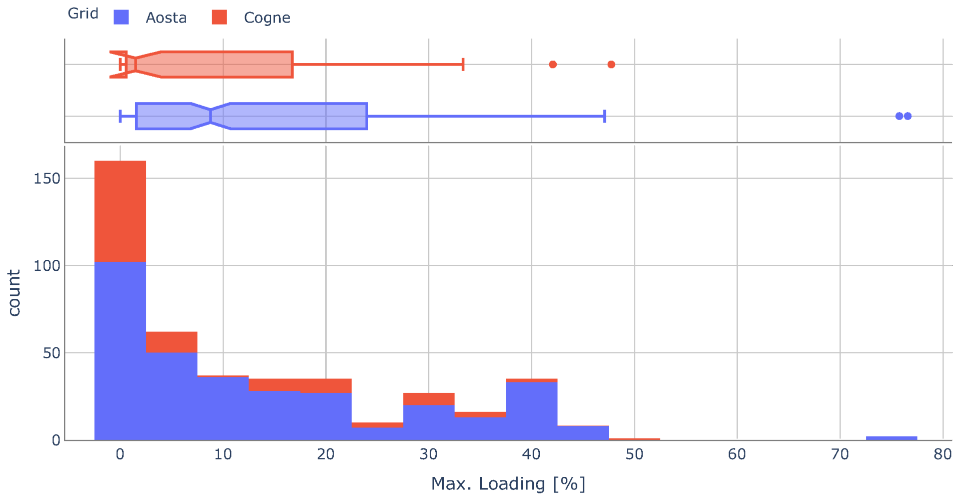


Figure 6.8: *Maximum loading of each branch of the considered networks. The histogram shows the probability distribution, the horizontal boxplot highlights the presence of the highest values.*

effect of selecting two objective functions based on energy balances, the two strategies presented in Section 6.2.2 have been adopted.

When considering the second strategy, the local source availability limits are needed. Thanks to a cooperation with the Regional Energy office of Valle d'Aosta, a suited estimation of the local resources availability has been performed. Specifically, five different energy sources have been considered according to the local source availability. The values are reported in Table 6.3. For each one, a normalized production profile has been computed, based on the average production of the monitored power plants in the area (measurements obtained from DSO data).

Table 6.3: *Energy sources availability in the two study cases.*

Energy source	Test grid 1	Test grid 2
Photovoltaics	96 MW	15 MW
Hydroelectric	0.9 MW	10 MW
Wind	0.5 MW	0.5 MW
CHP	12 MW	6 MW
Biogas	0.5 MW	0.5 MW

6.5.1 Energy storage system

It is trivial that, from the energetic point of view, the size of the ESS should be as big as possible. The main limit of this system is its cost. Therefore, including the ESS in the optimization function requires to consider the economic value of the energy stored and the cost of the ESS. For this reason, the optimization of strategy 1 and 2 are independent from the ESS size. In the Monte Carlo simulation, it is equal to 0 or selected from a uniform distribution probability with the following probabilities.

$$\begin{cases} ESS_{cap} = 0 & 25\% \text{ of the cases} \\ ESS_{cap} = U(0, ESS_{max}) & 75\% \text{ of the cases} \end{cases} \tag{6.23}$$

where the ESS_{max} is the maxium size of the ESS and it is equal to 200 MWh for test grid 1 and 20 MWh for test grid 2.

6.6 Results

6.6.1 Convergence

The converge criterion presented in Section 6.2.5 has been applied for both the test grids and optimization strategies, creating four scenarios. The value of the tolerance ϵ has been set to 0.1% and the number of consecutive iterations in which this tolerance has to respected has been set to 25. For each of the four scenarios considered, the Monte Carlo simulations have reached the convergence criterion with a numbers of iterations comprised between 536 and 589. In Table 6.4, the following variables related to the converge are reported: number of iteration required, mean value of the losses μ_{Loss} and their standard deviation σ_{Loss} at the end of the simulation, marginal variation of the losses and the standard deviation in the last step. The mean value of μ_{Loss} and the standard deviation band σ_{Loss} are depicted in Figure 6.9. On the right part of the figure, an horizontal histogram shows the distribution of the values for each considered case. The values of $\Delta\mu_{Loss}$ and $\Delta\sigma_{Loss}$ are reported in Figure 6.10. It is possible to see that the criterion based on the mean value is the less demanding and it is reached before the one based on the standard variation.

Table 6.4: *Convergence of the Monte Carlo simulations.*

Scenario	Test grid	Strategy	Iterations	μ_{Loss}	σ_{Loss}	$\Delta\mu_{Loss}$	$\Delta\sigma_{Loss}$
Scenario 1	Aosta	Strategy 1	536	2620.2	831.5	0.036%	0.059%
Scenario 2	Aosta	Strategy 2	579	2138.0	520.7	0.018%	0.071%
Scenario 3	Cogne	Strategy 1	589	504.0	214.0	0.048%	0.048%
Scenario 4	Cogne	Strategy 2	567	375.0	65.0	0.008%	0.082%

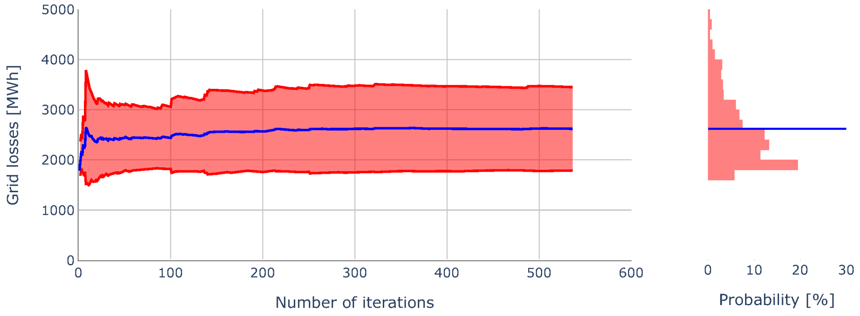
6.6.2 Optimal portfolio

The optimal portfolio for the four considered cases is reported in Figure 6.11. On the left, the optimal capacity for each source of the portfolio is represented versus the EC penetration (i.e. the share of the local needs included into the EC - see Eq.6.8). In the bar graph on the right, the penetration level is divided into ten sub-ranges and the mean capacity of each source is evaluated for each of them. When considering the first strategy, the installed capacity is proportional to the $EC_{penetration}$, since the production has to be equal to the energy request. It is interesting to notice that for Aosta this requires to install more than 150 MW of PV. Considering that the local source availability has been estimated to 96 MW, the exploitation of the solar source is not enough to produce the amount of energy that is request locally. Nonetheless, in the discussion of the results the penetration is not limited to feasible solution for a theoretical comparison.

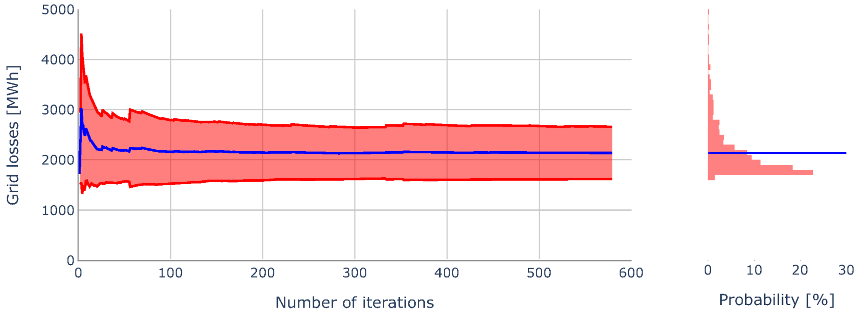
When considering the second strategy, the portfolio includes different energy sources. In the case of Aosta, an important contribution is provided by the CHP, that is included in the optimal portfolio up to the source limits equal to 12 MW. Also hydroelectric, biogas and wind are selected in the optimal portfolio, but their availability in the area is limited to few hundreds of kW, therefor their share in the portfolio is limited. Also for Cogne these energy sources are limited, but in this case, the limits are comparable with the local energy needs, therefore their contributions to the optimal portfolio is not negligible. It is worth to notice that different portfolios may be selected for the same EC penetration. Indeed, two or more ECs with the same energy consumption (i.e. the same value of $EC_{penetration}$) can be composed by different sets of members, each one with its own load profile. Therefore, the load profiles of the ECs are different, and the optimization process select the most appropriated portfolios for each one.

6.6.3 Energy community balance

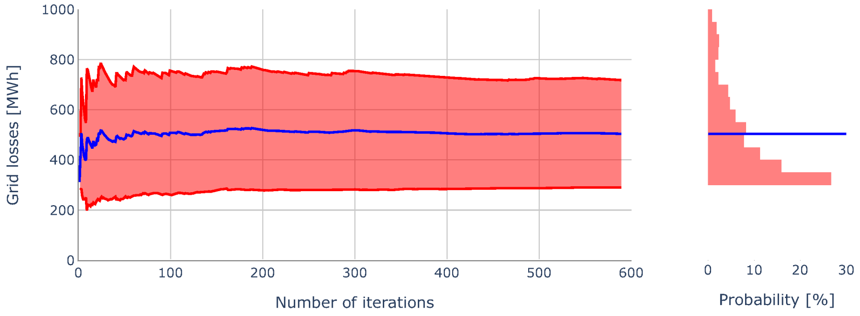
The energy produced by the EC's generators can be directly shared with the members if they require it, otherwise it can be stored in the ESS or injected into the HV network. The ratio of energy produced and consumed, hour by hour, within the EC has been evaluated for each iteration and the results are depicted in Figure 6.12. The



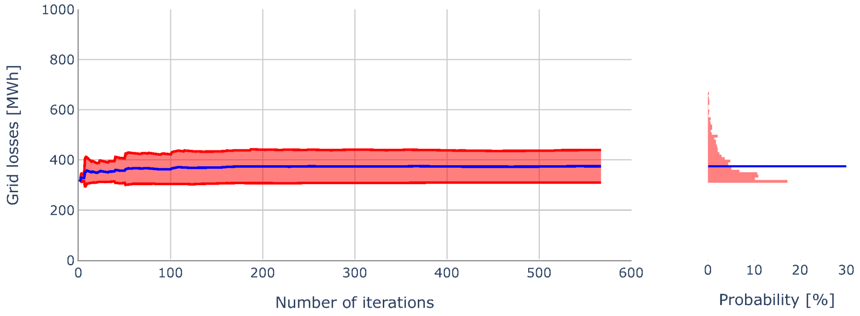
(a) Aosta study case - Strategy 1



(b) Aosta study case - Strategy 2

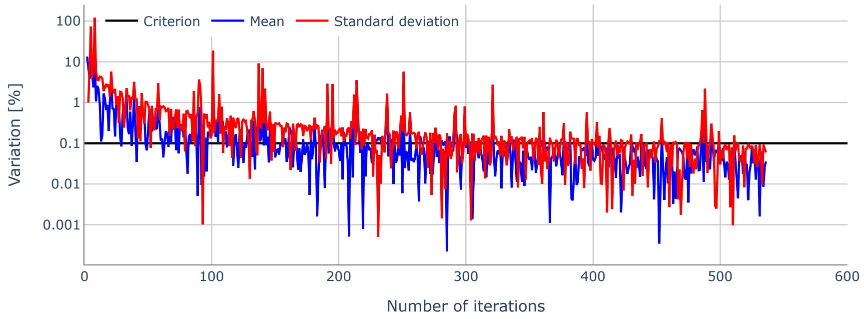


(c) Cogne study case - Strategy 1

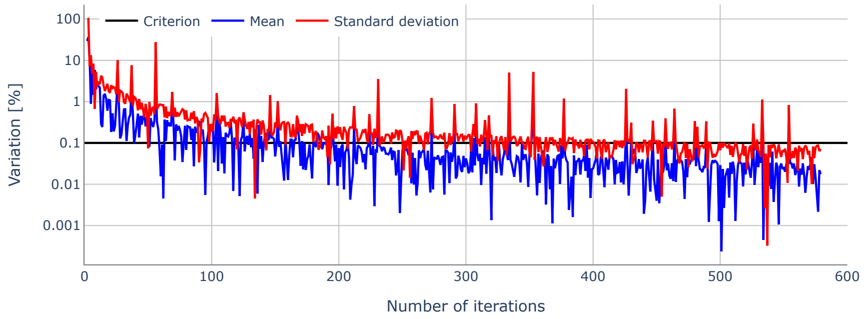


(d) Cogne study case - Strategy 2

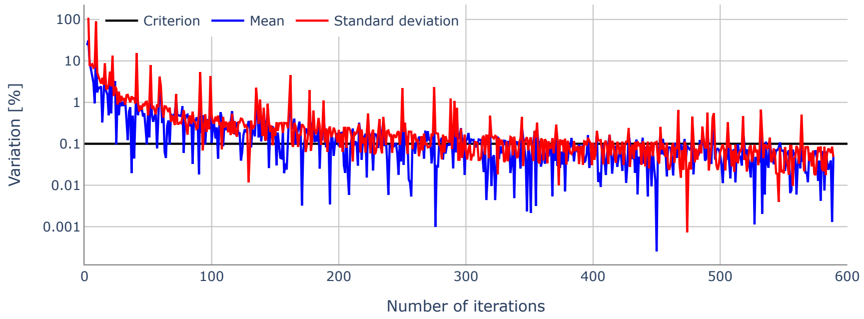
Figure 6.9: *Mean value of the grid losses updated after each iteration. Red band represents the standard deviation.*



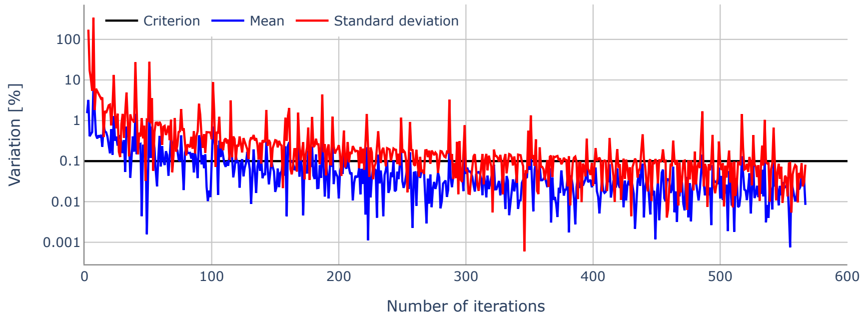
(a) Aosta study case - Strategy 1



(b) Aosta study case - Strategy 2

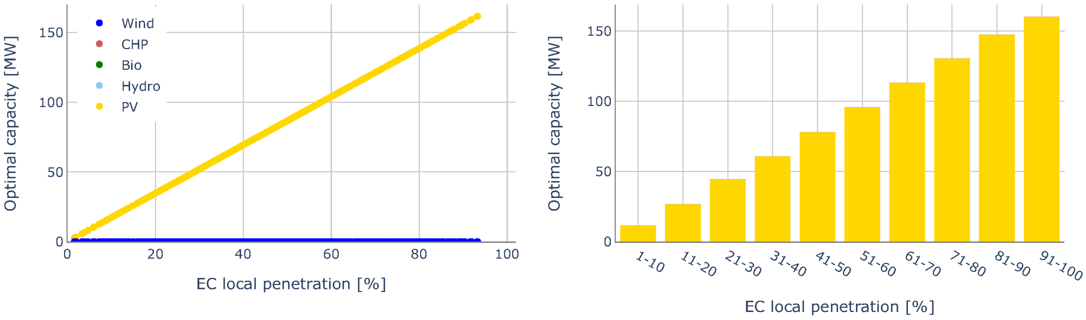


(c) Cogne study case - Strategy 1

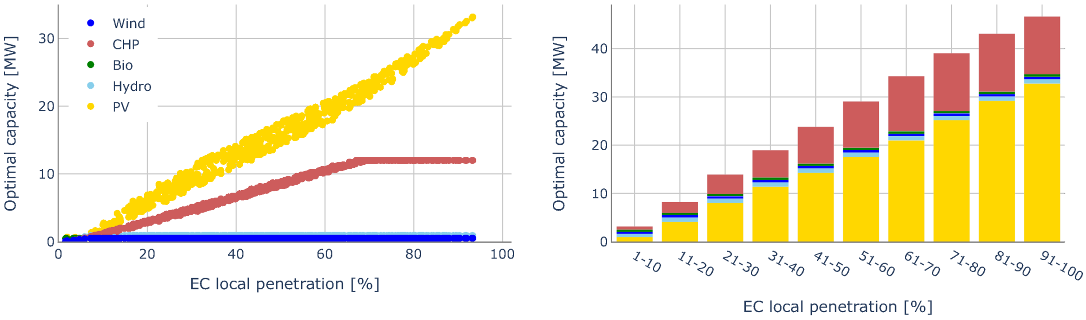


(d) Cogne study case - Strategy 2

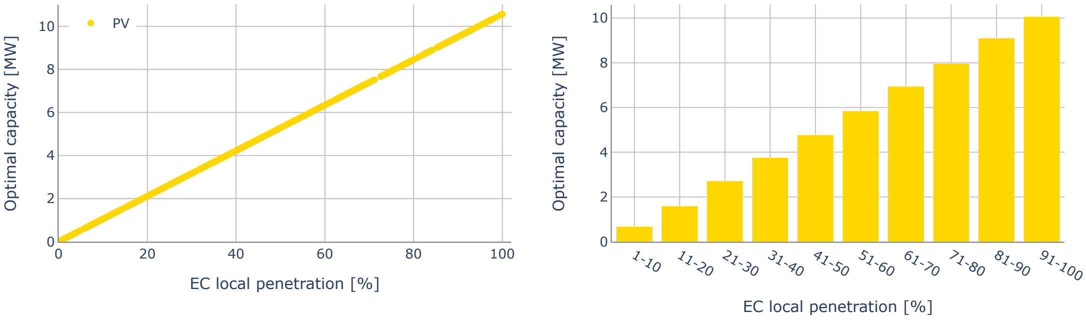
Figure 6.10: *Check of the convergence criterion.*



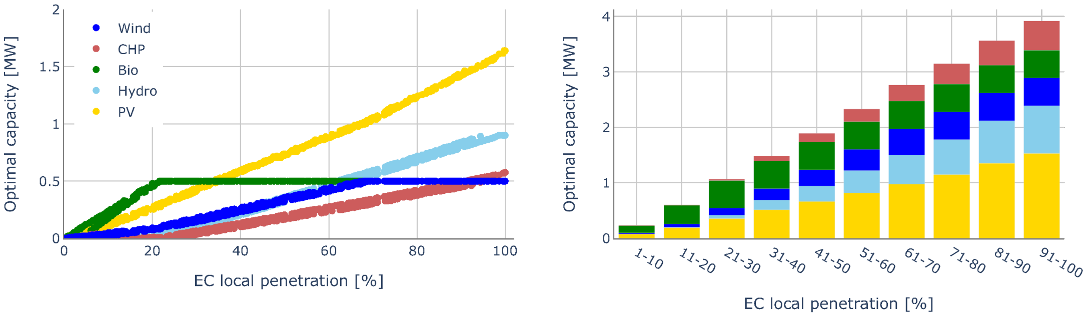
(a) Aosta study case - Strategy 1



(b) Aosta study case - Strategy 2



(c) Cogne study case - Strategy 1



(d) Cogne study case - Strategy 2

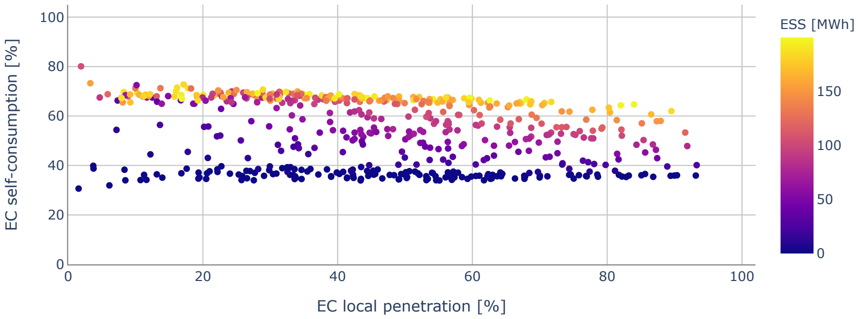
Figure 6.11: *Optimal portfolios variation with respect to EC penetration in the local energy system.*

self-consumption index of the EC is evaluated as:

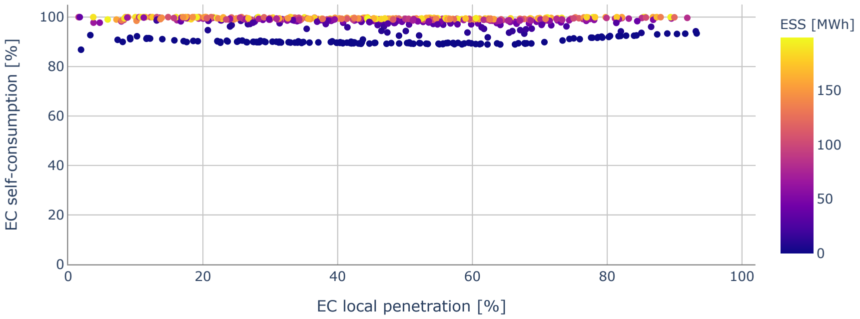
$$EC_{SC} = \frac{EC_{gen} - EC_{surplus}}{EC_{gen}} \tag{6.24}$$

Similar behaviours can be identified for Aosta and for Cogne when assuming the same optimization strategy. For the first strategy (Figure 6.12 (a) and (c)), the presence and the size of the ESS strongly impact the self-consumption. Without storage, the mean value of the self-consumption index is equal to 36.0% for Aosta and 39.6% for Cogne, and it is not affected by the EC penetration level. Considering the presence of the ESS, the self-consumption index can increase up to 80% and the $EC_{penetration}$ has a negative impact on its value. It means that an ESS that enables an high level of self-consumption for a small EC, will have a lower impact if adopted in a larger one. It is interesting to notice that there is an upper limit for the self-consumption values. This means that, even with huge ESSs, an EC based only on photovoltaic production and sized with the first strategy can not reach a 100% level of self-consumption (i.e. it will always have a surplus of energy). This is reasonable, considering that the portfolio is sized on the yearly consumption, but the production is concentrated in spring and summer. In this way, there is always a surplus of energy concentrated in summer and a deficit concentrated in the winter time. To balance this situation and increase the level of self-consumption, a seasonal storage would be required. The energy to store for such a long period is the order of GWh and it is not achievable with the ESSs limits considered in this model. A particular situation can be noticed for Cogne when small level of EC penetration are considered. In the range 0-20%, the values of self-consumption obtained with storage delineate two different patterns: in one case the values are aligned with the main linear trend that can be seen for higher value of penetration, in the other case the level of self-consumption achievable is lower. It has been verified that this is due to the presence, within the set of members of the EC, of a MV user with consumption concentrated in winter time (ski area). For the same reason explained before, the surplus of energy in summer increases and the self-consumption index decreases. A similar behaviour is not present in the case of Aosta since the number of users is higher and such discretization is not present.

