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Energy sharing in renewable energy communities: the Italian case

Supervisor
Prof. Marco MERLO

Co-Supervisor
Dr. Matteo MONCECCHI

Candidate
Stefano MENEGHELLO – 894472

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L'età della pietra non finì perchè ci fu una mancanza di pietre,
così l'età del petrolio non finirà perchè mancherà il petrolio.
Ahmed Zaki Yamani

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Extended Abstract

Introduction

The Clean Energy Package (CEP) is a set of eight Regulations and Directives that will shape European energy policies in the next future. Targets of the CEP are 40% of greenhouse gasses reduction, 32% of electricity consumption from renewable energy and 32,5% of improvement in energy efficiency by 2030. In order to fulfil these ambitious targets the European Commission took interest in Energy Communities (EC) as a tool that enables European citizens to take part to the so-called clean energy transition. The members of an EC are allowed to produce, consume and share energy within the community but also to actively participate in the energy market [1]. EC are mentioned in the CEP in two Directives[1], creating two distinct classes, the Citizens Energy Communities (CEC) and the Renewable Energy Communities (REC). The two definitions have some points in common but differ in the scope of their activities and from the help received by Governments. Table 1 summarises the main characteristics of the two classes of EC.

The deadlines for the transposition of the aforementioned Directives into the national laws of EU Member States are set to December 2020 and June 2021. In Italy the transposition process has already started and set a milestone in February 2020 with the first law[2] that establishes a transient regime for EC, nevertheless it is still an open issue whether EC will be economically convenient for Italian citizens with the current Italian regulatory framework. As a matter of fact, EC will compete with active users already performing self-consumption, an activity that is receiving beneficial incentives for the energy used on-site. The nature and the amount of the support schemes recognised to EC is still under discussion and needs to be defined by the Italian energy Authority. The incentive will have to favour the development of EC, but also to be cost reflective of the benefits EC will bring to the electric system, in order to avoid market distortions. On a recent document[3], the Authority established that the incentive should take into account the avoidance of transmission losses in the network, but still consider that EC make use of the distribution grid. It is therefore the scope of this thesis to develop a tool that reproduces the energy flows between users within a community and evaluates their economic feasibility in the Italian framework. The tool will be used in a short-term analysis, that evaluates the formation of an EC with users already possessing a generation plant optimised for their individual needs and in a long term-analysis that evaluates the profitability of investing in EC in three different configurations.

This thesis comprises a regulatory and

[1]see *Renewable Energy Directive (EU) 2018/2001 and Electricity Directive (EU) 2019/944* of the CEP

[2]see *Legge 28 Febbraio 2020, n. 8*

[3]see ARERA, *Documento per la consultazione 112/2020/R/EEL*

Subject	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
Control	Medium and large companies are excluded	Members in proximity to the project
Geographic limitation	Cross-border participation is allowed	Proximity to the project
Activities	Electricity generation and consumption, energy efficiency services, EV charging, management of distribution networks	Production, consumption and sale of electricity from RES and energy sharing
Member States support	Create a level playing field in the market	Create a level playing field in the market, remove administrative barriers, enforce support schemes

Table 1. Differences among CECs and RECs

legislative analysis of the Italian framework that defines the status of the self-consumption systems that will be the starting point for EC. A socio-technical literature review is aimed to identify the characteristics of EC that will be integrated in the modelling tool. A section is dedicated to describe the energy flows model and the MILP optimisation. Lastly, the tool will be applied to a case study set in Northern Italy with the objective of validating the model and draw the first conclusions about the recognition of EC in Italy.

1 Literature review

1.1 The Italian framework The literature review starts with a legislative and regulative analysis of self consumption systems. The legislative panorama is very repetitive and tangled and is the results of many years of legislative layering. The most important categories are three [2]. *Closed Distribution Systems* are private distribution grids in which the electricity production is integrated to the final customers that are in industrial or commercial sites. *Simple Systems of Production and Consumption* are one-to-one systems in which the electricity producer coincides with the consumer. It is the most common case for domestic self-consumption. *Historic cooperatives* are electric producers (mainly from RES) fulfilling the task of distributors for members and non-members. Their special status comes from a heritage of the past. Among these classes EC are more similar to historic cooperatives due to the dual connection of its members to RES production plants and the distribution grids. Closed Distribution Systems are reserved to industrial consumers, while the Simple Systems of Production and Consumption are reduced to one-to-one configurations.

The current incentives recognised to self-consumption systems are the following [3]:

Exemption of the variable costs of electricity[4]: self-consumed energy is exempted from the variable costs in the electricity bill of the items of wholesale cost of electricity, network costs and operating costs. As a consequence, the more energy is self-consumed, the more the user can save money in the bill. The amount of money that can be saved on the variable cost of energy has been addressed in literature as Self-consumption Saving index (SCSi) [4].

Valorization of the energy injected into the grid: there are two main mechanisms that grants to value the surplus energy of

[4]see DL 244/2016 (decreto milleproroghe 2016)

active users. Scambio sul Posto (SSP)[5], or in English on-site exchange is a self consumption mechanism that allows to value the electric energy produced on site. It is for all intent and purposes a net metering tool for "storing" in the national grid the electric energy produced, but not self-consumed, and use it again in a different moment. Ritiro dedicato (RID)[6] or in English dedicated withdrawal is a simplified mechanism of commercialization of energy that interposes the GSE between the energy producers and the electric system. A special minimum granted price (prezzo minimo garantito) is recognised to small size active users.