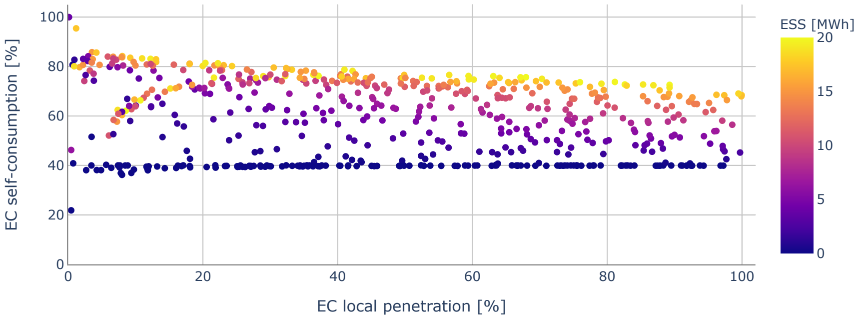
Considering the second strategy (Figure 6.12 (b) and (d)), the self-consumption index is much more higher: even in the cases without ESS the minimum values are on average 90.2% for Aosta and 88.6% for Cogne. This is possible thanks to the balanced portfolios that provide a production of energy distributed along the year, during days and nights. The presence of the storage rises the value of self-consumption, but its marginal contribution is less important than for the first strategy. For Aosta, an ESS smaller that 100 MWh is enough to reach 100% self-consumption for each penetration level. On the other hand, for Cogne is not always possible to reach this value. One more time, this is due to the seasonality of the production, and the impossibility to shift it for long periods. Specifically, in this case it is due to the important presence of hydroelectric in the optimal portfolio that cause on overproduction in summer: this presence starts to become important from a level of EC penetration of 20%, therefore it is possible to see that for penetration higher that this, the upper limit for the self-consumption is present.



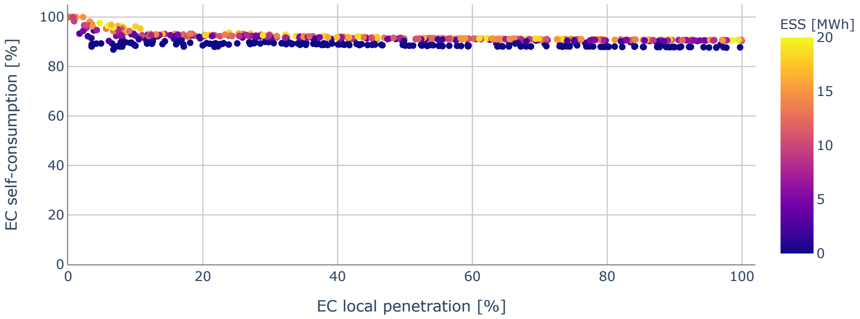
(a) Aosta study case - Strategy 1



(b) Aosta study case - Strategy 2



(c) Cogne study case - Strategy 1



(d) Cogne study case - Strategy 2

Figure 6.12: *Energy community self-consumption.*

6.6.4 Local area balance

The installation of DERs by mean of the EC may have positive impacts for the balance of the entire area. Two indexes are proposed for analysing this aspect. The first one is the percentage of local consumption that is satisfied with local production (Locally Produced Energy LPE).

$$LPE = \frac{Area_{gen} - Area_{export}}{Area_{load}} \tag{6.25}$$

The installation of new generators and ESS increases this value and this is directly causing a reduction in the energy import. The second considered index is the percentage of local production that is consumed locally (Locally Consumed Energy LPE).

$$LCE = \frac{Area_{gen} - Area_{export}}{Area_{gen}} \tag{6.26}$$

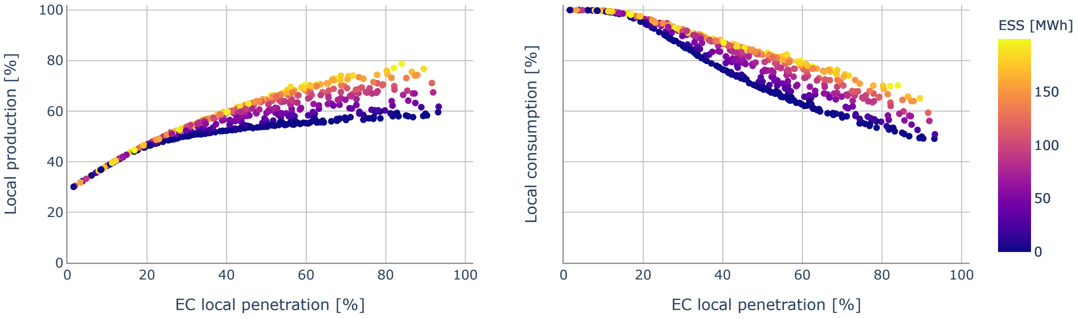
It accounts for the quantity of energy that is not exported from the area. From the economical side, a reduction in the import may generate saving, while an increasing in the export can generate revenues. Nonetheless, considering the energetic balance of the system, both import and export have to be reduced.

Locally produced energy

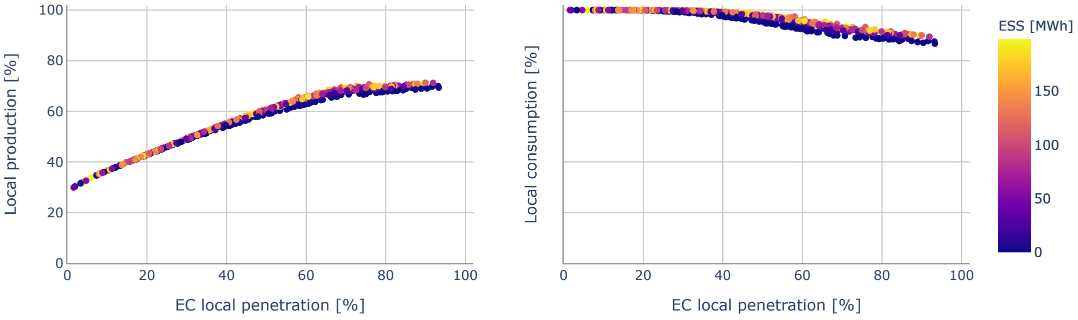
The values of LPE are shown in the left column of Figure 6.13. The initial value are strongly different (as detailed also in Table 6.2). In Aosta, they are producing locally only 29.6% of the energy needs, while in Cogne this value is equal to 72.8%. When considering the first optimization strategy, the presence of the energy community can increase this value for Aosta to values up to 78.8% and for Cogne up to 99.1%. With the first strategy, an important contribution for the increasing of LPE is given by the ESS. Small ECs (penetration lower than 20%) could contribute to the increasing of the index even without storage, but for higher penetrations it becomes crucial.

Locally consumed energy

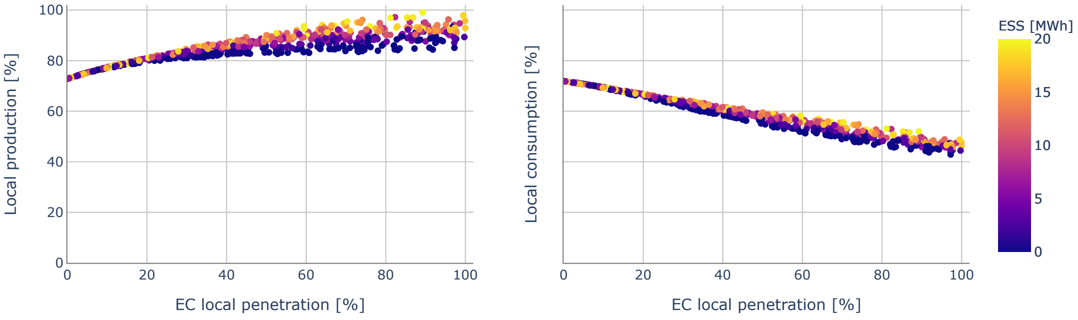
The higher the presence of new generators, the more difficult to consume locally the entire energy produced. The values of LCE are shown in the right column of Figure 6.13. For Aosta, all the energy produced in consumed locally in base case (with $EC_{penetration}$ equal to 0) and it is possible to reach certain levels of EC penetration without reducing this index (5.9% for strategy 1 and 17.6% for strategy 2). In other words, the area of Aosta does not have any export in the base case and there is the possibility to install new generators without causing export (i.e. reverse flow from MV to HV grid). After these levels of penetration, the LCE starts to worsening. The lower value reached considering the first strategy is equal to 49.1%, while considering the second strategy it does not go under 86.8%. Given the temporal distribution of the production, it is more easy to consume it locally. For Cogne, the initial value of LCE is 71.9% since the area is already exporting 28.1% of the energy produced locally. The presence of new generators of the energy community decreases the value of LCE in all the possible configurations. The minimum computed values are 42.9% for strategy 1 and 51.5% for strategy 2.



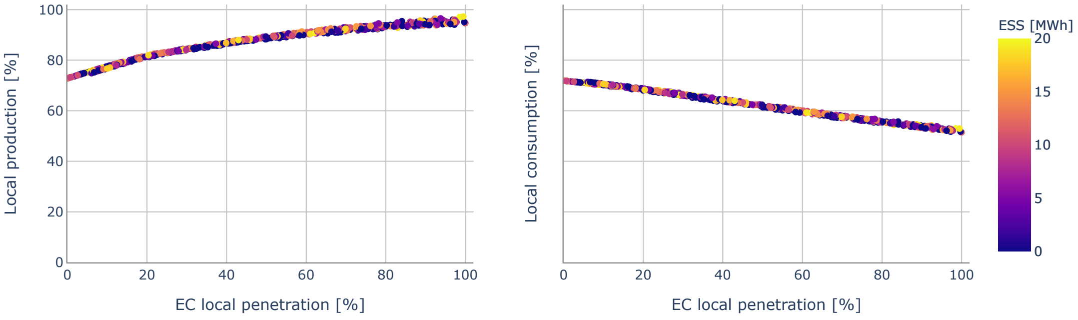
(a) Aosta study case - Strategy 1



(b) Aosta study case - Strategy 2



(c) Cogne study case - Strategy 1



(d) Cogne study case - Strategy 2

Figure 6.13: *Area self-sufficiency indicators. Local consumption % is the quote of local load satisfied with local production. Local consumption % is the quote of local production that is consumed by local load.*

6.6.5 Network impact

Losses

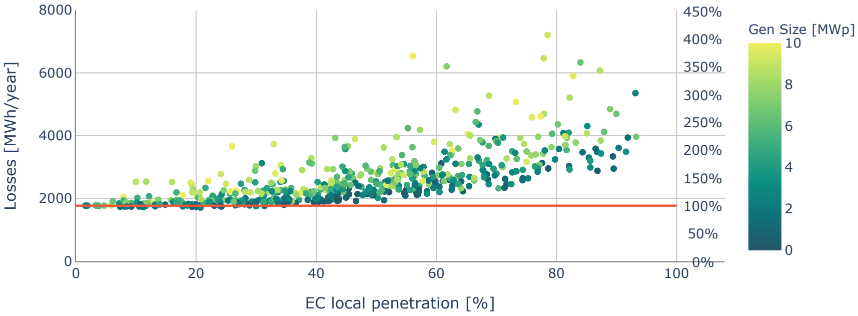
The generators and the storage of the EC are connected to the MV distribution network, therefore they will have an impact in the grid operation. Among the variables that is interesting to evaluate there are the losses of the network. Their importance is related, for example, for the definition of the tariff for the grid usage. The analysis showed that the value of the losses on the medium voltage level increase in most of the simulated cases, as reported in Figure 6.14. When considering the first strategy, the increment of losses is more important since they reach a maximum increment of +307% for Aosta and +363% for Cogne compared with the base case. For the second strategy the increment is lower, and the maximum values are respectively 227% and +112%. For Aosta, it is also possible to marginally reduce the network losses, and this happen mainly when the EC install generators with low rated power. With the first strategy, these reductions occur only in cases of penetration lower than 40.2%, with the second one it is possible to have a reduction also for high penetration (for $EC_{penetration}$ equal to 84.3, a reduction of 0.1% has been computed). The minimum value of the losses occurs when the EC adopts the second strategy and it is equal to 1,492 MWh, corresponding to a reduction of 5.54%. For Cogne, the probability that the EC reduces the losses is negligible: this happens in few cases and for a maximum value equal to 0.1%. It has also to be noticed that in Cogne the maximum sizes of the generators are generally lower because the total installed capacity is limited.

Maximum loading of the MV branches

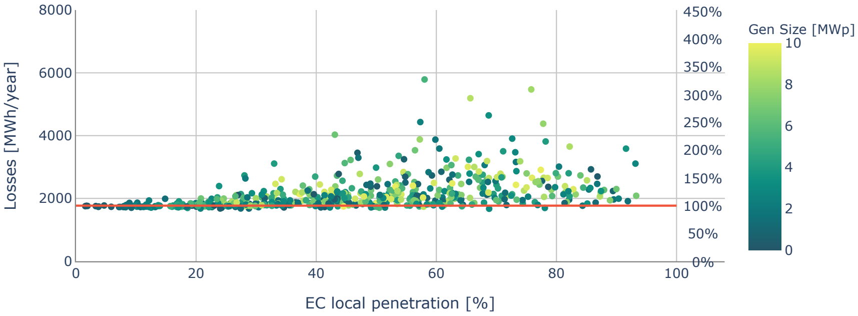
Another important electrical aspect is the loading of the network branches and it has been evaluated with two variables: the maximum loading registered on the network and the number of overloaded elements (i.e. with a loading higher that 100%). In Figure 6.15, the maximum loading of each simulation is reported in the form of boxplot, evaluated for different level of the EC penetration. The maximum loading for the base cases are the ones detailed in Table 6.2: 76% for Aosta and 47.7% for Cogne. It can be noticed that, considering the first strategy, for Aosta the overloading problem can be more severe and the maximum loading can reach theoretical values of 513%. For Cogne, applying the same strategy, the maximum loading is limited to 217%. The overloading appears to be a limited problem when the ECs adopt the second strategy for the portfolio definition. In this case, the maximum loading for Aosta is limited to 254% while for Cogne no overloading occurs (maximum value 86.2%).

Overloaded elements

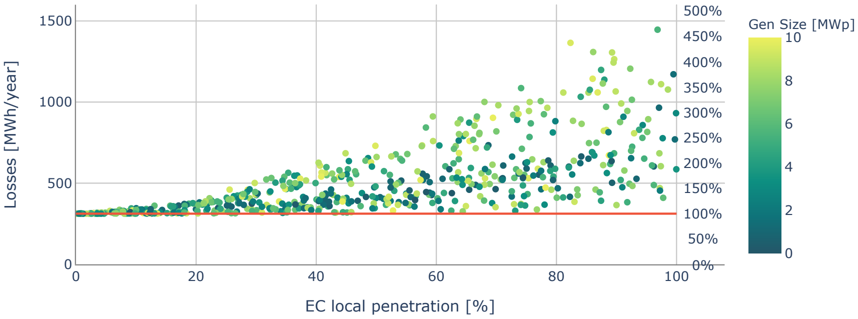
The maximum loading does not provide a complete description of the issue. From this information is not possible to know if there is only one element that is always overloaded or if all the grid branches are overloaded. To improve the information, the number of overloaded branches is considered. In Figure 6.16, it is reported in the same form of boxplot already adopted for the maximum loading. It is possible to observe that for Aosta the impact is more severe than for Cogne. Considering the first strategy, overloading occur in all the penetration range and affects, in the worst case, 79 elements (24% of the entire grid). With the second strategy the impact is more limited: the



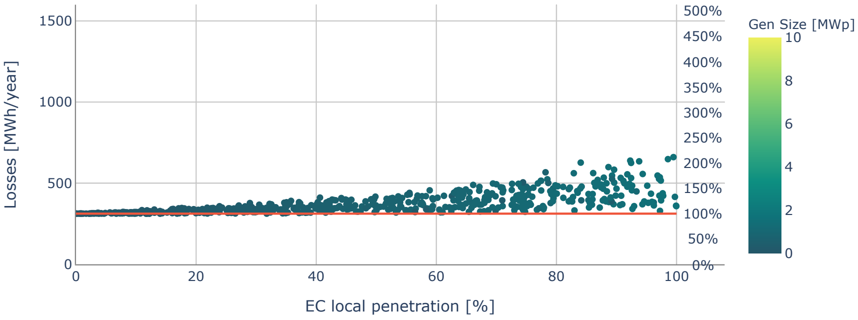
(a) Aosta study case - Strategy 1



(b) Aosta study case - Strategy 2

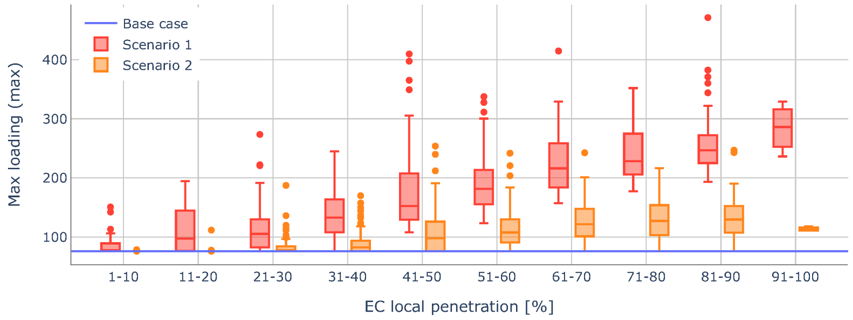


(c) Cogne study case - Strategy 1

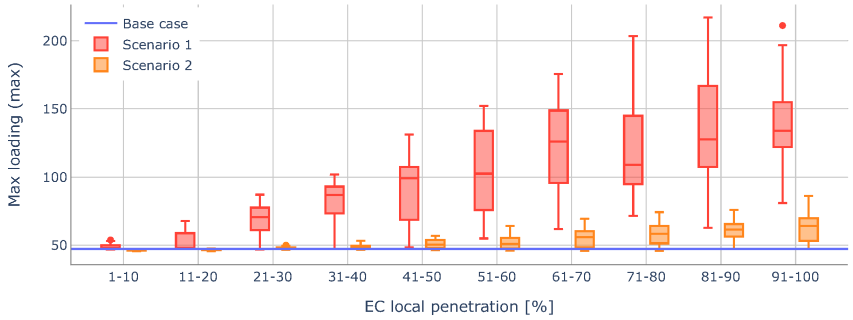


(d) Cogne study case - Strategy 2

Figure 6.14: *Yearly losses computed in the Monte Carlo simulation.*



(a) Aosta study case - Strategy 1 and 2



(b) Cogne study case - Strategy 1 and 2

Figure 6.15: *Maximum loading.*

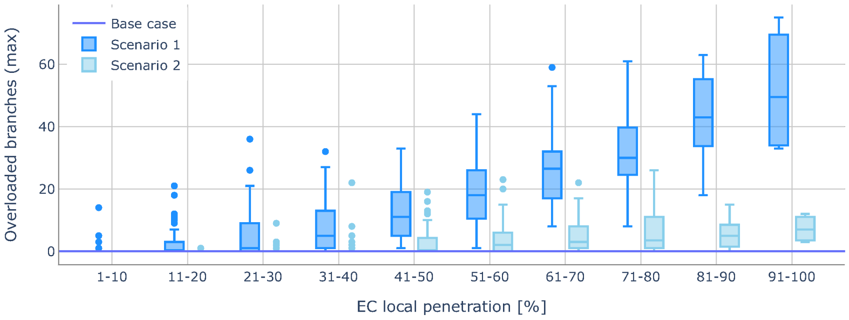
overloading starts from a penetration of 21-30% and affect a maximum of 26 elements (8.0% of the grid). For Cogne the problem is more contained, overloading violation occur only when considering the first strategy, starting from a penetration of 31-40% and they are limited to 15 (14.7% of the grid) elements. With the second strategy no elements are overloaded.

Overvoltages

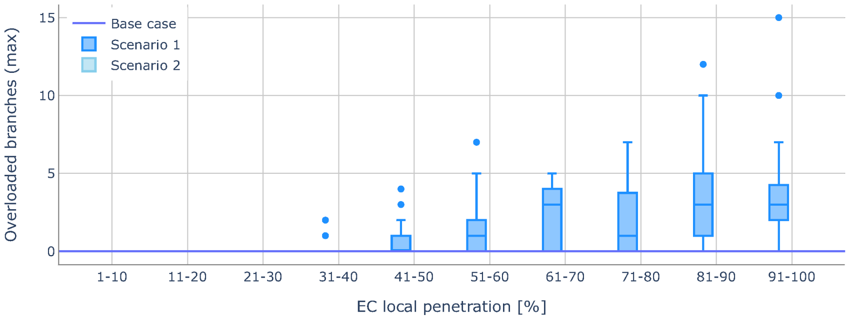
With respect to the voltage levels, the more interesting results are related to the maximum voltage reached during the simulated year. The boxplots in Figure 6.17, similarly to one already introduced for overloading, show the distribution of the maximum voltage obtained for each Monte Carlo iteration. Values greater than 1.1 p.u. are considered overvoltages[4]. It is interesting to notice that overvoltage issues are less severe than overloading ones. For both the test grids, they occur only when considering the first strategy (there is only one exception to this observation, with a penetration in the range 71-80% for the case of Aosta). When considering the first strategy, the probability of overloading is always less than 25%. This can be noticed looking at the third quartile of the boxplot (i.e. the upper limit of the rectangular box), that is always lower than 1.10. An interesting difference between Aosta and Cogne is the value of the maximum voltage of the grid in the base case scenarios (without any EC). For both the grids the voltage set-point in the primary substation is equal to 1 p.u., but in Aosta the maximum

---

[4] For the Italian quality requirements the voltage at the point of delivery must be in the range ±10%. With the considered assumption the voltage drop/rise on the LV lines and the tap changer of the MV/LV transformers are not considered.



(a) Aosta study case - Strategy 1 and 2



(b) Cogne study case - Strategy 1 and 2

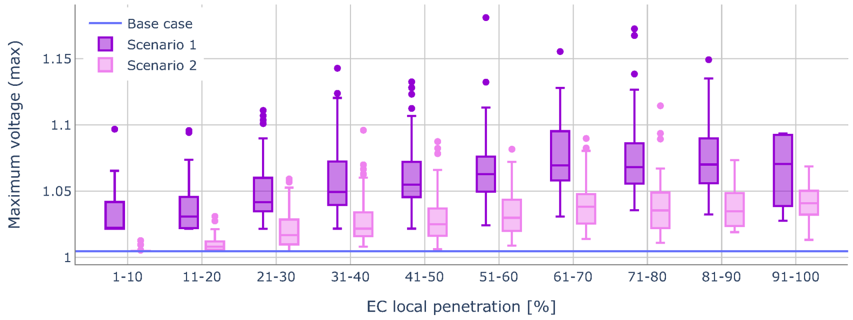
Figure 6.16: *Maximum number of overloaded elements versus the EC local penetration.*

voltage of the grid is 1.005, while in Cogne is 1.039. These different behaviours are due to the passive nature of the grid of Aosta on one side, and to the presence of the big hydroelectric power plant in Cogne on the other one. It it worthwhile to mention that there are possible strategies that have not been considered in this simulation that could reduce voltage issues. Among the most important there are the tap changing in the primary substation and the request of specific operating rules for DGs (reactive power control).

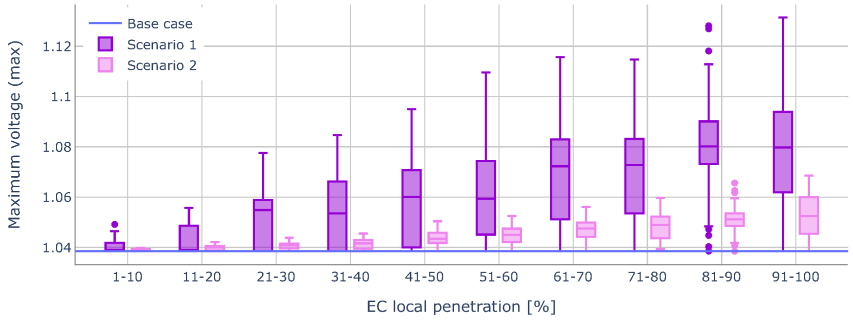
In Table 6.5, a comparison of the penetration limits obtained considering overloading and overvoltages issues is proposed. The penetration limit is defined as the maximum level for which the acceptable values are not exceeded (100% for loading and 1.10 p.u. for voltages). The limit is considered respected until the higher whisker of the boxplot does not exceed it (dots are considered outliers).

Table 6.5: *ECs acceptable penetration levels, based on overloading and overvoltages.*

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
Overloading	0%	21%-30%	21%-30%	91%-100%
Number of overloaded elements	1%-10%	31%-40%	31%-40%	91%-100%
Overvoltages	21%-30%	91%-100%	41%-50%	91%-100%



(a) Aosta study case - Strategy 1 and 2



(b) Cogne study case - Strategy 1 and 2

Figure 6.17: *Maximum voltage versus the EC local penetration.*

Generators and loads position

The last analysed point refers to the distribution of loads and generators of the EC on the network. A coincidence factor is evaluated for each feeder as the percentage of energy produced by the EC's generator located on the feeder, and the total energy request by the users located on the same feeder.

$$SF_f = \frac{E^f_{gen}}{E^f_{LV} + E^f_{MV}} \cdot 100 \tag{6.27}$$

A global index SF_{CE} related to the entire grid is then computed as:

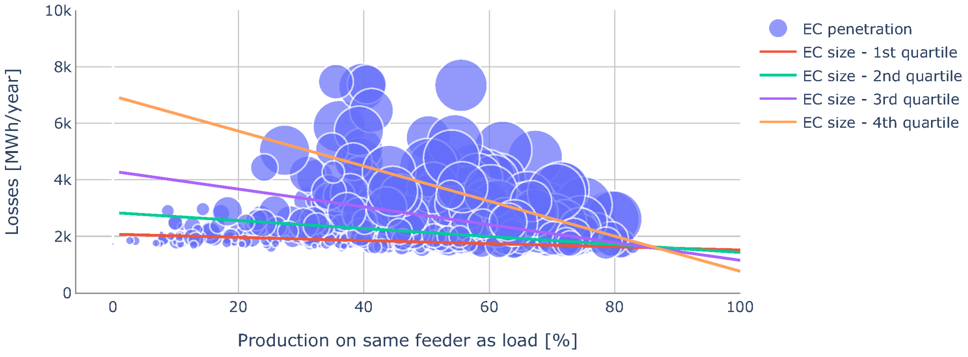
$$SF_{CE} = \sum SF_f \tag{6.28}$$

In Figure 6.18, the correlation between losses and the index SF_{CE} is reported in the form of bubble plot. The size of each bubble corresponds to the EC penetration (i.e. to the size of the EC). Considering the case of Aosta, a decreasing trend can be identified for both strategies. This means that, if generators and loads are distributed in a balanced way among the feeders, the increase of the losses can be avoided. Moreover, it is worth to notice that this trend is strongly depend on the size of the community: if a community is big, the importance of having an high value of SF_{CE} is crucial. To show this, the regression lines have been computed for each of the quartiles defined by the EC size. For the 1^{st} quartile (small energy community), the slope is negligible, but it becomes more and more important moving toward the 4^{th} quartile. The slopes of the regression lines are reported in Table 6.6

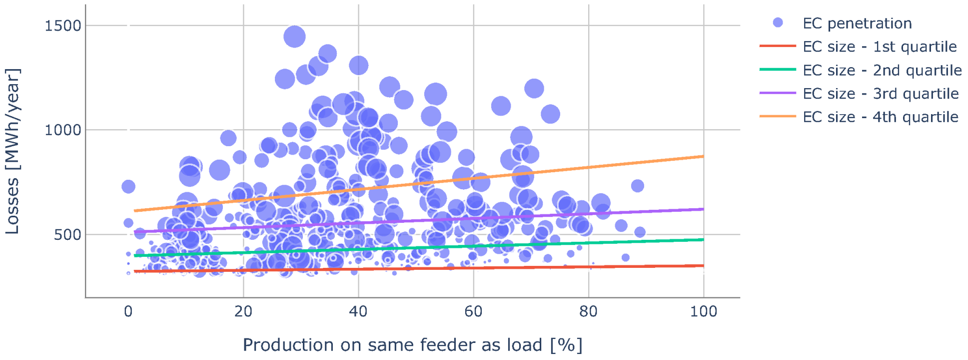
For Cogne, results do not show the same trend. On the contrary, there is a slightly positive slope that seems to deny what can be concluded from the urban case of Aosta, so that having loads and generators on the same feeders could reduce the losses. This behaviour can be explained considering the peculiar topology of the network. In Cogne, most of the load are located on the feeders in the upper part of the valley. Therefore, placing generators on the same feeder of the loads means to place them in the farthest nodes from the primary substation.

Table 6.6: *Linear regression coefficients that define the relationship between losses and the index SF_{CE} [MWh/year]. (Quartiles are defined based on the $EC_{penetration}$).*

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
1^{st} quartile	-4.78	-0.54	0.27	0.10
2^{nd} quartile	-17.17	-7.82	0.77	0.63
3^{rd} quartile	-30.42	-19.19	1.10	1.19
4^{th} quartile	-49.45	-21.36	2.63	1.52



(a) Aosta - Strategy 1



(b) Cogne - Strategy 1

Figure 6.18: *Losses dependency to the EC distribution among the feeders.*

6.6.6 Computational time

The methodology requires an important computational effort, mainly due to the quasi-dynamic load flow computation. The execution times for the considered scenarios are reported in Table 6.7. The procedure has been executed on a workstation equipped with an Intel® Core™i9-10980XE CPU @3 GHz (18 core) and 128 GB of RAM.

Table 6.7: *Computational time for the scenarios considered.*

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total time	93.6 h	75.3 h	14.3 h	13.0 h
Number of iterations	536	579	589	567
Time per iteration	10.48 min	7.80 min	1.46 min	1.38 min

6.6.7 Conclusion

Strategies that prefer the self-consumption have a positive impact of the energy balance of the entire area (reducing import and limiting the export of energy). Actually, self-consumption results to be a pivotal target in the EC design, suggesting it as a mandatory requirements in the regulatory framework. Also the grid can take benefits from such kind of strategy. Indeed, if in all the cases the MV distribution network will be stressed, ECs that will prefer a strategy based on self-consumption are a solution that can limit this negative effects. The trends are similar for both the test grids considered, nonetheless, they demonstrated that the EC impact can be different depending on the initial condition of the network. The urban network (Aosta) has a big deficit of energy, therefore, there is the possibility to install new generators without causing reverse flows and increasing the self-sufficiency of the area. Nevertheless, to achieve high levels of penetration of the EC, the generation portfolio becomes important. Furthermore, in the urban case it is hard to install generators different from PV and CHP. This increase the electrical problem because the production will be mostly concentrated in the sunny hours of the day. In the rural area (Cogne), there is already high production, so each new installation could increase the export from the area and the grid losses. Nonetheless, the energy sources availability is higher and it is possible to install hydroelectric power plant, wind turbine or generators based on biomass. This allows to cover the need of the community, limiting the number and magnitude of the overloading of the branches.

6.7 Summary

This chapter has addressed the problematic related to the impact of a new EC on a distribution network. The relationship between distributed generation and energy community has been evaluated and a review of the hosting capacity concept has been provided. A methodology based on Monte Carlo simulation has been proposed to evaluate the capacity of a network to host new ECs. The methodology can be adapted in order to properly consider the strategy of the EC for the definition of its DERs portfolio. It has been coded in Python and applied to two real-life MV test grids, modelled in DigSilent PowerFactory. The results showed that the strategy chosen by the EC have a strong impact on the network variables and that the negative impact can be limited if the EC portfolio is optimized for the EC internal self-consumption. The results highlights also the big differences between the rural and the urban context, specifically that in the urban context the energy deficit is higher, therefore there is large space for increasing the self-sufficiency. Nonetheless, to reach high penetration level, the high load density requires the installation of important generation portfolios that can have strong impact on the infrastructure in place. Moreover, in the urban context there is a mismatching between the load density and the scarcity of energy sources, therefore high penetration levels are difficult to reach.

CHAPTER 7

Conclusions

The main goal of the thesis has been to contribute expanding the knowledge about ECs, evaluating this new phenomenon from some of the main prominent viewpoints. The thesis has been arranged in two main parts: the framework of reference, in which the background analysis has been developed, and a second part named "Methods and models for REC development", in which the main issues to be faced in order to unlock the development of ECs have been investigated.

The schema presented in the first chapter is reported in Figure 7.1, to recap the proposed methodological frame. In particular, the modelling framework is divided into three parts according to the considered perspectives. A different chapter has been dedicated to each of the coloured block of the schema and suited models and numerical results (correlated to real-life study cases) have been reported. In particular, the research path could be classified as:

- the development of a reference framework about the European and Italian legislation and regulation (Chapter 2);
- the development of a framework, complementary to the first, based on the research perspectives in the field of ECs (Chapter 3);
- the proposal of a model of REC that takes into account energy sharing and self-consumption, whose aim is to define the optimal planning of the community DERs (Chapter 4);
- the proposal of a game theoretic approach for evaluating a fair distribution of the benefits among the shareholders of an EC (Chapter 5);
- the development of a methodology for evaluating the impact of the ECs on the distribution network (Chapter 6).

A brief summary of the thesis contributions is discussed below.

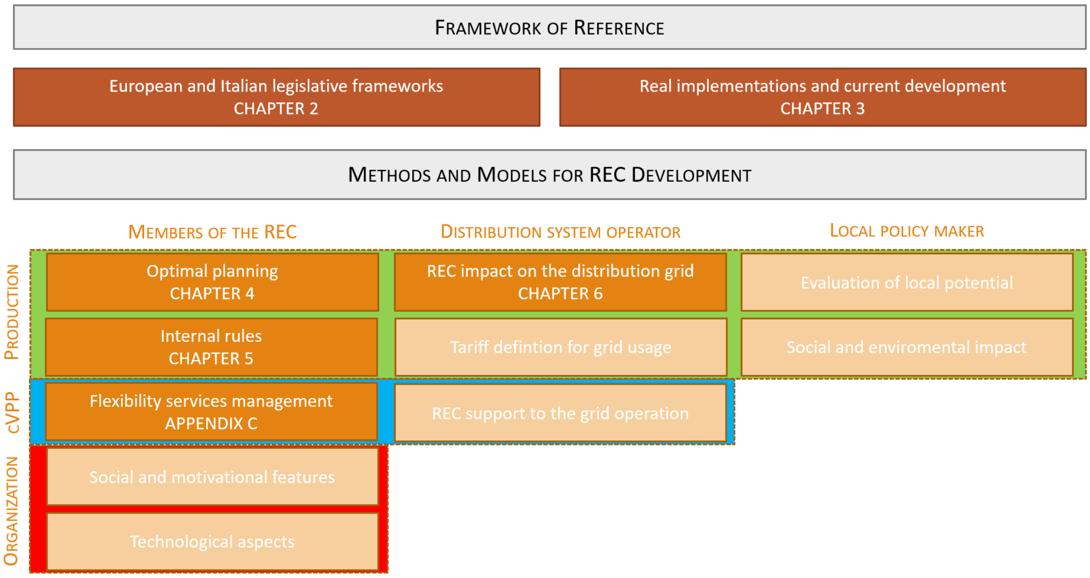


Figure 7.1: *Schematic overview of the structure adopted to organize the topics concerning ECs.*

Part 1 - Framework of reference

European and Italian legislative frameworks

In Chapter 2 the main legislative and regulatory pillars that define the characteristics and the field of action of the ECs have been provided. The European Directives that require national definitions of the ECs have been detailed and the status of the ongoing transposition process has been described, focusing on the Italian case. Finally, the characteristics of the experimental phase currently in place in Italy have been presented. These information defined the background on which methods and models for the analysis of ECs have been built.

Review on energy communities

In Chapter 3 the framework of reference has been completed with the review on current development in the scientific literature. It has been noticed how a literature specifically focused on the new European definitions of CEC and REC is still lacking. Nonetheless, there is a large diversity of initiatives in the energy sector that can be considered community-based and possible classifications have been proposed. Given their explicit relationship with the European policies, the projects that are most focused on the up-to-date definitions are directly funded by the European Commission. A review of these projects has been performed and the main research trends have been identified. Specifically, it has been noticed that the oldest projects were focused on the legal and social aspects of the EC while the most recent ones are based on technical aspects and, specifically, on the definition of community-based virtual power plants.

Part 2 - Methods and models for EC development

Energy community modelling

Chapter 4 has addressed the issue of EC modelling. A bibliographic review has been performed looking for possible similarities and connections with already available models and tools. Then, a model capable to evaluate energy and economical exchanges within a REC has been proposed. The peculiarity of the model is to consider separately self-consumed and shared energy. The goal of the model is to find the optimal portfolio of DERs in terms of installed generators and storage, optimizing the net present value of the investment. The model and methodology proposed constitute a tool that supports the planning of the community investments. A theoretical case study based on ten members has been introduced to test the model.

Benefits sharing within a REC

In Chapter 5 the problem of benefits sharing in a REC has been addressed. Game theory algorithms have been identified as a suitable approach; some elements from the cooperative and non-cooperative game theory have been presented, with examples of energy sharing situations. The REC model proposed in Chapter 4 has been formalized as a cooperative game, and the problem of benefits sharing among the community members has been faced. A two steps distribution rule, based on the Shapley value among clusters of members followed by a proportional allocation, has been proposed. The methodology has been applied to a real-life case study based on the Italian scenario, considering an EC with more than one hundred members.

Energy communities impact on the distribution network

Chapter 6 has addressed the problematic related to the impact of a new EC on a distribution network. The relationship between distributed generation and EC has been evaluated and a review of the hosting capacity concept has been provided. A methodology based on a Monte Carlo algorithm has been proposed in order to evaluate the impact of the EC over the distribution grid. The methodology can be adapted in order to properly consider the strategy of the EC for the definition of its DERs portfolio. It has been applied to two real-life MV test grids. The results demonstrated that the strategy chosen by the EC has a strong impact on the network variables and, in particular, negative impacts can be limited if the EC portfolio is optimized for the internal self-consumption.

7.1 Critical discussion and opportunities

In order to critically evaluate the EC scenarios, it is necessary to point out how such a topic is still not consolidated. EC concept has been recently proposed and worldwide both research bodies and industry are committed in a wide evolution process. In such a scenario it is clear that several lacks could be identified and, on top of that, several opportunities should be properly investigated.

ECs evolution

This thesis has introduced models and methodologies based on the most updated legislation for ECs and/or the most reasonable hypothesis about their final configuration. Nonetheless, the definition of the legislative and regulatory framework for ECs in all the European countries is an on-going process. Therefore, looking forward, further effort will be required to adapt the hypothesis of the models to the most updated ECs configurations. The transposition of the European Directives into the national laws is a cornerstone in this evolution. It will be crucial to identify common characteristics or differences and, consequently, to generalize models and methodologies in order to fit with as many Member State as possible.

EC modelling

This thesis has proposed a model for EC planning which is based on detailed data of available resources and EC members' needs. The contemporaneity of production and consumption is considered, moreover self-consumed and shared energy are specifically distinguished. However, the methodology considers inflexible load and uncontrollable production. The possible developments are oriented towards the consideration in the planning stage of the possibility for users to adapt their load (demand response) or to properly schedule controllable generators.

Redistribution of the generated value

This thesis has proposed a model to redistribute the value generated by an EC among community members. Nonetheless, this kind of approach can be adopted only if the generated value is defined by mean of a transferable utility function (e.g. it is only economical). However, given their social and environmental implications, ECs generate also non-transferable utility. To consider this aspect in redistribution strategies, further development and investigation of different approaches are required.

Impact on the network

This thesis has introduced a methodology for the evaluation of the ECs impact of the MV distribution network. Nonetheless, for an evaluation of the overall impact on the electrical system, research activity is required to investigate the effects on the LV distribution network (e.g. including in the analysis also jointly acting self-consumers) and on the HV transmission system (e.g evaluating if the increased self-sufficiency of some regions could actually reduce losses and needs of reinforcements).

APPENDIX A

Directive (EU) 2018/2001 - Article 22 (Renewable energy communities)

DIRECTIVE (EU) 2018/2001
OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL
of 11 December 2018
on the promotion of the use of energy from renewable sources
(recast)

Article 22

1. Member States shall ensure that final customers, in particular household customers, are entitled to participate in a renewable energy community while maintaining their rights or obligations as final customers, and without being subject to unjustified or discriminatory conditions or procedures that would prevent their participation in a renewable energy community, provided that for private undertakings, their participation does not constitute their primary commercial or professional activity.

2. Member States shall ensure that renewable energy communities are entitled to:

   (a) produce, consume, store and sell renewable energy, including through renewables power purchase agreements;

   (b) share, within the renewable energy community, renewable energy that is produced by the production units owned by that renewable energy community, subject to the other requirements laid down in this Article and to maintaining the rights and obligations of the renewable energy community members as customers;

(c) access all suitable energy markets both directly or through aggregation in a non-discriminatory manner.

3. Member States shall carry out an assessment of the existing barriers and potential of development of renewable energy communities in their territories.

4. Member States shall provide an enabling framework to promote and facilitate the development of renewable energy communities. That framework shall ensure, inter alia, that:

   (a) unjustified regulatory and administrative barriers to renewable energy communities are removed;

   (b) renewable energy communities that supply energy or provide aggregation or other commercial energy services are subject to the provisions relevant for such activities;

   (c) the relevant distribution system operator cooperates with renewable energy communities to facilitate energy transfers within renewable energy communities;

   (d) renewable energy communities are subject to fair, proportionate and transparent procedures, including registration and licensing procedures, and cost-reflective network charges, as well as relevant charges, levies and taxes, ensuring that they contribute, in an adequate, fair and balanced way, to the overall cost sharing of the system in line with a transparent cost-benefit analysis of distributed energy sources developed by the national competent authorities;

   (e) renewable energy communities are not subject to discriminatory treatment with regard to their activities, rights and obligations as final customers, producers, suppliers, distribution system operators, or as other market participants;

   (f) the participation in the renewable energy communities is accessible to all consumers, including those in low-income or vulnerable households;

   (g) tools to facilitate access to finance and information are available;

   (h) regulatory and capacity-building support is provided to public authorities in enabling and setting up renewable energy communities, and in helping authorities to participate directly;

   (i) rules to secure the equal and non-discriminatory treatment of consumers that participate in the renewable energy community are in place.

5. The main elements of the enabling framework referred to in paragraph 4, and of its implementation, shall be part of the updates of the Member States' integrated national energy and climate plans and progress reports pursuant to Regulation (EU) 2018/1999.

6. Member States may provide for renewable energy communities to be open to cross-border participation.

7. Without prejudice to Articles 107 and 108 TFEU, Member States shall take into account specificities of renewable energy communities when designing support schemes in order to allow them to compete for support on an equal footing with other market participants.

APPENDIX B

Directive (EU) 2019/944 - Article 16 (Citizen energy communities)

DIRECTIVE (EU) 2019/944
OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL
of 5 June 2019
on common rules for the internal market for electricity
and amending Directive 2012/27/EU
(recast)

Article 16

1. Member States shall provide an enabling regulatory framework for citizen energy communities ensuring that:
    (a) participation in a citizen energy community is open and voluntary;
    (b) members or shareholders of a citizen energy community are entitled to leave the community, in which case Article 12 applies;
    (c) members or shareholders of a citizen energy community do not lose their rights and obligations as household customers or active customers;
    (d) subject to fair compensation as assessed by the regulatory authority, relevant distribution system operators cooperate with citizen energy communities to facilitate electricity transfers within citizen energy communities;
    (e) citizen energy communities are subject to non-discriminatory, fair, proportionate and transparent procedures and charges, including with respect to registration and licensing, and to transparent, non-discriminatory and cost-reflective network charges in accordance with Article 18 of Regulation (EU) 2019/943,

ensuring that they contribute in an adequate and balanced way to the overall cost sharing of the system.

2. Member States may provide in the enabling regulatory framework that citizen energy communities:

   (a) are open to cross-border participation;

   (b) are entitled to own, establish, purchase or lease distribution networks and to autonomously manage them subject to conditions set out in paragraph 4 of this Article;

   (c) are subject to the exemptions provided for in Article 38(2).

3. Member States shall ensure that citizen energy communities:

   (a) are able to access all electricity markets, either directly or through aggregation, in a non-discriminatory manner;

   (b) are treated in a non-discriminatory and proportionate manner with regard to their activities, rights and obligations as final customers, producers, suppliers, distribution system operators or market participants engaged in aggregation;

   (c) are financially responsible for the imbalances they cause in the electricity system; to that extent they shall be balance responsible parties or shall delegate their balancing responsibility in accordance with Article 5 of Regulation (EU) 2019/943;

   (d) with regard to consumption of self-generated electricity, citizen energy communities are treated like active customers in accordance with point (e) of Article 15(2);

   (e) are entitled to arrange within the citizen energy community the sharing of electricity that is produced by the production units owned by the community, subject to other requirements laid down in this Article and subject to the community members retaining their rights and obligations as final customers.

   For the purposes of point (e) of the first subparagraph, where electricity is shared, this shall be without prejudice to applicable network charges, tariffs and levies, in accordance with a transparent cost-benefit analysis of distributed energy resources developed by the competent national authority.

4. Member States may decide to grant citizen energy communities the right to manage distribution networks in their area of operation and establish the relevant procedures, without prejudice to Chapter IV or to other rules and regulations applying to distribution system operators. If such a right is granted, Member States shall ensure that citizen energy communities:

   (a) are entitled to conclude an agreement on the operation of their network with the relevant distribution system operator or transmission system operator to which their network is connected;

(b) are subject to appropriate network charges at the connection points between their network and the distribution network outside the citizen energy community and that such network charges account separately for the electricity fed into the distribution network and the electricity consumed from the distribution network outside the citizen energy community in accordance with Article 59(7);

(c) do not discriminate or harm customers who remain connected to the distribution system.

APPENDIX C

Advanced operation of ECs

In most of the practical cases, the activities of an EC are limited to production, self-consumption and energy sharing. Indeed, these three elements are at the core of the EC models presented in the thesis. However, an EC is entitled to perform also more advanced services, such as optimizing the internal scheduling of its DERs to provide the members extra savings (e.g consuming when the EC's generators are producing) or income (e.g participating to ancillary service markets). The field of action is widespread and the purpose of this thesis is not to focus on a specific advanced application. Nonetheless, a preliminary investigations is reported in this appendix. Specifically, the possibility to control a fleet of electric vehicles (EVs) in an aggregated form is presented. The purpose of the aggregation is to provide ancillary services to the grid. Actually, not having a dedicated regulatory framework for EC, the model proposed has been set with respect to the standard ancillary service market in place in Italy. Given the potentially high number of users of an EC, aggregating their load and exploiting their flexibility can be an interesting opportunity for providing revenues to the community members. Specifically, the usage of electric cars represents a promising application, considering their high energy request and flexibility margins. More than specific contribution to the research, it represents a case study to introduce the topics.

C.1 EV flexibility services

The charging of a fleet of electric vehicles is a process with some degrees of flexibility. Often, cars are parked for a long time, and their complete charge can be obtained in a fraction of this time. Nonetheless, knowing with a certain degree of confidence the time at which the parking lot will be left, the charging power of each car could be modulated, speeding up or slowing down the process, ensuring in any case to reach the complete charge at the desired time. This flexibility can be exploited by an EC that aggregates and controls the loads of its members to provide power balance regulation to the electric grid. A preliminary work has been done in order to evaluate the possibility to adapt the charging rate of a fleet of cars to obtain an income from the electricity markets. The goal is to quantify the benefits that could be achieved in the Italian framework. Theoretically, this kind of aggregation could be realized both with centralized parking garages and with fleets of cars distributed among different parking lots (e.g. private cars of the members of an EC). However, data related to distributed fleets are not easily available, and a dataset based on a real parking garage has been used to investigate this service.

The procedure developed is based on two steps: first, a daily average power profile for the fleet charging is estimated by mean of repeated Monte Carlo simulations, then a single day is considered and the real time operation is simulated. The average daily profile is used at day D-1 to submit requests on the Day-Ahead Market (DAM), to buy the amount of energy needed to charge the vehicles (on a predictive basis). In an EC configuration, this can be considered incremental with respect to the other needs of the community itself. In this way, a binding schedule of supply is defined, specifying the amount of energy that the electric vehicles should absorb from the network at every hour of day D. Then, the daily operation of the garage is simulated for day D: during the relevant Ancillary Service Market (ASM) sessions (e.g. 4 h before the real-time), the fleet manager/aggregator submits bids for up/downward reserve (increasing or reducing the power for the charging process), that are then selected by the TSO according to a pay-as-bid approach. The aggregator participates with a strategy that is based on the average power profile, but can be calibrated during the day based on the real time status of the parking (e.g. number of cars and their state of charge). The combination of DAM and ASM schedules represents a commitment toward the market that the aggregator must respect; otherwise, it is subject to imbalance fees. The acceptation of the offers is estimated based on a simulation of the market and the economic benefits are evaluated.

C.1.1 Dataset description

The dataset on which the model is based consists of two parts, relating to different elements considered for the scenario generation: parking variables and car models.

Parking dataset

The information about the parking garage has been obtained from the website of the municipality of Milan[1], where the number of places available in the main interchange parking garages of the city is updated in real time (i.e. each minute). In this preliminary work, such parking garages have been adopted as a study case, specifically the ones located close to the train or metro stations outside the city. This garages are mainly used by commuters, that move from the surroundings to the city centre with a daily routine. For this reason they have very similar trends, as shown in Figure C.1, where the presence profiles in the main seven garages of the city is represented in terms of absolute number of cars and relative occupation of the garage.

Processing these data allows to define the probability distributions regarding entry

---

[1] https://www.muoversi.milano.it/

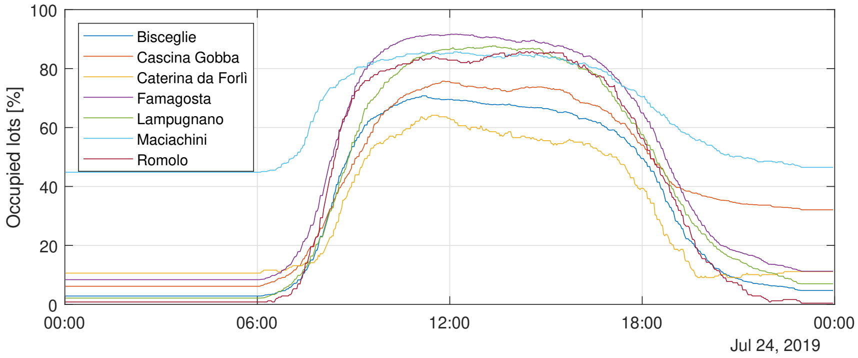


Figure C.1: *Absolute and relative occupation of the parking garages during a working day.*

and exit from the garage. For the simulation of the case study the pasking of Bisceglie has been selected as a reference. The average movement of cars is reported for each minute in Figure C.2. It can be notice that the movement of cars in entry and exit can be approximated with normal distributions.

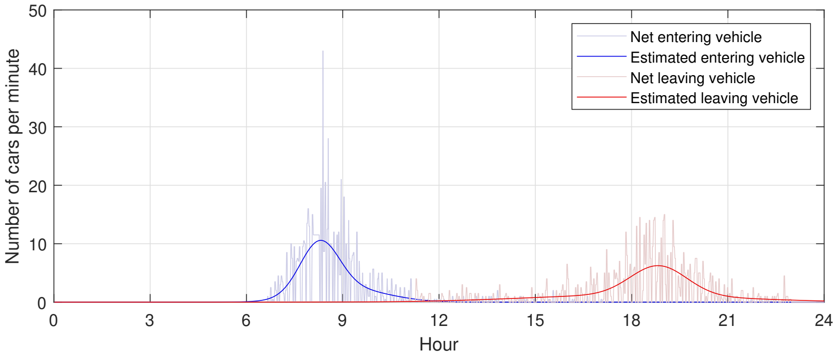


Figure C.2: *(a) Probability of entry and exit from the considered garage during the day (b) Cumulative probability.*

Cars dataset

The car models considered in this study are the ten best-selling electric cars in the Italian market in the first half of 2019. For each of them, the following information have been collected: the number of cars sold, the battery capacity and the maximum charging power. In case a car model was available in several versions (i.e. with different battery sizes), the value of the most popular sub-model was considered. The ten cars considered are shown in Table C.1, where it is reported also the market share, derived from the number of sales. This has been adopted as the probability for each car to be selected in the scenario creation with the Monte Carlo method.

C.1.2 Daily scenario creation

To simulate the operation of the parking, a daily scenario is necessary (e.g. number, models, time of connection of each car...). An algorithm has been developed to generate a scenario based on a Monte Carlo approach. The result of the scenario creation is a

Table C.1: *Electric car models considered according to the sales in Italy in the first semester of 2019.*

Model	**Capacity [kWh]**	**Sales Number**	**Sales Share**	**Power [kW]**
Renault Zoe	46.8	1335	28.7%	43
Tesla Model 3	75.0	958	20.6%	22
Smart ForTwo	18.5	707	15.2%	22
Nissan Leaf	30.0	560	12.0%	7
Smart ForFour	17.6	267	5.7%	22
Hyundai Kona	41.0	225	4.8%	7
BMW I3	33.0	221	4.7%	11
Tesla Model S	102.0	149	3.2%	22
Tesla Model X	75.0	116	2.5%	22
Jaguar I-PACE	90.0	115	2.5%	7

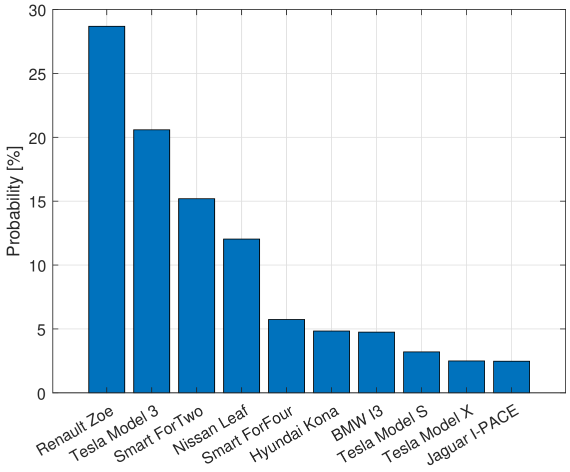


Figure C.3: *Probability distribution of the electric car models.*

group of time vectors $P_i(t)$ that represent, for each car i entering the parking garage during the day, the charging power necessary to reach the required SOC at the time of leaving. The sum of the power profiles of the individual cars defines the total power profile P_{tot} that the aggregation of loads needs to draw from the distribution network during the day under consideration.

The steps for the scenario creation are reported in the following list, the probability distribution functions for the stochastic definition of the variables are reported in Table C.2.

1. Selection of the number of cars N that park in the garage during the day;
2. For each car i from 1 to N:
   (a) Selection of the car model, consequently the capacity of the battery Cap_i and the maximum charging power P_i^{max} are defined;
   (b) Selection of time of entry t_i^{in};
   (c) Selection of time of exit t_i^{out};
   (d) Selection of the SOC at the entrance SOC_i^{ini};
   (e) Selection of the final SOC requested SOC_i^{req};
   (f) Computation of the energy request:

   $$E_i = (SOC_i^{req} - SOC_i^{ini}) \cdot Cap_i \tag{C.1}$$

   (g) Computation of the theoretical power for constant charging:

   $$P_i^{avg*} = \frac{E_i}{t_i^{out} - t_i^{in}} \tag{C.2}$$

   (h) Possible saturation of the theoretical power P_i^{avg*} due to the maximum power limit:

   $$P_i^{avg} = \begin{cases} P_i^{avg*} & \text{if } P_i^{avg*} \leq P_i^{max} \\ P_i^{max} & \text{if } P_i^{avg*} > P_i^{max} \end{cases} \tag{C.3}$$

   (i) Computation of the maximum reachable state of charge SOC_i^{fin} give power limits:

   $$SOC_i^{fin} = \begin{cases} SOC_i^{req} & \text{if } P_i^{avg*} \leq P_i^{max} \\ SOC_i^{ini} + P_i^{max} \cdot (t_i^{out} - t_i^{in}) & \text{if } P_i^{avg*} > P_i^{max} \end{cases} \tag{C.4}$$

   It is worthwhile to notice that the final SOC requested by the car may not be reachable considering the limited parking time and/or the limited charging power.

   (j) For each car, the power request P_i is defined for each minute t of the day. It is assumed that, without considering market participation, charging occurs at constant power P_i^{avg} for the entire time window in which the car is connected.

   $$P_i(t) = \begin{cases} 0 & \text{if } t \leq t_i^{in} \\ P_i^{avg} & \text{if } t_i^{in} < t \leq t_i^{out} \\ 0 & \text{if } t > t_i^{out} \end{cases} \tag{C.5}$$

3. The total power request of the fleet is the sum the profiles of all the cars.

$$P_{tot}(t) = \sum_{i=1}^{N} P_i(t) \tag{C.6}$$

4. In order to know the flexibility margin theoretically available, the maximum power P_{tot}^{max} that could be withdrawn from the grid is computed.

$$P_{tot}^{max}(t) = \sum_{i=1}^{N} P_i^{max}(t) \tag{C.7}$$

   where:

$$P_i^{max}(t) = \begin{cases} 0 & \text{if } t \leq t_i^{in} \\ P_i^{max} & \text{if } t_i^{in} < t \leq t_i^{out} \\ 0 & \text{if } t > t_i^{out} \end{cases} \tag{C.8}$$

Each of the stochastically defined variable is selected from a probability distribution function: in some cases this distribution is obtained from the initial dataset, in other cases it is obtained by mean of hypotheses. Stochastic variables and related distribution functions are reported in Table C.2.

Table C.2: *Probability distribution functions.*

Variable		Probability distribution
N	Number of electric cars parking in the day	Normal $N(\mu = 1000, \sigma = 200)$
t_i^{in}	Arrival time of car i	From monitored data (Figure C.2)
t_i^{out}	Departure time of car i	From monitored data (Figure C.2)
$model_i$	Model of car i	From car sales data (Figure C.3)
SOC_i^{ini}	SOC of car i at the arrival time t_i^{in}	Normal $N(\mu = 40, \sigma = 20)$
SOC_i^{req}	SOC requested for car i at time t_i^{out}	Constant and equal to 100%

C.1.3 Daily average scenario

The parking manager has to submit requests on the DAM to buy the amount of energy needed to charge the vehicles on day D. This request has to be based on a prediction of the load and a possible option is to evaluate the daily average scenario. In order to do it, a Monte Carlo approach is adopted and a set of daily scenarios is created. By generating a large number of days of operation N_{MC}, an average profile of withdrawal from the network $\hat{P}_{tot}(t)$ can be built.

$$\hat{P}_{tot}(t) = \frac{1}{N_{MC}} \sum_{N_{MC}} P_{tot}(t) \tag{C.9}$$

This profile is useful also to formulate offers on the ASM. In fact, the power that is possible to offer upwards (i.e. by decreasing the load) for a given hour, will be, at most, the power that is expected to be withdrawn in the same hour. Similarly, the maximum power that can be offered downward (i.e. by increasing the load) will be limited to the maximum power that the cars connected at that time are able to absorb $\hat{P}_{tot}^{max}(t)$.

$$\hat{P}_{tot}^{max}(t) = \frac{1}{N_{MC}} \sum_{N_{MC}} P_{tot}^{max}(t) \tag{C.10}$$

Applying this methodology to the case of the garage of Bisceglie, the daily average profiles have been defined and they are shown in the Figure C.5 (a).

It is important to notice that the charging profiles computed refer exclusively to the instantaneous power exchanged by each battery, while they do not consider the evolution of the SOC of the batteries. Indeed, the closer the time of departure of a car, the less the possibility to act on its charging schedule. Taking into account this aspect is fundamental in order to present effective offers on the ASM, since the flexibility service has to be guaranteed in a continuous manner for the defined time. For this reason, the theoretical power profiles cannot be fully exploited, as the batteries would charge/discharge quickly, thus making it difficult to comply with dispatching orders received in the hours following a first call. Therefore, a market strategy needs to be defined, offering minute by minute a different percentage of the theoretical maximum power. The choice of the percentage to offer can be optimized thanks to the experience accumulated with the results of subsequent simulations. For the purpose of this study, two exponential functions are used to define the upward and downward offers (τ = 200 min). The resulting power profiles offered on the ASM are shown in Figure C.5 (b).

$$\hat{P_{up}}(t) = \hat{P}_{tot}(t) \cdot (1 - \exp^{t/\tau}) \tag{C.11}$$

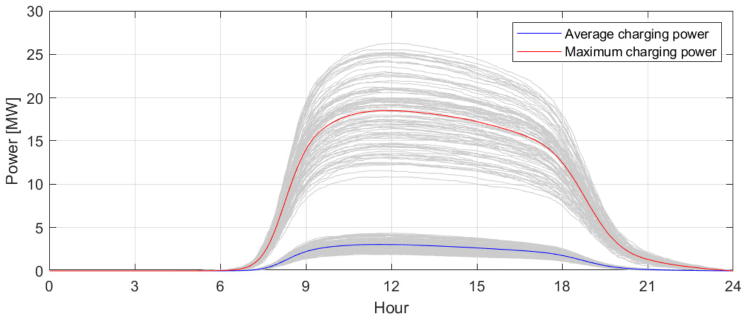
$$\hat{P_{dw}}(t) = \hat{P}_{tot}^{max}(t) \cdot (1 - \exp^{t/\tau}) \tag{C.12}$$

C.1.4 On-line operation

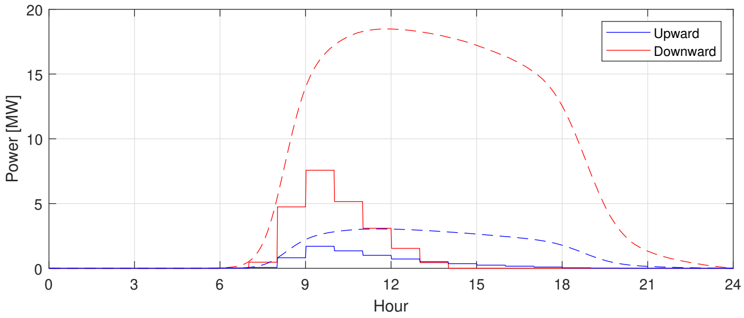
Once the average scenario has been defined, as illustrated above, it is possible to proceed to the simulation of a single day, from minute 1 until minute 1440, for a period of 24 hours. The goal is to define the ability of the garage manager to bid on the ASM effectively, thus meeting both the dispatch orders and the charging requests that come from the cars minute by minute. The simulation requires to create a daily scenario with the methodology already presented. Obviously, although the daily car movements and power profiles are built initially, the trend of the variables is not known *a priori*; on the contrary, the garage manager/aggregator gets progressive knowledge of the trend of the variables, and the comparison with the reference profiles influences its choices and scheduling.

Charging scheduling

At each minute t the charging schedule for each car is updated according to cars' and market's requests. First of all, a baseline power $P_i^{base}(t)$ is defined for each car. It is evaluated considering no ASM participation. The power request to charge each car up to its final SOC is computed with an algorithm analogue to the one described in Section C.1.2:



(a) Profiles of the average power request and the maximum power limit, depicted over the results of the Monte Carlo iterations.



(b) Baseline for upward and downward offers compared with power profiles.

Figure C.4: *Results of the daily average scenario.*

- The energy needed to finalize the charge is computed considering the current SOC.

$$E_i(t) = (SOC_i^{req} - SOC_i(t)) \cdot Cap_i \tag{C.13}$$

- The theoretical power for constant charging is evaluated considering the remaining time.

$$P_i^{avg*}(t) = \frac{E_i(t)}{t_i^{out} - t} \tag{C.14}$$

- The baseline power $P_i^{base}(t)$ is therefore evaluated considering the maximum power limit:

$$P_i^{base}(t) = \begin{cases} P_i^{avg*}(t) & \text{if } P_i^{avg*}(t) \leq P_i^{max} \\ P_i^{max} & \text{if } P_i^{avg*}(t) > P_i^{max} \end{cases} \tag{C.15}$$

Then, the subset $N_{flex}(t)$ of the parked cars that can be used for providing flexibility service at time t is defined. From the entire set, cars are excluded if:

- the departure is expected in less than 60 minutes;

$$t_i^{out} - t < 60$$

- the maximum power is request to reach their final SOC in the residual time.

$$P_i^{base}(t) = P_i^{max}$$

Once the subset of cars qualified to provide the requested market service is defined, the power requested by ASM $P_{mkt}(t)$ is distributed among them by mean of a coefficient α_i, defined as:

$$\alpha = \begin{cases} \frac{\Delta P_i^{av\downarrow}}{\Delta P_{tot}^{av\downarrow}} & \text{if } P_{mkt}(t) > 0 \\ \frac{\Delta P_i^{av\uparrow}}{\Delta P_{tot}^{av\uparrow}} & \text{if } P_{mkt}(t) < 0 \end{cases} \tag{C.16}$$

where:

- $\Delta P_i^{av\downarrow}$ is the maximum withdrawal reduction for each car and it is equal to its power request for the baseline charging:

$$\Delta P_i^{av\downarrow}(t) = P_i^{base}(t) \tag{C.17}$$

- $\Delta P_{tot}^{av\downarrow}$ is the maximum overall reduction, evaluated as:

$$\Delta P_{tot}^{av\downarrow}(t) = \sum_{N_{flex}(t)} \Delta P_i^{av\downarrow}(t) \tag{C.18}$$

- $\Delta P_i^{av\uparrow}$ is the additional power that could be absorbed by each car i and it is the difference between the maximum power limits for its charging and the power for its baseline charging:

$$\Delta P_i^{av\uparrow}(t) = P_i^{max} - P_i^{base}(t) \tag{C.19}$$

- $\Delta P_{tot}^{av\uparrow}$ is the additional power that could be absorbed from the entire fleet:

$$\Delta P_{tot}^{av\uparrow}(t) = \sum_{N_{flex}(t)} \Delta P_i^{av\uparrow}(t) \tag{C.20}$$

- $P_{mkt}(t)$ is the power requested is the bids on the ASM are accepted (see below).

The charging power for each car will be the sum of the power request for its baseline charging, plus its contribution to provide the market service.

$$P_i(t) = P_i^{base}(t) + \alpha \cdot P_{mkt} \tag{C.21}$$

The SOC of each car i is consequently updated:

$$SOC_i(t) = SOC_i(t-1) + \frac{P_i(i) \cdot \Delta t}{Cap_i} \tag{C.22}$$

In the event that it is not possible to supply all the power requested by the market, the power not supplied is calculated as the difference between the power requested and the maximum power available from the parking lot (whether up or down).

Bids updating

A key point of the time-real simulation are the minutes in which the aggregator have the opportunity to modify the bids submitted on the ASM. As already seen, on the basis of the average daily profiles carried out, initial profiles for the upward $\hat{P}_{up}(t)$

and downward $\hat{P}_{dw}(t)$ offers can be computed. However, during the day it is possible to reshape these offers according to what has been recorded in the garage up to each specific moment. In particular, on the Italian ASM the process of updating bids can be done at 03:00, 07:00, 11:00, 15:00 and 19:00. The difference between the expected value (profile of the average scenario $\hat{P}_{tot}(t)$) and the value actually recorded $P_{tot}(t)$ is evaluated.

$$\Delta P_{tot}(t) = \frac{\hat{P}_{tot}(t) - P_{tot}(t)}{\hat{P}_{tot}(t)} \cdot 100 \tag{C.23}$$

A calibration factor CF is then evaluated as:

$$CF(t) = \frac{1}{t} \cdot \sum_{t^*=1}^{t} \Delta P_{tot}(t^*) \tag{C.24}$$

The base profiles of the power offered upward and downward are consequently updated:

$$\hat{P}_{up}(t) = \hat{P}_{up}(t) \cdot (1 - CF(t)) \tag{C.25}$$

$$\hat{P}_{dw}(t) = \hat{P}_{dw}(t) \cdot (1 + CF(t)) \tag{C.26}$$

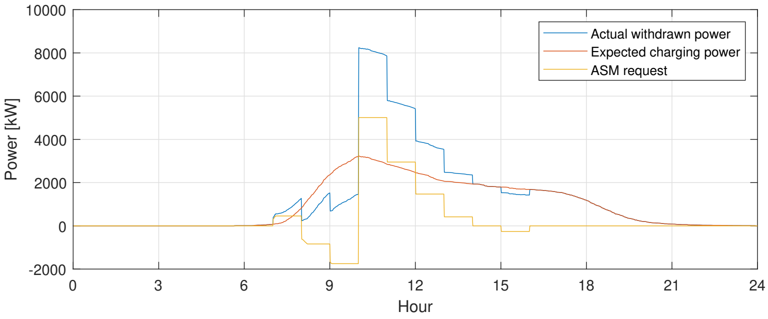
It is possible to distinguish two cases:

- if the actual charging profile $P_{tot}(t)$ is on average higher than the expected one $\hat{P}_{tot}(t)$, the calibration factor CF is positive. Since the energy requested from the fleet is higher than expected, the maximum charging power (i.e. the upward offer) is increased, on the contrary the downward offer is decreased.
- if the actual charging profile $P_{tot}(t)$ is on average lower than the expected one $\hat{P}_{tot}(t)$, the calibration factor CF is negative. Since the energy requested from the fleet is lower than expected, the maximum charging power (i.e. the upward offer) has to be reduced, on the contrary the downward offer is increased.

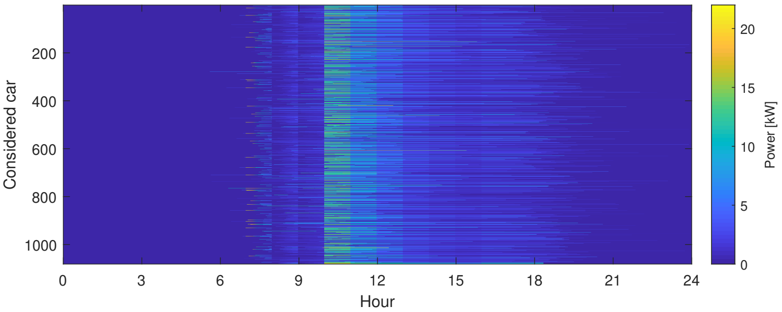
For each hour of the day, the acceptance or rejection of the offers is evaluated. This evaluation is carried out through a market model based on a decision tree algorithm developed ad hoc for the Italian dispatching service market. For the purpose of this work it can be considered as a black box that simulates the market results. If the offer is accepted, then the resulting power request $P_{mkt}(t)$ is not null. The acceptance or rejection of the offers presented makes it possible to evaluate the power that theoretically the garage should supply to the market: this power is considered as constant at hourly level in this example, however in the Italian market the compliance with market results is evaluated in terms of total energy supplied in each quarter-hour.

C.1.5 Results

On the simulated day, 1081 cars have parked in the garage, drawing 31.2 MWh for their charging. Among these, 7.7 MWh have been withdrawn to comply the with the downward request from the ASM. The aggregation provided also 2.8 MWh of upward service. In some cases the aggregator was not capable to provide the requested service for an amount of 0.1 MWh. In Figure C.5 (a), the baseline charging profile for the aggregation is shown in red, while the request from the ASM are represented in orange. It can be notice that in the first hours of the day the aggregator received an upward request (i.e. to decrease the load), followed by a downward request (i.e. to increase the load). The effect of this orders on the charging of each car can be seen in Figure C.5 (b), where the peak of power from 11 to 12 a.m. is clearly visible for most of the connected cars.



(a) Overall power exchanges.



(b) Charging power for each car.

Figure C.5: *Power exchanges resulting from the daily operation.*

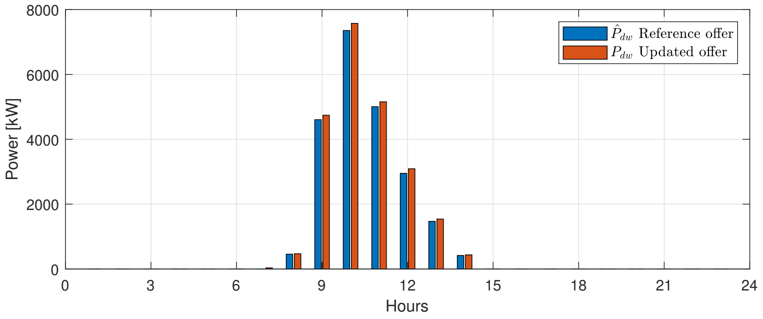
Figure C.6 shows, for the day under analysis, the reformulation of the offers carried out. The y-axis shows the quantities offered in MWh/h, while the x-axis shows the hours of the day. The blue bars represent the values of the reference offers, while the orange represent the values of the offers once reformulated. It can be notice that there is a positive calibration of the downward offers in all the hours of the day, on the contrary upward offers are generally reduced. This behavior may indicate a greater presence of cars compared to the average scenario, or also a greater request to recharge the cars due to low values of the initial SOC of the fleet. In both cases, there is a greater power required for charging, with therefore less reserve availability for upward and more reserve availability for downward compared to what was expected.

From the economical point of view:

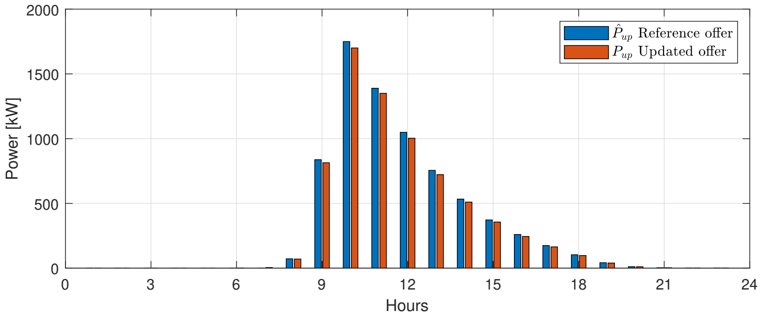
- The energy withdrawal at the DAM conditions is evaluated 210 €/MWh[2] and corresponds to a cost of 4.94 k€;

---

[2] MTA3 tariff



(a) Downward offer.



(b) Upward offer.

Figure C.6: *Reference and updated offers presented on the ASM.*

- The energy withdrawal due to downward service is evaluated 160 + 20 €/MWh and corresponds to a cost of 1.39 k€.
- The value of the upward service is evaluated as the offered price (120 €/MWh) and corresponds to a revenue of 336 €.
- The value for the service requested but not performed, evaluated 150 €/MWh, corresponds to a cost of 15 €.

It follows that the manager of the garage charged cars for a total of about 31.2 MWh with a total cost of 6.00 k€. The unit price paid for the energy withdrawn is therefore 192 €/MWh. By participating to the ASM, the fleet manager obtain saving equal to 18 €/MWh, that is 35.4% of energy price and 8.4% of the overall tariff taken as reference in this case study (210 €/MWh). It is worthwhile to mention that providing upward and downward services may cause, later, a difference from the baseline profile resulting from the DAM. The integrated (DAM and ASM) market strategy should be optimized in order to minimize the imbalance risk, otherwise the revenues obtained from the ASM could be compromised by the imbalance cost.

C.1.6 Conclusion

The aggregation of a fleet of electric vehicles for the provision of V1G services (adapting charging power) has been modelled within a specific framework. Within the model, a daily operation scenario is defined considering the charging requests of each car of the fleet. A Monte Carlo approach is adopted to build a single scenario and an average one is computed with repeated simulations. The aggregator defines the baseline market strategy based on the daily average scenario and updates it in real time according to the specific status of the fleet. The model has been tested on a case study focused on a big parking garage given the availability of data, but it could be possible to apply it also to a distributed fleet as the one of private cars of the members of an EC. The application shows that it is possible to obtain savings from the participation to the Italian ASM, with a simple strategy based on constant prices and variable quantities. Further investigation could evaluate the probability distribution of the results when simulating different days. Moreover, it could focus on the improvement of the strategy in order to maximise the revenues. Nevertheless, the main goal of the proposed algorithm is to point out how an advanced operation of the assets could provide economic benefits to the ECs. Moreover, EV charging scheduling may be an interesting option for an EC, but a further step could include in the scheduling strategy also other flexible loads of the EC. Among the most interesting ones there are thermal loads, given the natural inertia of heating and cooling systems. This may increase the quantities that could be offered on the ASM and, consequently, the EC revenues. It is worthwhile to point out that, given the regulatory framework today in place, the proposed approach is just a theoretical investigation, demonstrating the feasibility and quantifying the possible benefits, whilst its implementation in real life project is not yet allowed.

APPENDIX *D*

Cooperation with Eilhicha s.a.

Real life operation of an energy community could be a complex activity. Many aspects have to be considered and technological, socio-economic, environmental and institutional issues have to be faced. To better understand this complexity, within the PhD, a cooperation has been set up with the Peruvian company Eilhicha. As detailed in the following sections, Eilhicha can be considered as an energy community in a rural context of a developing country. It is both producer, supplier and DSO of the electrical system of Chacas-San Luis. The author spent two months in Peru between December 2018 and February 2019, analysing and participating to the Eilhicha activities and providing them some technical contributions such as data analysis and grid modelling. The main outputs and lessons-learnt of the collaboration are reported in this appendix.

D.1 Chacas-San Luis electrical system

D.1.1 Peruvian context

Peru is a developing country with a population of 32.5 million. The continued primacy of Lima - the capital - with its attractions and the poverty of the rest of the country produces an internal migration from the Andes to the main city [157]. Due to this, the rural area of Peru are more and more abandoned, and today 80% of the population lives in urban areas [158]. Peruvian government and NGOs are trying to stop this phenomena improving the quality of life in rural areas. The creation of infrastructures and the access to electricity is one the of the key aspects of this process. Thanks to their efforts, access to electricity in rural areas almost doubled in the last decade, rising from 45% in 2008 to 82% in 2018. According to the World Bank [158], Electricity consumption is increasing year after year, in 2018 every Peruvian consumed 1.5 MWh of electricity (+50% with respect to 2008), while the Total Primary Energy supply (TPES) per capita was 0.8 toe/cap (+33% with respect to 2008)[1]. The majority of electricity is generated with Hydro (55.2%) and Natural Gas (38.2%) [159]. According to the International Hydropower Association (IHA) Peru has 5.4 GW of hydropower installed capacity and a total potential estimated at around 70 GW. The Amazon basin region holds 97.7 per cent of Peru's water resources. The National Energy Plan 2014-2025 developed by the Ministry of Energy and Mining expects Peruvian energy demand to grow between 4.5 to 6.5 per cent a year by 2025, which, according the the IHA, will be satisfied primarily by hydropower [160].

D.1.2 History of Chacas and Eilhicha

Chacas is a rural village in the district of Asunciòn, in Ancash region, located 300 km further north of Lima. It is located in a valley near Huascaran National Park in the Cordillera Blanca mountain range. Thanks to the proximity of a such mountain range there is a large availability of hydro power generation. An Italian NGO named Operazione Mato Grosso (OMG) has been working in the area since the 70s of the last century. OMG created schools, hospitals and many other public services. Among these, it contributed to the electrification of the area, founding the company Eilhicha (Empresa de Interes Local HIdroelectrica de CHAcas - Hydroelectric company of local interest of Chacas). The company has been formally founded in 1994, it started its operation producing energy for the hospital of Chacas, but then the entire village was connected. In the following years, also the village of San Luis was connected and nowadays, thanks to the participation of Eilhicha to the national plan of electrification the entire valley of Chacas is connected to the grid of Eilhicha. In the meanwhile, the company received from the Ministry the formal role of DSO for the entire area. The local grid has been operated in islanded mode until 2011, when a connection with the national grid was realized. This connection gives the possibility to sell energy surplus and contributes to the stabilization of the system frequency. The shareholders of the company are the local parish and the municipality and the purpose is providing cheap electricity to local households and small business. The revenues from Eilhicha's operation are used for social purposes.

D.1.3 Eilhicha s.a. within the Energy Community framework

Eilhicha can be considered within the framework of energy communities proposed in [54] and explained in Section 3.1.3. The roles that Eilhicha plays are reported in Figure D.2 and are describe in the following.

- **Facilitator**. This role is mainly linked to the activity of the NGO Operazione Mato Grosso. OMG was the founder of the first power plant of the company and it still plays an important role in the evolution of the company and the implementation of new solutions. It contributes in the organization of the activities and in financing the projects. Indeed, most of the Eilhicha's investments are funded by mean of private voluntary donations. Friends and supporters of the OMG's missioners collects and send money to Peru to finance them. Furthermore, the OMG

---

[1] The following values for 2018 are proposed for comparison [159]:
Electricity consumption [MWh/cap]: Central & South America 2.1, China 4.9, Italy 5.2, EU28 6.0, USA 12.8
Total Primary Energy supply [toe/cap]: Central & South America 1.2, China 2.3, Italy 2.4, EU28 3.1, USA 6.7

Figure D.1: *Employees and volunteers of Eilhicha in front of the company's office. Eilhicha created jobs for more than 30 local people, Italian volunteers actively contribute to the management.*

contribution is not limited to money-raising, but most of the workers that contribute to the new realizations are voluntaries that offer their qualified experience and time for free. An example of this is provided by the group named "Gruppo Turbine Schio". This is a group of specialized and skilled people, ex-employees of the company De Pretto Escher Wyss (nowadays Andritz Hydro), that restores decommissioned hydroelectric power plants for non-profit companies.

- **Producer**. Like in many other energy communities, the production of energy has been the starting point for Eilhicha. It has always been a producer of renewable energy and today it is owner of three different power plants. The first one is named *Collo* and it is a repowering of the first hydropower plant that was build for the Hospital. In 2000 the existing generator was substituted by a more powerful one (730 kW) and it is still in operation. The second power plant is named Jambòn and it is equipped with two generation groups: both are based on Francis turbines and the rated powers are 380 kW (2005) and 780 kW (2010). Finally, Huallin is the most recent power plant (2015), it is a fully automatized power plant with a rated power of 4 MW[2]. The size of this machine is quite big because, in the meanwhile, the system has been interconnected to the main grid and this allows to sell the energy surplus. All of them are fed by different run-off river water supply basins. Another hydroelectric power plant (Collo II) is expected to be installed soon.
- **Supplier**. The company is the local electricity supplier and the service is provided with important discounts for poor people. Playing this role allows to avoid third party extra-cost and to directly supply the energy produced locally. This also create jobs for the administrative and office activities of the company. Eilhicha is also responsible to the unbalances among production and consumption. This is

---

[2] For the sake of completeness it should be said that Huallin power plant is not owned by Eilhicha itself, but from the association "Santa Lucia", controlled in any case by Operazione Mato Grosso.

trivial when operating in islanded mode since the balance is required for technical reasons, but it is important also when connected to the main grid for commercial reasons.

- **Distribution System Operator**. Eilhicha received from the Ministry of Energy and Mines of Peru the concession for the electricity distribution in the area. It is the owner of the oldest part of the network, but it manages also the most recent expansions, founded by the Ministry of Energy and Mines for completing the electrification program. The network is described in the following paragraphs. The operation of the distribution network is the activity that requires more resources and around twenty technicians are hired at full time. Eilhicha is also responsible for the metering service. Since the meters require a manual reading, tens of people widespread in the villages are also hired per day for the reading service.

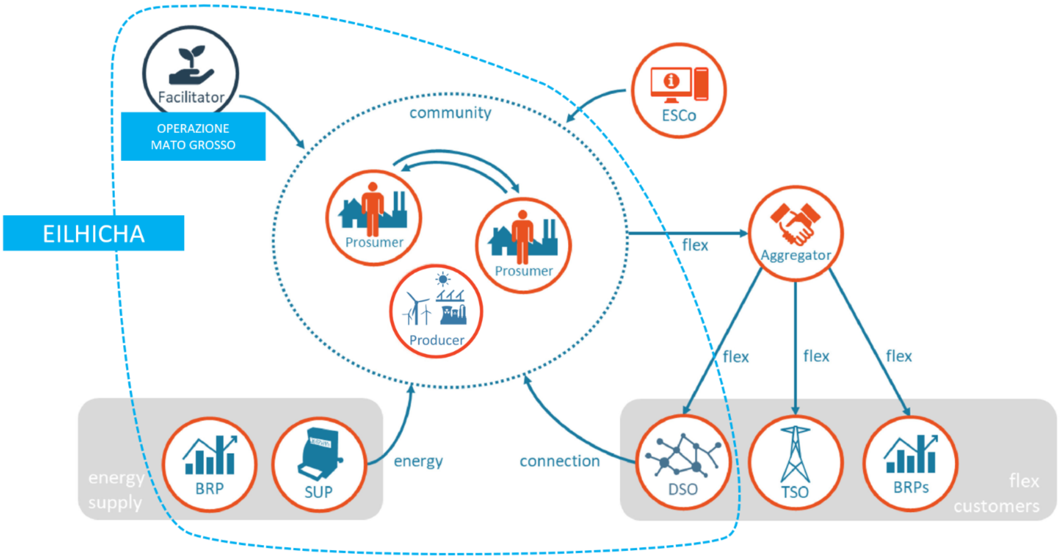


Figure D.2: *Eilhicha s.a. within the framework proposed in [54] (See Section 3.1.3 for more details).*

D.2 Activities

The collaboration between Politecnico di Milano and Eilhicha is still ongoing. The activities that have been performed until now are:

- Historical data analysis from the commercial database.
- Migration of grid model from CAD to GIS.
- Creation of an electrical DigSilent model for the MV grid.
- Electrical data collection and other on-field activities.

The main results of these activities are detailed in the following paragraphs.

D.2.1 Grid modelling - GIS

The electrical system of Chacas-San Luis is widespread along all the valley. Generators are located in the upper part of the valley (south-west) at 3500-4000 meters above see level. The interconnection with the national grid is in the lower part of the valley (North), near the village of Pomallucay. Customers are spread through all the valley, but the most consuming ones are concentrated in the two main villages (Chacas and San Luis). The geographical visualization of the grid is reported in Figure D.3. It is characterized by a radial topology: in the center there is the power plant Jambòn and at the end of one feeder there is the connection with the national grid.

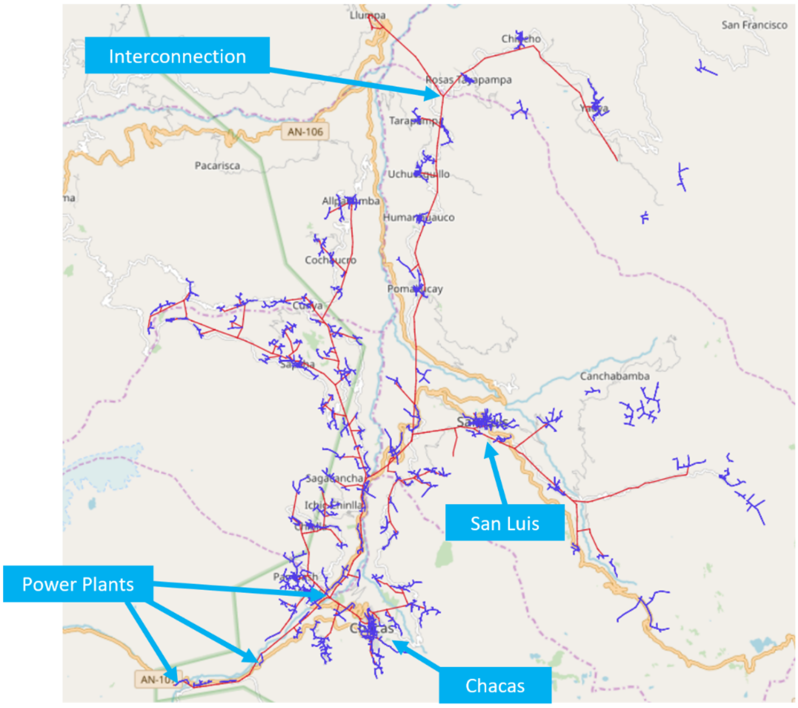


Figure D.3: *GIS model visualization of the electrical system of Chacas-San Luis.*

The nominal voltage of the MV distribution grid is 22.9 kV. The total length of the MV lines is 135.2 km, and the distance between valley top and bottom is more than 30 km. Distribution system is composed by 919 MV branches, 792 MV-towers and 138 MV/LV transformers. The nominal voltage of the 138 LV distribution networks is 400 V and they are composed of 4539 LV branches and 4192 LV towers. In Figure D.3 the MV network is represented in red and the LV networks are in blue. In the norther and eastern parts of the area, some low voltage networks are not connected to the MV one. This shows the progress in the electrification of the area: the LV lines have already been build in some villages, while the the connection to the MV network is still missing. These are due to the grid expansion that is going to be performed for the implementation by the Ministry of Energy and Mines of the last steps (IV and V ETAPA) of the National Plan of Electrification, called *Plan Nacional de Electrification Rural (PNER)*. The aim of the last step is to connect 32 new villages. It is expected to be completed in 2022 and will deliver electricity to 489 new households (1912 people estimated). Before starting the collaboration with Politecnico di Milano, Eilhicha was managing the distribution network by mean of a CAD file. The migration of the model to a GIS one enabled more advanced opportunities. First of all, the possibility to visualize the position of the elements on a map simplifies the comprehension since the visual format is easily understood by most of the people. This is useful, for example, for technicians that have to operate maintenance, for people that have to manually read the meters for collecting measures, for identify building for new connections and evaluate the distance from the existing lines. An example of the user interface provided by the software QGIS is reported in Figure D.4. The model of the grid is shown for the city center of Chacas, it is possible to easily identify each tower, branch of line, meter and public light of the area. Moreover, the usage of a GIS model enables easier interactions with the grid database. For example, reports required by the Ministry of Energy or the national Authority related to the status of the network can be automatically generated based on the GIS model. A further option that has been enabled thanks to the GIS migration is the interaction with the commercial database. Today many information about customers, meters and contracts are duplicated in both the grid model and in the commercial database used for the billing. This organization is inefficient and the risk of errors and inconsistencies is high. The GIS model could enable an easier interaction with the commercial database and it could eliminate this risk. Finally, based on the opportunities provided by the GIS model, an automatic Python procedure has been developed to create an electrical model of the network starting from the geopackage format.

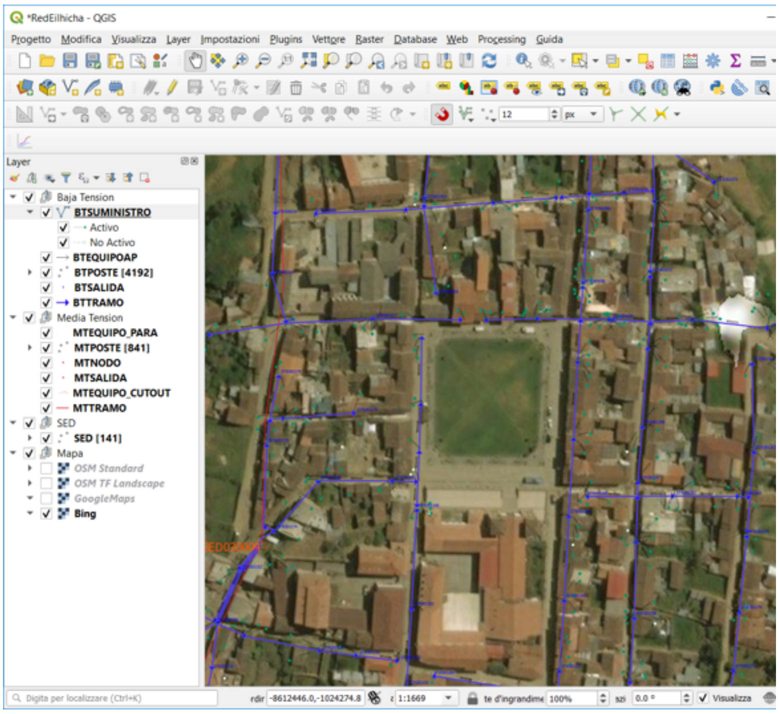


Figure D.4: *View of the GIS model of the distribution network in the center of Chacas (QGIS software).*

D.2.2 Commercial data analysis

An overview on the customers of Eilhicha is proposed in the following. Data are taken by Eilhicha database for a time windows between January 2003 and January 2018. The total number of customers in January 2003 was 888 and most of them were households and small business (only 16 three-phase connection were present). In 2018, 5484 customers were connected to the system. Most of them have been connected to the grid during the last few years, thanks to the National Plan of Electrification. The number of customers of Eilhicha (that is also the number of households/small business with access to electricity) increased more than 500% between 2003 and 2018. If this analysis is limited to the three-phase connections, it can be noticed that they increased even more (+1180%). The number of users for each year and the growing trend can be observed in Figure D.5.

The majority of customers is provided by a 3 kW electric connection, a value much more higher than the power they actually need. The great majority of customers have a low load demand and energy request during the year. The customers of Eilhicha have been clustered according to their monthly average consumption. The resulting clusters for the last available five years are reported in Figure D.6, and the relative percentages of each cluster for 2018 in Figure D.7. There is an important number of users with null or negligible electricity consumption. In 2018, 7% customers consumed 0 kWh/month, while many other customers (28%) had a very low electricity consumption (between 1 and 10 kWh/month). Half of the customers (49.0%) had an electricity consumption ranging between 10 and 100 kWh/month. A minor set of users (16%) consumed between 100 and 500 kWh and less that 1% of the users (25) had an electricity consumption higher that 500 kWh. These consumers are the Mama Ashu hospital, municipality, local parish and some little local businesses.

It is interesting to highlight that the majority of such low-consuming customers lives in scattered, low populated and difficult access areas, while the majority of electricity consumption is concentrated close the main towns and to the generators. A big portion of the distribution grid was thus installed only for reaching the less-consuming (and poor) users. This is a typical issues when dealing with rural electrification processes and a benchmark between grid extension and off-grid solutions has to be considered.

D.2.3 Grid modelling - Electrical model

As introduced in the previous sections, grid is being expanding, load demand is growing and different interventions are going to be implemented or are in a planning stage:

- A new hydroelectric power plant is expected to be installed near the existing one in Collo. The new generator is expected to produce 1 MW.
- A new medium voltage connection (60 kV) is planned in order to provide a direct connection for the Huallin power plant to the national grid. Today the rated power of the Huallin power plant is not exploited because of the limited capacity of the current connection lines. This new connection will allow increase the revenues from the sale of energy.
- New villages are going to be connected for the completion of the rural electrification program.

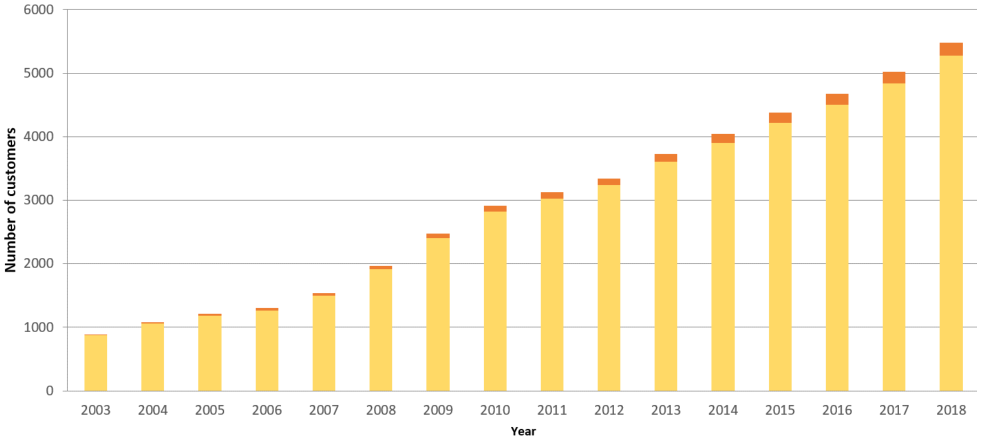


Figure D.5: *Growth of the number of customers of Eilhicha: single-phase and three-phase connections are depicted respectively in yellow and orange.*

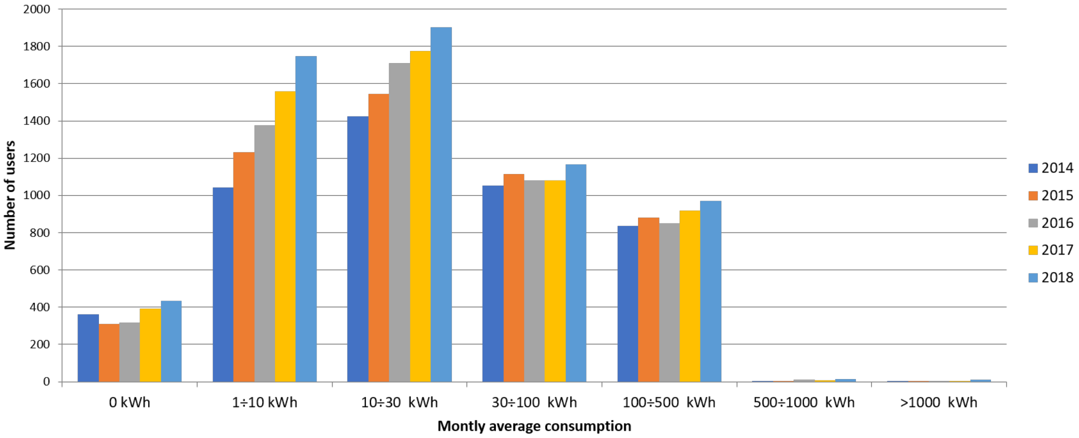


Figure D.6: *Number of customers of Eilhicha clustered according to their monthly average consumption, trend of the last five available years.*

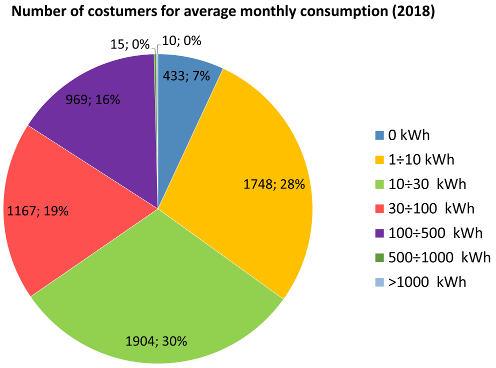


Figure D.7: *Number of customers of Eilhicha according to their monthly average consumption (Jan 2018).*

- The users' energy need is going to increase given the possibility provided by to socio-economic development. This increasing has been estimated as 5% per year.

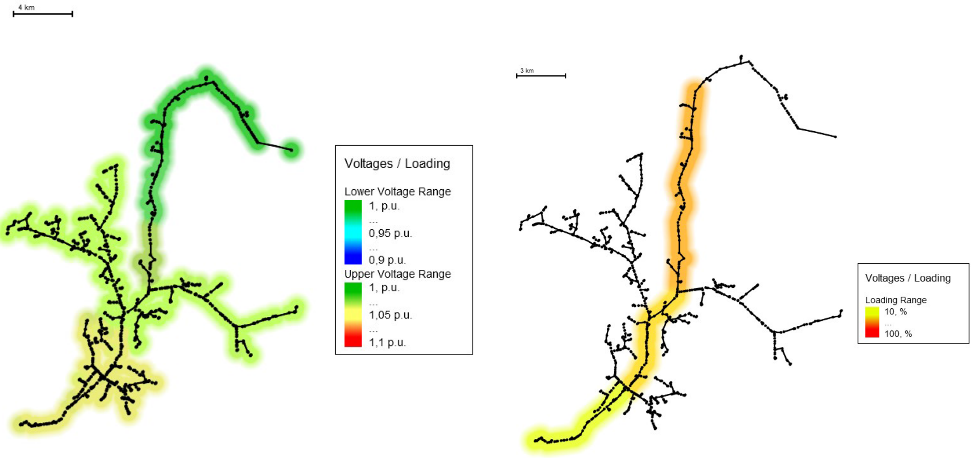
Considering all of such information, an electric model of the network became interesting for an optimal management and planning. Indeed, a grid model is necessary for evaluating the operation of a power system, identifying grid's strengths and weakness, and it is a powerful tool for a robust planning of interventions and grid reinforcement. Besides all these things a three phase unbalanced grid model will also allow to identify problems in the grid operation. All of these benefits are expected to increase quality of the service, to ease daily operation for the distribution activity and, not least, to decrease electricity bill to final customers. Given the non-profit purposes of the company, the German firm DigSilent gently provided a free licence of their software PowerFactory for Eilhicha. Therefore, an automatic procedure has been developed in order to create the PowerFactory electrical model starting from the most updated GIS one. Thanks to the DigSilent grid model, different analysis have been performed in order to improve both the grid operation and the grid planning. This allowed to evaluate the following scenarios for the Chacas-San Luis electrical system.

Base Case

First, a load flow analysis has been performed based on the actual state of the grid. The simulation has been computed in the peak load condition, that has been identified on July 11 2018 at 20:00. In this specific hour of the year, the total load of the distribution grid was 950 kW. Load requests of each zone were: 50 kW in Huallin, 57 kW in Pampash, 324 kW in Chacas and 519 kW in San Luis. The load of each zone has been distributed among the secondary substations according to the number of users connected. To supply this load and sell part of the energy produced, three of the four generators were in operation: Huallin power plant was producing 1100 kW, Collo 540 kW and Jambon 340 kW. In Figure D.8 the resulting heatmaps of voltage distribution across the grid (left) and line loading (right) are depicted. As expected, voltage results higher on the valley top and constantly decreases moving to the interconnection point. This is congruent with the presence of generators grouped in this grid zone. The maximum bus voltage calculated is 1.046 pu. The branches where the maximum loading occur are the ones along the main line that connect generators and the interconnection point (the color scale in Figure D.8(b) has been adapted to highlight only values higher than 10%). It can be noticed that the lines with the highest loading are not close to the power plants (in this area conductors have higher cross sections, 35 and 50 square millimeters), but after the town of San Luis. Indeed, in this part of the grid, conductors are made of aluminium, with 25 square millimeters section. The maximum loading is 38.2%, but the majority of lines are under-exploited: 75% of the lines, in the peak condition, present a loading factor lower than 1% while only 6% of have a loading factor higher than 30%. The grid losses results to be equal to 162 kW (8.1% of the generated power), and most of them are due to the power flowing on the main line that connects Huallin to the interconnection point.

New interconnection

In this scenario, the new direct interconnection between Huallin power plant and the national grid is considered. The results obtained by this simulation are then compared



(a) Voltage level (b) Line loading

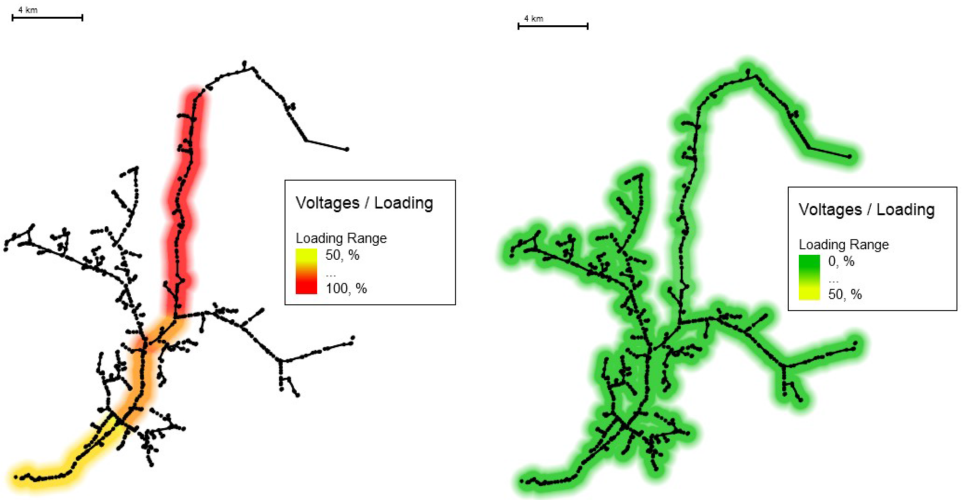
Figure D.8: *Results of the load flow for the base case scenario.*

with base case ones. As already introduced, Huallin power plant has a rated power of 4 MW but, due to the technical limits of the distribution grid it is not possible to generate the maximum power and it is operated at maximum 1.1 MW. It is possible to evaluate that, if the power plant of Huallin operates at maximum power, the maximum line loading between Huallin and the interconnection would be 109.9% with 54 branches of line exceeding 100%. Furthermore, line losses would be 1.39 MW, so almost 30% of the electricity production. In addition, voltage magnitudes, especially in the nodes close to the power plants, would exceed 1.1 p.u. making this solution unfeasible. Tanks to the new interconnection, Huallin power plant can operate at maximum power and the production does not need to transit on the grid backbone along the valley. The resulting loading and losses reduction are evaluated. Also in this case the maximum loading occurs near the interconnection, when the line cable decreases its cross area, but it is limited to 16.4% (Figure D.9(b)). The voltage level is more constant and closed to 1 p.u., while total grid losses decrease from 162.2 to 25.5 kW, confirming that the transit of the power generated by Huallin was responsible for most of them.

Grid extension and load increasing

New villages on the valley bottom are going to be connected to the grid thanks to the "V Etapa" electrification stage, the expected load has already been evaluated by the government. To simulate this scenario, these new loads are connected to the distribution grid and a load flow is performed. Considering both the interconnection in Huallin and the realization of the new electrification stage, the Chacas grid has been evaluated over the long term period. Specifically, load is expected to increase with 5% rate each year. Load flow are evaluated after 5, 10, 15 and 20 years from the base case.

As we can see in Table D.1, the average line loading is expected to increase from 2.00 to 4.84%, the maximum value from 16.4% to 39.07%. Therefore we can conclude that, also on the long term period, the rated power of the line will not be a problem for the grid operation, since during the peak load conditions line loading is expected to stay below 40%. Losses will increase from 25.5 to 159.6 kW. Considering also the



(a) Without the new interconnection. (b) With the new interconnection.

Figure D.9: *Loading on the lines when Huallin is producing at nominal power.*

increase in load demand it is meaningful to observe the rate between losses and peak load. Actually, losses (25.5 kW) represent 2.4% of peak load (1070 kW), while in 20 years from now this rate will increase to 5.6%. Despite such increasing, we can conclude that losses will still represent a small fraction of loading. Moreover, considering conductors and equipment of the grid frozen for twenty years is a worsening condition. It is probable that in the meanwhile, for ordinary maintenance, some of the oldest and worst branches will be replaced and the grid will be reinforced.

Table D.1: *Future projections of peak load, line loading and losses*

	Peak load [MW]	**Loading Avg [%]**	**Loading Max [%]**	**Losses [kW]**	**Losses over Peak Load**
Today	1.07	2.00	16.4	25.5	2.4%
5 Years	1.37	2.37	18.9	34.6	2.5%
10 Years	1.75	3.08	25.7	62.5	3.6%
15 Years	2.22	4.14	35.4	120.6	5.4%
20 Years	2.84	4.84	39.1	159.6	5.6%

D.3 Conclusions

Within the on-field activities performed in Chacas, the work has been based mainly on software tools devoted to support the energy community in the management of the distribution grid. Nevertheless such an experience allowed to gain a real-life feeling on the criticalities in the day by day operation of an energy community. One of the most interesting aspects of Eilhicha is that, thanks to the NGO commitment, it is a clear example of a company in the energy sector that, aligned with the European principles for EC, provides "economic or social community benefits for its shareholders or members or for the local areas where it operates, rather than financial profits" [22].

APPENDIX E

Lab IoT and energy storage system testing

The energy storage system (ESS) is one of the elements that could improve the ECs capabilities and performances the most. The application seen in the chapters of this thesis can confirm it. In the REC model presented in Chapter 4, the ESS allows to increase the energy shared and the self-sufficiency of the community. This has a positive impact on the energy balance of the entire area and on the usage of the infrastructure, as detailed in Chapter 6. Finally, ESSs are the core of the flexibility services presented in Chapter C. Given the key role of these systems, specific attention is required to properly model them. Therefore, within the PhD activities, laboratory tests have been performed on a commercial domestic ESS, to gain real-life experience on such systems and, consequently improving the ESS models adopted. Specifically, the problem of identifying test procedures that can be used to quantify the performance of these devices has been addressed. Indeed, a test profile in terms of exchanged power should be defined for each particular service the ESS is in charge of, with the final goal to reproduce realistic on-field working conditions. This has been done for self-consumption (that is the most common application when considering households usage) and for primary frequency regulation. In this appendix, the setup of the lab and the main purposes and results of the tests are reported.

E.1 Setup of the lab

The tests on the ESS has been conducted in the IoT Lab of the Energy Department of Politecnico di Milano. The Lab is devoted to the research on the Internet of Things (IoT) concept, and it aims to create a suitable environment for the research, design, development and test of IoT solutions, with specific reference to energy and power systems applications. These solutions typically include distributed sensors and controllers, generation units (typically from RES), ESS, smart appliances, e-mobility, etc. One of the goals of the Lab is to deploy batteries in domestic users' premises and to remotely control them to perform both front of the meter and behind the meter services.

A commercial ESS has been used for performing the research activities. The equipment under study is an all-in-one solution for domestic photovoltaic application: PV MPPT, inverter, transformer, PLC and the battery are integrated in a single cabinet [161]. In particular, a sodium-nickel chloride battery (FZSoNick 48TL200, 48 V - 200 Ah [162]) is adopted. The EES has been made available to the IoT lab in the framework of the InteGRIDy project [163], in order to properly design the storage control laws and to enable the remote control of the apparatus, application of particular interest for future aggregators. The setup of the lab with the integration of the considered equipment is presented in Figure E.1. The pictures of the devices are reported in Figure E.4.

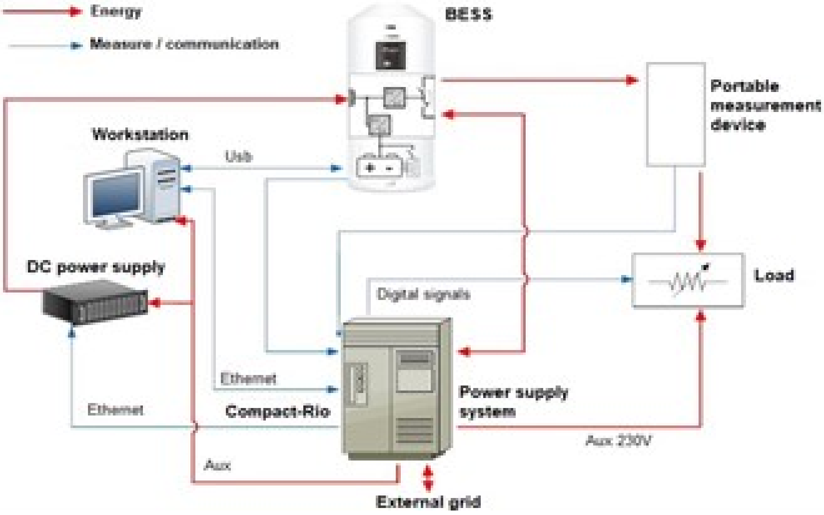


Figure E.1: *IoT Storage Lab architecture.*

Figure E.2: *Devices of the Lab IoT for the test bench: (from left to right) ESS, CompactRio controller, resistive load, (top) portable measurement device, (bottom) DC power supply.*

E.2 Case 1: Self-consumption

A first study has been performed to define a set of test profiles representing typical self-consumption behaviours in domestic applications. Starting from load profiles of several households, the corresponding daily battery profiles have been derived and then studied with a clustering approach. In this way, four clusters of daily profiles have been identified. By mean of numerical simulations, it has been verified that profiles that belong to the same cluster have a similar impact on the battery performances. Furthermore, the four profiles that are representative of each cluster (centroids) have been tested on the real system. Daily profiles with time steps of one minute have been tested in one-day-long experiments. The DC supplier has been controlled in order to emulate the PV production and the resistive load in order to emulate the household consumption. The ESS has been left free to follow its own control logic, with the purpose of maximising the self-consumption. The experimental efficiency of the ESS has been evaluated and compared with the numerical results. In the following, the most relevant element for the procedure are reported.

E.2.1 Numerical model

To evaluate the numerical efficiency of the ESS, few models have been founded in the literature. With respect to the technology in use in the Zhero system (ZEBRA battery) [164, 165], present two electrical models for the single cell, while [166] proposes an approach to mathematically represent the whole battery device. Considering data availability and the detailed experimental procedure, the latter has been adopted as a reference model. Its equivalent electrical circuit is described in Figure 1 and consists of a voltage source connected in series with a resistor and two RC branches. To the purpose of this work, a number of residential customers power profiles have been developed to test the effectiveness of the ESS in increasing the user's self-consumption. With this aim, the software Load Profile Generator [115] has been used to generate daily load profiles of typical households with a time sample of one minute. Combining each profile with a standard PV production profile the corresponding battery exchange power profiles is obtained. Considering that 126 different households have been considered and for each one 365 daily profiles have been generated, the resulting dataset contains 44115 profiles (actually, possible combinations are 45990, but some of them have been discarded because considered not relevant for the analysis, e.g. absence of load). The battery profile construction has been carried out by identifying the power of the ESS that, hour by hour, allows matching the load and PV production profiles. Specifically, the standard PV profile of sunny days has been adopted as per unit reference, and the size of the PV for each household has been defined in order to achieve a PV production that is equivalent to the daily energy demand.

From the set of load profiles, a set of battery profiles has been obtained. Each one of these profiles has been applied to the numerical model of the ESS, in order to evaluate the theoretical efficiency in the specific condition. The efficiency values η_{num}, calculated with the following equation, range between 90% and 100%, as it is possible to see in Figure E.3.

$$\eta_{num} = \frac{Energy_{supplied}}{Energy_{absorbed}} \text{ with } \Delta SOC = 0 \tag{E.1}$$

It has been notice that PV production can be different from the load energy demand, therefore a procedure for SOC restoration is required to obtain the verify the condition of $\Delta SOC = 0$. At the end of the profile, battery must be charged up to the initial

SOC with a given power value. This value is the maximum between the power that is maintained for half of the battery charge time and 0.05C[1], assuming that a so low C-rate cannot affect the performances.

E.2.2 Profile clustering

Cluster analysis has the purpose of dividing dataset in a certain number of groups, called clusters, so that elements of the same cluster must have similar features and, at the same time, they must also show a dissimilarity from those of another cluster. The level of similarity has been determined by algorithms that work with proper logics. One of these is k-means, that belongs to the "partitioning method" category, in which algorithms create a given number of partitions inside the initial dataset so that each element must belong just to one of these: this is the simplest and the most intuitive idea to achieve a clustering.

The most intuitive way to cluster the battery profiles could be considering directly the numerical efficiency as a feature. Nonetheless, for practical reasons this option has been excluded. Indeed, with such an approach, to identify the cluster to which a new profile belongs, the numerical computation of the efficiency has to be executed. To avoid this, the clustering need to be based on other features. A set of features has been defined, it include:

- the maximum power in absolute value of each daily battery profile;
- the battery energy content variation, defined as the difference between maximum and minimum of the battery cumulative energy curve corresponding to each profile
- the time ratio between all the charge and discharge period that takes place within each profile and so during 24 h,
- the number of current sign changes;

Moreover, other cluster analyses have been performed in order to evaluate the evolution of the profiles in time or frequency domain. In this latter case, Fast Fourier Transform (FFT) has been used to produce, as clustering inputs, the real and imaginary part of the complex number representing harmonics.

To identify the best set of features, a key performance indication has been defined as:

$$KPI = \sum_{k=1}^{N_{cluster}} \sum_{i=1}^{N_{profiles} \in k} \left(\eta_{i,k} - \eta_{centroid,k}\right)^2 \tag{E.2}$$

Where:

- $N_{cluster}$ is the number of clusters selected;
- $N_{profiles} \in k$ is the number of profiles belonging to cluster k;
- $\eta_{i,k}$ is the numerical efficiency of the profile i in cluster k;
- $\eta_{centroid,k}$ is the numerical efficiency of the centroid of cluster k.

---

[1] C-rate is the rate at which a battery is charged relative to its capacity

In other words, the KPI is minimum for the clustering approach that provides results closest to a clustering based on efficiency.

The optimal clustering solution is obtained with four clusters, adopting as features the maximum power in absolute value and the battery energy content variation. In Figure E.3 (a) the points representing the numerical efficiency resulted from the simulation of each profile are coloured based on the cluster to which they belong. It is possible to see that even if the information about the efficiency in not an input of the cluster definition algorithm, there is a clear relationship between clusters and efficiency.

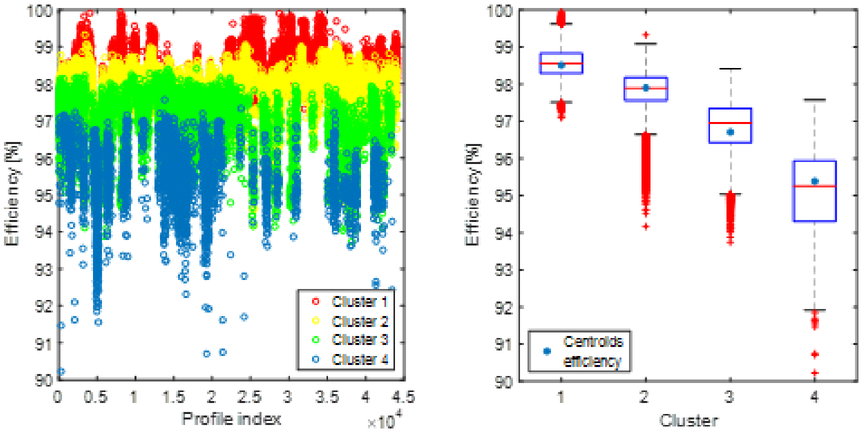


Figure E.3: *(a) Efficiency computed for each battery profile, colored in accordance with the cluster belonging (b) Box plot of the efficiency for the profiles within each cluster.*

In Figure E.4 the centroid profile of each cluster is depicted in the time domain. The chromatic scale shows the relative frequency wherewith the profiles of the considered cluster show a specific power value.

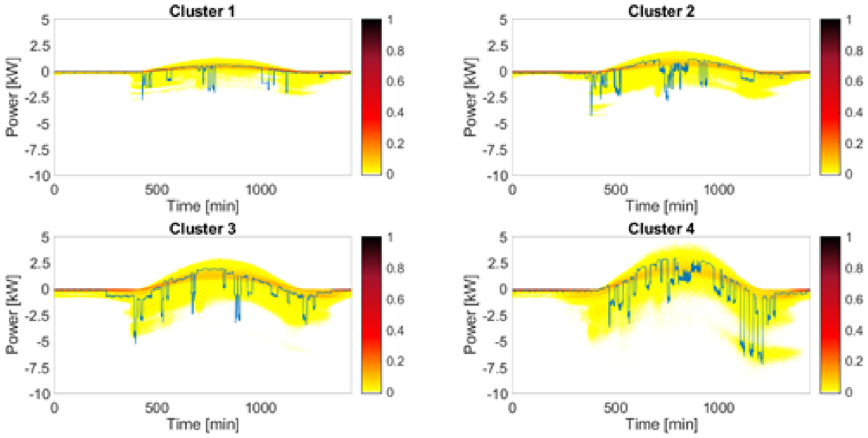


Figure E.4: *Profiles in time domain grouped by cluster and their respective centroids.*

E.2.3 Experimental evaluation

Once obtained the four characteristics profiles, these have been tested on the real system. Since the commercial ESS integrates also auxiliary equipment, it has been necessary to quantify their consumption through appropriate tests. Indeed, the mathematical approach proposed aims at evaluating the efficiency of the battery, not of the whole system. To this purpose, it has been necessary to give a definition of experimental efficiency in order to evaluate the behaviour of the electrochemical battery unit, regardless of ESS auxiliaries consumption E_{aux}.

$$\eta_{exp} = \frac{E_{load} + E_{aux} + E_{grid,injection}}{E_{PV} + E_{grid,withdrawal}} \text{ with } \Delta SOC = 0 \tag{E.3}$$

In the previous equation, E_{PV} is the energy measured at the PV plant terminals. When PV production and BESS injections are not enough, energy is absorbed from the external grid $E_{grid,withdrawal}$. This definition, for the reasons given above, considers the energy supplied to the load E_{load}, the one injected into the grid $E_{grid,injection}$, and that absorbed by the auxiliaries E_{aux} as useful effects. As for the numerical evaluation, in order to obtain reliable results, efficiency must be computed on a cycle with an overall SOC variation equal to zero. Therefore, SoC have been restored at the end of each profile with the same procedure described for the numerical model. The results of the experimental efficiency are reported in Table E.1 and they are compared with the numerical efficiency. An overall view shows that the trend defined by the cluster analysis is globally respected, therefore the experimental tests have confirmed the theoretical outcome.

Table E.1: *Comparison between numerical and experimental electrochemical efficiency of the centroid profiles.*

Profile	Numerical efficiency	Experimental efficiency
I	98,5 %	95,4 %
II	97,9 %	94,9 %
III	96,7 %	94,5 %
IV	95,4 %	93,7 %

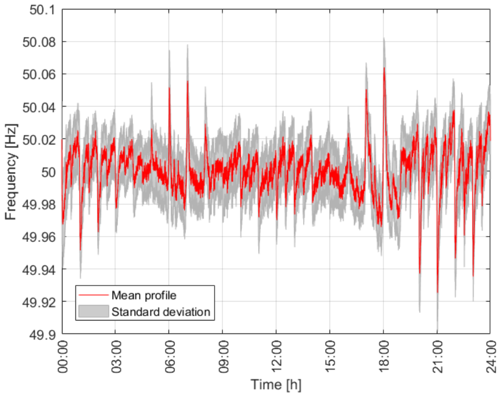
E.3 Case 2: Primary frequency control

The second interesting solution that has been tested is the usage of the same ESS for providing primary frequency regulation. Obviously, this type of service will not be the main control logic for an EC, nonetheless it could become an interesting opportunity if integrated within the self-consumption control logic. This kind of multi-service operation allows to exploit at maximum the ESS and could increase the EC revenues. Primary frequency regulation is nowadays identified as one of the most promising, and economically interesting, regulation services for an ESS. Nevertheless it is quite complex to properly evaluate the ESS performances due to the stochastic nature of the frequency signal.

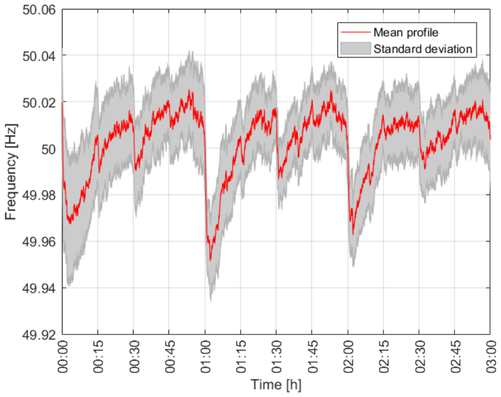
A preliminary experimental activity developed within the IoT Storage Lab provided to collect measurements of the power system frequency. These have been acquired with a 10 Hz sampling time without interruptions for 33 days. The acquired data have been subdivided into daily profiles in order to compare them and to find if there are common characteristics with regard to the daily trend. To do this, once obtained all the single daily profiles, a mean daily profile has been evaluated and its standard deviation has been computed for each instant. The mean profile obtained can be seen in Figure E.5 (a) and it clearly shows that there are more than one periodic trends inside the signal. A periodic behavior of the frequency can be observed at begin of each hour: at this instant of time the frequency rises or decreases sharply and, after a transient behavior, it returns close to the initial value. During the night and the central hours of the day the frequency is commonly higher than 50 Hertz and the begin of the hour it decreases sharply; on the contrary in the early morning and in late afternoon the frequency has a typical value lower but it increases sharply when a new hour begins. Furthermore, we can observe that during the night the variations are higher, this is due to the inertia of the grid that is lower during this periods.

If we zoom on a shorter window of the daily profile other trends appear (an example is shown in Figure E.5 (b), where it is possible to see the mean profile and the standard deviation from midnight to 3 a.m.). In this case the hourly trend appears clearly, but also other trends with shorter periods are visible. In particular a 30 minutes and a 15 minutes periodic behaviors can be observed. These are easily explicable because their period of time corresponds to the typical periods of the electrical energy market.

After having identified the main characteristics of the frequency signal, and therefore of the energy and power request for providing primary frequency regulation, the performance of the ESS providing this service has been evaluated. In Figure E.6, the result of a daily test are depicted: the theoretical control law is shown in blue while the operation points of the ESS during the tests are in orange. Thanks to this test, it has been demonstrated that the commercial system could provide adequate response for the primary frequency regulation. Therefore, it has been confirmed the possibility to provide services to the grid also with small ESS for domestic application.



(a) Daily profile



(b) Zoom on three hours

Figure E.5: *Daily mean frequency profile and standard deviation.*

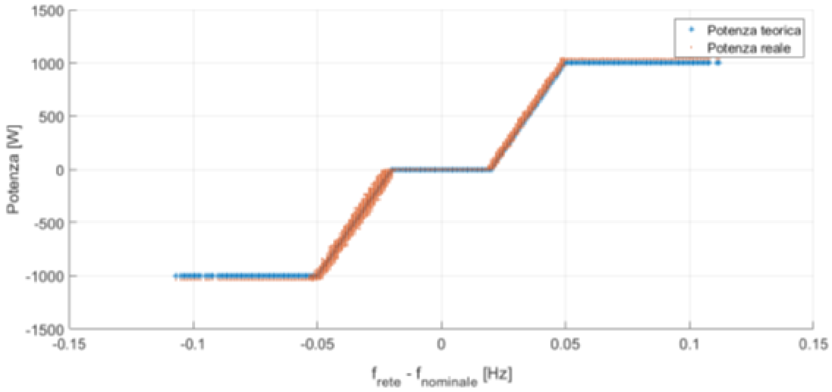


Figure E.6: *Results of the test for primary frequency regulation provided by the Zhero system. Control law is in blue, measured points in orange.*

List of Figures

List of Tables

Bibliography

[1] REScoop 20-20-20 Consortium. *Best practices Report I*. Available online *(Accessed on 30-01-2021)*.

[2] REScoop 20-20-20 Consortium. *Best practices Report II*. Available online *(Accessed on 30-01-2021)*.

[3] Eurostat. *Shedding light on energy in the EU - A guided tour of energy statistics*, 2020. Available online *(Accessed on 30-01-2021)*.

[4] Nimby Forum. *L'Era del Dissenso - Osservatorio Nimby Forum 13a edizione 2017/2018*, 2018. Available online *(Accessed on 30-01-2021)*.

[5] L.F.M. van Summeren and A.J. Wieczorek. *Defining community-based Virtual Power Plant*. cVPP project. 2018. Available online *(Accessed on 30-01-2021)*.

[6] Union of the German Academies of Sciences and Humanities, German National Academy of Sciences Leopoldina, National Academy of Science and Engineering. Centralized and decentralized components in the energy system. The right mix for ensuring a stable and sustainable supply. Available onlineAvailable online *(Accessed on 19-03-2021)*.

[7] Universal Smart Energy Framework. Usef: The framework explained, 2015. Available online *(Accessed on 30-01-2021)*.

[8] REScoop.eu. *Q&A - What are citizen and renewable energy communities?*, 2019. Available online *(Accessed on 30-01-2021)*.

[9] Joint Research Centre of the European Commission. *Blockchain in Energy Communities*, 2017. https://doi.org/10.2760/121912.

[10] M. Moncecchi, S. Meneghello, and M. Merlo. Energy sharing in renewable energy communities: The italian case. 2020. https://doi.org/10.1109/UPEC49904.2020.9209813.

[11] M. Moncecchi, C. Brivio, S. Mandelli, and M. Merlo. Battery energy storage systems in microgrids: Modeling and design criteria. *Energies*, 13(8):2006, 2020. https://doi.org/10.3390/en13082006.

[12] M. Moncecchi, S. Meneghello, and M. Merlo. A game theoretic approach for energy sharing in the italian renewable energy communities. *Applied Sciences (Switzerland)*, 10(22):1–25, 2020. https://doi.org/10.3390/app10228166.

[13] M. Moncecchi, D. Falabretti, and M. Merlo. Regional energy planning based on distribution grid hosting capacity. *AIMS Energy*, 7(3):264–284, 2019. https://doi.org/10.3934/energy.2019.3.264.

[14] S. M. Mirbagheri, M. Moncecchi, D. Falabretti, and M. Merlo. Hosting capacity evaluation in networks with parameter uncertainties. In *18th International Conference on Harmonics and Quality of Power (ICHQP)*, 2018. https://doi.org/10.1109/ICHQP.2018.8378891.

[15] A. Dimovski, M. Moncecchi, D. Falabretti, and M. Merlo. Pv forecast for the optimal operation of the medium voltage distribution network: A real-life implementation on a large scale pilot. *Energies*, 13(20), 2020. https://doi.org/10.3390/en13205330.

[16] M. Moncecchi, A. Borselli, D. Falabretti, L. Corghi, and M. Merlo. Numerical and experimental efficiency estimation in household battery energy storage equipment. *Energies*, 13(11), 2020. https://doi.org/10.3390/en13112719.

[17] European Union. Consolidated version of the Treaty on European Union, 2016. Available online *(Permalink)*.

[18] European Union. Consolidated version of the Treaty on the Functioning of the European Union, 2016. Available online *(Permalink)*.

[19] European Commission. Europe 2020 - A European strategy for smart, sustainable and inclusive growth. 2010. Available online *(Permalink)*.

[20] European Commission. Energy Union Package Communication, 2015. Available online *(Permalink)*.

[21] Directorate-General for Energy (European Commission). Clean energy for all Europeans. 2019. https://doi.org/10.2833/9937.

[22] Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources, 2018. Available online *(Permalink)*.

[23] Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU, 2019. Available online *(Permalink)*.

[24] European Commission. The European Green Deal. 2019. Available online *(Permalink)*.

[25] Renewable Energies Agency. Renewable energy in the hands of people, 2016. Available online *(Accessed on 30-01-2021)*.

[26] Heinrich-Böll-Stiftung. Energy atlas 2018: Figures and facts about renewables in europe, 2018. Available online *(Accessed on 30-01-2021)*.

[27] B. Kampman and J. Blommerde. Ce delft - the potential of energy citizens in the european union, 2016. Available online *(Accessed on 30-01-2021)*.

[28] T. Huld, K. Bódis, I. Pascua, E. Dunlop, N. Taylor, and A. Jäger-Waldau. The rooftop potential for pv systems in the european union to deliver the paris agreement. *European Energy Innovation*, Spring 2018:12, 03 2018. https://doi.org/10.1016/j.rser.2019.109309.

[29] Joint Research Centre of the European Commission. *PV Status Report 2019*. 2019. https://doi.org/10.2760/326629.

[30] Greenpeace EU, REScoop.eu, Energy Cities, and Friends of the Earth. Unleashing the power of community renewable energy, 2019. Available online *(Accessed on 30-01-2021)*.

[31] J. Roberts, F. Bodman, and R. Rybski. Clientearth. community power: Model legal frameworks for citizen-owned renewable energy, 2014. Available online *(Accessed on 30-01-2021)*.

[32] F. Tounquet. Energy communities in the european union. *ASSET project - Final report*, 2019. Available online *(Accessed on 30-01-2021)*.

[33] J. Roberts, D. Frieden, and S. D'Herbemont. Energy community definitions. *Deliverable Developed Under the Scope of the COMPILE Project*, 2019. Available online *(Accessed on 30-01-2021)*.

[34] M. Pezzaglia (Gruppo Professione Energia). *Self-consumption in energy user systems*, 2019. Available online *(Accessed on 30-01-2021)*.

[35] ARERA. Memoria dell'Autorità di Regolazione per Energia Reti e Ambiente in merito all'affare sul sostegno alle attività produttive mediante l'impiego di sistemi di generazione, accumulo e autoconsumo di energia elettrica (atto n. 59), 2019. Available online *(Accessed on 30-01-2021)*.

[36] M. Pezzaglia (Gruppo Professione Energia). Energy user systems - A unitary vision between past, present and future., 2018. Available online *(Accessed on 30-01-2021)*.

[37] Ministero dello sviluppo economico. Strategia Energetica Nazionale (SEN), 2017. Available online *(Accessed on 30-01-2021)*.

[38] Ministero dello sviluppo economico. Piano nazionale integrato energia e clima (PNIEC), 2020. Available online *(Accessed on 30-01-2021)*.

[39] Consiglio Regionale della Regione Piemonte. Legge regionale n. 12 del 3 agosto 2018. Promozione dell'istituzione delle comunità energetiche, 2018. Available online *(Accessed on 30-01-2021)*.

[40] Consiglio Regionale della Regione Puglia. Legge Regionale n.45 del 9 agosto 2019, 2019. Available online *(Accessed on 30-01-2021)*.

[41] Consiglio Regionale della Regione Liguria. Legge Regionale n. 13 del 2020 - Promozione dell'istituzione delle comunità energetiche, 2020. Available online *(Accessed on 30-01-2021)*.

[42] Consiglio Regionale della Regione Calabria. Legge Regionale n.25 del 10 novembre 2020 - Promozione dell'istituzione delle comunità energetiche da fonti rinnovabili, 2020. Available online *(Accessed on 30-01-2021).*

[43] Consiglio Regionale della Regione Lombardia. Deliberazione Consiglio regionale 28 luglio 2020 - n. XI/1154. Ordine del giorno concernente le iniziative per promuovere la creazione di comunità energetiche e per lo sviluppo di un reddito energetico regionale, 2020. Available online *(Accessed on 30-01-2021).*

[44] M. Pezzaglia (Gruppo Professione Energia). Comunità dell'energia - Approfondimenti per il recepimento nazionale e analisi comparata delle leggi regionali sulla promozione delle comunità dell'energia, 2018. Available online *(Accessed on 30-01-2021).*

[45] Commissione industria commercio turismo del Senato della Repubblica. Green Energy. Il sostegno alle attività produttive mediante generazione, accumulo e autoconsumo di energia elettrica. Resoconto di consultazione, 2019. Available online *(Accessed on 30-01-2021).*

[46] Repubblica Italiana. Legge 28 febbraio 2020, n. 8. Gazzetta ufficiale della Repubblica Italiana n.51 del 29 Febbraio 2020, 2020.

[47] M. Pezzaglia (Gruppo Professione Energia). Renewable collective self-consumption and renewable energy communities. Analysis of the first transposition of Directive (EU) 2018/2001 in Italy., 2019. Available online *(Accessed on 30-01-2021).*

[48] ARERA. Deliberazione 4 agosto 2020 - 318/2020/R/EEL, 2020. Available online *(Accessed on 30-01-2021).*

[49] Ministero dello sviluppo economico. Individuazione della tariffa incentivante per la remunerazione degli impianti a fonti rinnovabili inseriti nelle configurazioni sperimentali di autoconsumo collettivo e comunità energetiche rinnovabili, in attuazione dell'articolo 42-bis, comma 9, del decreto-legge n. 162/2019, convertito dalla legge n. 8/2020., 2020. Available online *(Permalink).*

[50] European Commission. COM/2016/0860 - Clean Energy For All Europeans. 2016. Available online *(Permalink).*

[51] Delega al Governo per il recepimento delle direttive europee e l'attuazione di altri atti dell'Unione europea - Legge di delegazione europea 2019-2020, 2020.

[52] Consiglio Regionale della Regione Campania. Legge Regionale n.38 del 29 dicembre 2020 - Disposizioni per la formazione del bilancio di previsione finanziario per il triennio 2021-2023 della Regione Campania - Legge di stabilità regionale per il 2021., 2020. Available online *(Accessed on 04-03-2021).*

[53] T. Van der Schoor and B. Scholtens. The power of friends and neighbors: a review of community energy research. *Current Opinion in Environmental Sustainability*, 39:71 – 80, 2019. Open Issue 2019.

[54] L.F.M. Van Summeren, A.J. Wieczorek, G.J.T. Bombaerts, and G.P.J. Verbong. Community energy meets smart grids: Reviewing goals, structure, and roles in virtual power plants in ireland, belgium and the netherlands. *Energy Research Social Science*, 63:101415, 2020.

[55] B.P. Koirala, E. Koliou, J. Friege, R.A. Hakvoort, and P.M. Herder. Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems. *Renewable and Sustainable Energy Reviews*, 56:722 – 744, 2016.

[56] K. Orehounig, R. Evins, and V. Dorer. Integration of decentralized energy systems in neighbourhoods using the energy hub approach. *Applied Energy*, 154:277 – 289, 2015.

[57] A.J. Dinusha Rathnayaka, V.M. Potdar, T. Dillon, and S. Kuruppu. Framework to manage multiple goals in community-based energy sharing network in smart grid. *International Journal of Electrical Power & Energy Systems*, 73:615–624, 2015.

[58] G. Walker, N. Simcock, and S.J. Smith. Community energy systems. *International Encyclopedia of Housing and Home, 1st ed.; Smith, SJ, Ed*, pages 194–198, 2012.

[59] M. Harcourt, K. Ogilvie, M. Cleland, E. Campbell, B. Gilmour, R. Laszlo, and T. Leach. Building smart energy communities: implementing integrated community energy solutions.

[60] M. Warneryd, M. Håkansson, and K. Karltorp. Unpacking the complexity of community microgrids: A review of institutions' roles for development of microgrids. *Renewable and Sustainable Energy Reviews*, 121:109690, 2020.

[61] M. E. Wainstein, R. Dargaville, and A. Bumpus. Social virtual energy networks: Exploring innovative business models of prosumer aggregation with virtual power plants. In *2017 IEEE Power Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, pages 1–5, 2017.

[62] K. Orehounig, G. Mavromatidis, R. Evins, V. Dorer, and J. Carmeliet. Towards an energy sustainable community: An energy system analysis for a village in switzerland. *Energy and Buildings*, 84:277–286, 2014.

[63] A.J. Dinusha Rathnayaka, V.M. Potdar, T. Dillon, and S. Kuruppu. Framework to manage multiple goals in community-based energy sharing network in smart grid. *International Journal of Electrical Power & Energy Systems*, 73:615 – 624, 2015.

[64] G. Walker, P. Devine-Wright, S. Hunter, H. High, and B. Evans. Trust and community: Exploring the meanings, contexts and dynamics of community renewable energy. *Energy policy*, 38(6):2655–2663, 2010.

[65] G. Walker and P. Devine-Wright. Community renewable energy: What should it mean? *Energy policy*, 36(2):497–500, 2008.

[66] G. Mendes, C. Ioakimidis, and P. Ferrão. On the planning and analysis of integrated community energy systems: A review and survey of available tools. *Renewable and Sustainable Energy Reviews*, 15(9):4836 – 4854, 2011.

[67] A. Fleischhacker, G. Lettner, D. Schwabeneder, and H. Auer. Portfolio optimization of energy communities to meet reductions in costs and emissions. *Energy*, 173:1092 – 1105, 2019.

[68] J. S. Vardakas, I. Zenginis, N. Zorba, C. Echave, M. Morato, and C. Verikoukis. Electrical energy savings through efficient cooperation of urban buildings: The smart community case of superblocks' in barcelona. *IEEE Communications Magazine*, 56(11):102–109, 2018.

[69] QUEST. Canada's energy transformation - Evolution of revolution? Available online *(Accessed on 19-03-2021)*.

[70] Pembina Intitute. Diesel Reduction Progress in Remote Communities. Available online *(Accessed on 19-03-2021)*.

[71] Environmental and Energy Study Institute - Community Energy. Available online *(Accessed on 19-03-2021)*.

[72] US Community Energy Website (USCEW). Available online *(Accessed on 19-03-2021)*.

[73] A. Suwa and Y. Ogahara. Decentralised energy production and community sustainability. How hydroelectricity shall contribute to local development. International Public Policy Association (ICPP3). Available online *(Accessed on 19-03-2021)*.

[74] Fukushima Community Power Declaration, 2016. Available online *(Accessed on 19-03-2021)*.

[75] A. Ambole, K. Koranteng, P. Njoroge, and D. Logedi Luhangala. A review of energy communities in sub-saharan africa as a transition pathway to energy democracy. *Sustainability*, 2021.

[76] C. Avilés A., S. Oliva H., and D. Watts. Single-dwelling and community renewable microgrids: Optimal sizing and energy management for new business models. *Applied Energy*, 254:113665, 2019.

[77] Quest. Project website *(Accessed on 30-01-2021)*.

[78] Victoria State Government. Renewable communities program. Available online *(Accessed on 30-01-2021)*.

[79] F. Avelino, R. Bosman, G. Paradies, N. Frantzeskaki, B. Pel, S. Akerboom, D. Scholten, P. Boontje, and J. Wittmayer. The (self-)governance of community energy: Challenges prospects. *Drift practice brief*, 02 2014.

[80] S.J.W. Klein and S. Coffey. Building a sustainable energy future, one community at a time. *Renewable and Sustainable Energy Reviews*, 60:867 – 880, 2016.

[81] E. Klaassen and M. Van Der Laan. Usef white paper energy and flexibility services for citizens energy communities a solid foundation for smart energy futures, 2018. Available online *(Accessed on 30-01-2021)*.

[82] C. Park and T. Yong. Comparative review and discussion on p2p electricity trading. *Energy Procedia*, 128:3–9, 09 2017.

[83] Universal Smart Energy Framework. Usef white paper - flexibility value chain 2.0. 2018. Available online *(Accessed on 30-01-2021)*.

[84] Rescoop.eu. Project website *(Accessed on 30-01-2021)*.

[85] Community Power. Project website *(Accessed on 30-01-2021)*.

[86] WISE Power. Project website *(Accessed on 30-01-2021)*.

[87] WiseGRID. Project website *(Accessed on 30-01-2021)*.

[88] WiseGRID Consortium. Wisecoop and wisecorp apps design. *Deliverable Developed Under the Scope of the WiseGRID Project*, 2018. Available online *(Accessed on 30-01-2021)*.

[89] FLEXCoop. Project website *(Accessed on 30-01-2021)*.

[90] FLEXCoop Consortium. Models of der devices and associated forecasting algorithms. *Deliverable Developed Under the Scope of the FLEXCoop Project*. Available online *(Accessed on 30-01-2021)*.

[91] FLEXCoop Consortium. Local demand manager specifications and intra-building optimization algorithms. *Deliverable Developed Under the Scope of the FLEXCoop Project*. Available online *(Accessed on 30-01-2021)*.

[92] FLEXCoop Consortium. Flexcoop global demand manager. *Deliverable Developed Under the Scope of the FLEXCoop Project*. Available online *(Accessed on 30-01-2021)*.

[93] Compile. Project website *(Accessed on 30-01-2021)*.

[94] SocialRES. Project website *(Accessed on 30-01-2021)*.

[95] S. Caneva, P. Alonso Gomez, M. Kovarova, I. Lizarralde, I. Valentin, A. Abi Akle, M. Hamwi, V. Kromrey, D. Vedel, A. Wotjen, A. Schneller, L. Domrose, A. Ferrari, C. Crippa, E. Denny, M. Regidor, S. Mulero, I. Lacoste, R. Ruiz, and M. Policarp. Fostering socially innovative and inclusive strategies for empowering citizens in the renewable energy market of the future. In *36th EU PVSEC, the European Photovoltaic Solar Energy Conference. Marseille, France*, 09 2019.

[96] COMERES. Project website *(Accessed on 30-01-2021)*.

[97] REScoopVPP. Project website *(Accessed on 30-01-2021)*.

[98] T. Khatib, I.A. Ibrahim, and A. Mohamed. A review on sizing methodologies of photovoltaic array and storage battery in a standalone photovoltaic system. *Energy Conversion and Management*, 120:430 – 448, 2016.

[99] Sunanda Sinha and S.S. Chandel. Review of software tools for hybrid renewable energy systems. *Renewable and Sustainable Energy Reviews*, 32:192 – 205, 2014.

[100] Homer Energy website. `https://www.homerenergy.com/`. (*Accessed on 02-01-2021*).

[101] RETScreen website. `https://www.nrcan.gc.ca/maps-tools-publications/tools/data-analysis-software-modelling/retscreen/7465`. (*Accessed on 02-01-2021*).

[102] iHOGA website. `https://ihoga.unizar.es/en/`. (*Accessed on 02-01-2021*).

[103] PVsyst website. `https://www.pvsyst.com/`. (*Accessed on 02-01-2021*).

[104] NREL System Advisor Model (SAM). `https://sam.nrel.gov/`. (*Accessed on 02-01-2021*).

[105] Y. Hong, W. Chang, Y. Chang, Y. Lee, and D. Ouyang. Optimal sizing of renewable energy generations in a community microgrid using markov model. *Energy*, 135:68 – 74, 2017.

[106] M.B. Shadmand and R.S. Balog. Multi-objective optimization and design of photovoltaic-wind hybrid system for community smart dc microgrid. *IEEE Transactions on Smart Grid*, 5(5):2635–2643, 2014. cited By 141.

[107] C. Brivio, M. Moncecchi, S. Mandelli, and M. Merlo. A novel software package for the robust design of off-grid power systems. *Journal of Cleaner Production*, 166:668 – 679, 2017.

[108] S. Corigliano, M. Moncecchi, M. Mirbagheri, M. Merlo, and M. Molinas. Microgrid design: sensitivity on models and parameters. In *2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I CPS Europe)*, pages 1–6, 2019.

[109] M. Moncecchi, C. Brivio, S. Corigliano, A. Cortazzi, and M. Merlo. Battery modeling for microgrid design: a comparison between lithium-ion and lead acid technologies. In *2018 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, pages 1215–1220, 2018.

[110] J. Dorfner. *Open source modelling and optimisation of energy infrastructure at urban scale*. PhD thesis, Technische Universität München, 2016.

[111] H. Awad and M. Gül. Optimisation of community shared solar application in energy efficient communities. *Sustainable Cities and Society*, 43:221 – 237, 2018.

[112] M. Shakouri, H.W. Lee, and Y. Kim. A probabilistic portfolio-based model for financial valuation of community solar. *Applied Energy*, 191:709 – 726, 2017.

[113] E. Atashpaz-Gargari and C. Lucas. Imperialist competitive algorithm: An algorithm for optimization inspired by imperialistic competition. In *2007 IEEE Congress on Evolutionary Computation*, pages 4661–4667, 2007.

[114] GPE Energy user systems and private networks. Self consumption saving index. Available online *(Accessed on 30-01-2021)*.

[115] Load Profile Generator. https://www.loadprofilegenerator.de/ *(Accessed on 30-01-2021)*.

[116] PVGIS. https://ec.europa.eu/jrc/en/pvgis *(Accessed on 30-01-2021)*.

[117] ISTAT. Annuario statistico italiano 2018: Popolazione e famiglie, 2019.

[118] Odyssee-Mure Project. Sectoral profile - households, 2019. Available online *(Accessed on 22-03-2021)*.

[119] Agenzia delle Entrate. Testo unico del 22 dicembre 1986 n. 917 (Testo unico delle imposte sui redditi). Available online *(Accessed on 19-03-2021)*.

[120] EnelX and Forum Ambrosetti. Electrify 2030 - L'elettrificazione e i suoi impatti sulle filiere industriali: nuove opportunità per un futuro sostenibile in Europa e in Italia. Available online *(Accessed on 19-03-2021)*.

[121] Gestore mercati energetici - statistiche. Available online *(Accessed on 19-03-2021)*.

[122] A. Caramizaru and A. Uihlein. Energy communities: An overview of energy and social innovation. *JRC Science for Policy Report JRC119433*, 2020.

[123] R.B. Myerson. *Game Theory*. Harvard University Press, 2013.

[124] P. Vytelingum, T.D. Voice, S.D. Ramchurn, A. Rogers, and N.R. Jennings. Agent-based micro-storage management for the smart grid. In *Proceedings of the 9th International Conference on Autonomous Agents and Multiagent Systems: Volume 1 - Volume 1*, AAMAS '10, pages 39–46, Richland, SC, 2010. International Foundation for Autonomous Agents and Multiagent Systems.

[125] W. W. Weaver and P. T. Krein. Game-theoretic control of small-scale power systems. *IEEE Transactions on Power Delivery*, 24(3):1560–1567, 2009.

[126] I. Maity and S. Rao. Simulation and pricing mechanism analysis of a solar-powered electrical microgrid. *IEEE Systems Journal*, 4(3):275–284, 2010.

[127] W. Tushar, C. Yuen, D.B. Smith, and H.V. Poor. Price discrimination for energy trading in smart grid: A game theoretic approach. *IEEE Transactions on Smart Grid*, 8(4):1790–1801, 2017.

[128] R. Dai, H. Charkhgard, Y. Chen, and Y. Kuang. Balancing benefit distribution for energy storage sharing based on nash bargaining solution. In *2019 IEEE Power Energy Society General Meeting (PESGM)*, pages 1–5, 2019.

[129] H. Wang and J. Huang. Incentivizing energy trading for interconnected microgrids. *IEEE Transactions on Smart Grid*, 9(4):2647–2657, 2018.

[130] W. Saad, Z. Han, and H. V. Poor. Coalitional game theory for cooperative micro-grid distribution networks. In *2011 IEEE International Conference on Communications Workshops (ICC)*, pages 1–5, 2011.

[131] C. Long, Y. Zhou, and J. Wu. A game theoretic approach for peer to peer energy trading. *Energy Procedia*, 159:454–459, 2019.

[132] R. Pilling, S.C. Chang, and P.B. Luh. Shapley value-based payment calculation for energy exchange between micro-and utility grids. *Games*, 8(4):45, 2017.

[133] A. Chiş and V. Koivunen. Coalitional game-based cost optimization of energy portfolio in smart grid communities. *IEEE Transactions on Smart Grid*, 10(2):1960–1970, 2019.

[134] T. Huld, R. Müller, and A. Gambardella. A new solar radiation database for estimating pv performance in europe and africa. *Solar Energy*, 86(6):1803–1815, 2012.

[135] T. Ackermann, G. Andersson, and L. Söder. Distributed generation: a definition. *Electric Power Systems Research*, 57(3):195 – 204, 2001.

[136] ARERA. Relazione 04 agosto 2020 - 320/2020/I/eel, 2020. Available online *(Accessed on 30-01-2021)*.

[137] S.M. Mirbagheri, D. Falabretti, V. Ilea, and M. Merlo. Hosting capacity analysis: A review and a new evaluation method in case of parameters uncertainty and multi-generator. 2018. https://doi.org/10.1109/EEEIC.2018.8494572.

[138] N. Etherden, M. Bollen, S. Ackeby, and O. Lennerhag. The transparent hosting-capacity approach–overview, applications and developments. In *International Conference and Exhibition on Electricity Distribution: 15/06/2015-18/06/2015*, 2015.

[139] S.M. Ismael, S.H.E. Abdel Aleem, A.Y. Abdelaziz, and A.F. Zobaa. State-of-the-art of hosting capacity in modern power systems with distributed generation. *Renewable Energy*, 130:1002 – 1020, 2019.

[140] O. Lennerhag, S. Ackeby, M. Bollen, G. Foskolos, and T. Gafurov. Using measurements to increase the accuracy of hosting capacity calculations. *CIRED - Open Access Proceedings Journal*, 2017:2041–2044(3), October 2017.

[141] E. Zio, M. Delfanti, L. Giorgi, V. Olivieri, and G. Sansavini. Monte carlo simulation-based probabilistic assessment of dg penetration in medium voltage distribution networks. *International Journal of Electrical Power Energy Systems*, 64:852 – 860, 2015.

[142] J. Widén, E. Wäckelgøard, J. Paatero, and P. Lund. Impacts of distributed photovoltaics on network voltages: Stochastic simulations of three swedish low-voltage distribution grids. *Electric Power Systems Research*, 80(12):1562 – 1571, 2010.

[143] M. Kolenc, I. Papič, and B. Blažič. Assessment of maximum distributed generation penetration levels in low voltage networks using a probabilistic approach. *International Journal of Electrical Power Energy Systems*, 64:505 – 515, 2015.

[144] A. Ballanti, F. Pilo, A. Navarro-Espinosa, and L. F. Ochoa. Assessing the benefits of pv var absorption on the hosting capacity of lv feeders. In *IEEE PES ISGT Europe 2013*, pages 1–5, 2013.

[145] Z. Abdmouleh, A. Gastli, L. Ben-Brahim, M. Haouari, and N. Ahmed Al-Emadi. Review of optimization techniques applied for the integration of distributed generation from renewable energy sources. *Renewable Energy*, 113:266 – 280, 2017.

[146] M. Pesaran H.A, P.D. Huy, and V.K. Ramachandaramurthy. A review of the optimal allocation of distributed generation: Objectives, constraints, methods, and algorithms. *Renewable and Sustainable Energy Reviews*, 75:293 – 312, 2017.

[147] S. Conti and S. Raiti. Probabilistic load flow using monte carlo techniques for distribution networks with photovoltaic generators. *Solar Energy*, 81(12):1473 – 1481, 2007.

[148] M. Delfanti, D. Falabretti, and M. Merlo. Dispersed generation impact on distribution network losses. *Electric Power Systems Research*, 97:10 – 18, 2013.

[149] D. Bertini, D. Falabretti, M. Merlo, D. Moneta, J. Silva De Assis Carneiro, and A. Silvestri. Hosting capacity of italian lv distribution networks. In *CIRED 2011*, pages 1–4, 2011.

[150] M. Delfanti, M. Merlo, G. Monfredini, V. Olivieri, M. Pozzi, and A. Silvestri. Hosting dispersed generation on italian mv networks: Towards smart grids. In *Proceedings of 14th International Conference on Harmonics and Quality of Power - ICHQP 2010*, pages 1–6, 2010.

[151] P.T. Manditereza and R. Bansal. Renewable distributed generation: The hidden challenges - a review from the protection perspective. *Renewable and Sustainable Energy Reviews*, 58:1457 – 1465, 2016.

[152] J. Guerrero, A. C. Chapman, and G. Verbič. Decentralized p2p energy trading under network constraints in a low-voltage network. *IEEE Transactions on Smart Grid*, 10(5):5163–5173, 2019.

[153] M.I. Azim, W. Tushar, and T.K. Saha. Investigating the impact of P2P trading on power losses in grid-connected networks with prosumers. *Applied Energy*, 263(C), 2020.

[154] J. Zhang, C. Hu, C. Zheng, T. Rui, W. Shen, and B. Wang. Distributed peer-to-peer electricity trading considering network loss in a distribution system. *Energies*, 12(22):4318, 2019.

[155] J. M. Delarestaghi, A. Arefi, and G. Ledwich. The impact of peer to peer market on energy costs of consumers with pv and battery. In *2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, pages 1–6, 2018.

[156] ARERA. Delibera arg/elt 99/08. Testo integrato delle connessioni attive - TICA Available online *(Accessed on 19-03-2021)*.

[157] Bill Chambers. The barriadas of lima: Slums of hope or despair? problems or solutions? *Geography*, 90(3):200–224, 2005.

[158] World Bank Statistics for Peru. Available online *(Accessed on 30-01-2021)*.

[159] International Energy Agency 2018 Statistics. Available online *(Accessed on 30-01-2021)*.

[160] International Hydropower Association Hydropower status report 2018. Available online *(Accessed on 30-01-2021)*.

[161] Une S.r.l. Zhero system. Available online *(Accessed on 30-01-2021)*.

[162] FZSoNIck 48TL200 battery datasheet. Available online *(Accessed on 30-01-2021)*.

[163] Integridy project. Project website *(Accessed on 30-01-2021)*.

[164] S. Dambone Sessa, G. Crugnola, M. Todeschini, S. Zin, and R. Benato. Sodium nickel chloride battery steady-state regime model for stationary electrical energy storage. *Journal of Energy Storage*, 6:105 – 115, 2016.

[165] S. Dambone Sessa, F. Palone, A. Necci, and R. Benato. Sodium-nickel chloride battery experimental transient modelling for energy stationary storage. *Journal of Energy Storage*, 9:40 – 46, 2017.

[166] M. Musio and A. Damiano. A non-linear dynamic electrical model of sodium-nickel chloride batteries. In *2015 International Conference on Renewable Energy Research and Applications (ICRERA)*, pages 872–878, 2015.