Fiscal benefits[7]: the installation of a PV on a domestic roof and an eventual storage system connected to it is subjected to a fiscal detraction of the income tax equal to 50% of the initial investment spread over 10 years.

1.2 Social benefits EC are willing to bring closer Europeans to renewable energy projects and to make them actively participate to the clean energy transition [5]. Past experience in co-owned energy projects taught that the involvement of the population into the decision making process allowed to overcome their resistance (the so-called NIMBY syndrome) towards their implementation [6]. More local jobs are created and participants of the community feel more engaged in the promotion of renewable energy, making them more aware of their energy habits [7]. Most importantly, due to their non-profit nature, EC will tackle the issue of energy poverty, by performing energy efficiency measures to decrease consumption, reduce energy supply tariffs for vulnerable households or establish a fund within the community to help needing neighbourhoods [8].

1.3 Technology analysis Even though the configurations of EC will vary depending on the Country of application and local characteristics, the exploited technology is very similar to the one currently used in micro-grids and distributed energy systems and can be divided into three layers [9].

Physical energy assets include generation means for distributed energy generation such as PV panels, wind turbines, CHP plants and storage systems such as electrochemical batteries and electric vehicles. When considering domestic self-consumption systems, the coupling among multiple crystalline silicon PV modules [10] and lithium-ion batteries is the most spread solution [11].

The information and communication technology layer comprises all the components, physical and virtual, that allow to measure and manage the energy flows in and out the community. Smart meters are the most common example, allowing to keep track of the energy flows of the users in real time [12]. The ICT layer also groups all those hardware and software that allow communication between the users of the community and allow energy trading among members in the cases the community is organised with an internal market.

Grid access is an essential prerequisite for the development of EC, that can become a true barrier if it is costly, lengthy and complicated [13]. From another point of view, EC will bring various disruptions in the daily operations of distribution and transmission networks. At a system level, ECs reduce transportation and transformation losses. On the other hand, TSOs have to maintain some reserve capacity to operate the system safely even when the

[5] see deliberazione ARERA 570/2012/R/efr

[6] see deliberazione ARERA 280/07

[7] see art.16 bis D.p.r 917/86, Testo unico delle imposte sui redditi

production of EC is null. At a local level, EC will provide balancing services and increase demand flexibility with the use of storage systems and electric vehicles [14].

1.4 Game Theory In order to model users' behaviour in an EC, one of the most adopted mathematical technique is the Game Theory. Given the nature of EC, cooperative games are more suitable to mathematically describe the interactions between community members [15]. A particular solution of cooperative games, the Shapley value, is the most fair method to allocate costs and profits of shared infrastructures [16] . A coalitional game is uniquely defined by the pair $(\mathbf{N}, v(\mathbf{S}))$, where $\mathbf{N}$ denotes the set of players and $v(\mathbf{S})$ is the value of the coalition $\mathbf{S} \subseteq \mathbf{N}$. The payoff x_i of the player $i \in \mathbf{S}$, part of the coalition, is determined by an allocation criterium. Shapley value ϕ is expressed as:

$$\phi_i(v) = \sum_{\mathbf{S} \subseteq \mathbf{N} \setminus \{i\}} \frac{|S|!(N-|S|-1)!}{N!}[v(\mathbf{S} \cup \{i\}) - v(\mathbf{S})] \tag{1}$$

where the marginal contribution $[v(\mathbf{S} \cup \{i\}) - v(\mathbf{S})]$ of the player i in the coalition $\mathbf{S}$ 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 $\mathbf{S}$. Shapley value allocates fairly the payoff among the members of the coalition only if the game is convex, that is for each player $i \in \mathbf{N}$ the value of the coalition with the player is higher than without the player. Shapley value will be used in the model to allocate possible profits coming form the formation of the community.

2 Proposed Methodology

2.1 Energy sharing strategies This section describes the model design to simulate the energy fluxes and compute the costs incurred by each users. Five different configurations will be modelled.

Stand-alone configuration
While passive users only withdraw the energy from the grid, the generated energy $E_i^{gen}(t)$ by active users is first self-consumed and, depending on the load $E_i^{load}(t)$, surplus energy $E_i^{surplus}(t)$ is injected into the grid or the needed energy $E_i^{need}(t)$ is withdrawn from the grid.

$$E_i^{need}(t) = \begin{cases} E_i^{load}(t) - E_i^{gen}(t), & \text{if } E_i^{load}(t) \geq E_i^{gen}(t) \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

$$E_i^{surplus}(t) = \begin{cases} E_i^{gen}(t) - E_i^{load}(t), & \text{if } E_i^{gen}(t) > E_i^{load}(t) \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

$$E_i^{self}(t) = E_i^{gen}(t) - E_i^{surplus}(t) \tag{4}$$

The energy exchanges with the grid are the energy withdrawn $E_i^{with}(t)$ and the energy introduced $E_i^{int}(t)$:

$$E_i^{with}(t) = E_i^{need}(t) \tag{5}$$

$$E_i^{int}(t) = E_i^{surplus}(t) \tag{6}$$

The electricity bill is payed monthly and is computed as:

$$\begin{aligned} C_i =& c_{fixed} + c_{power} * P_i + c_{energy}^{grid} * \sum_m E_i^{with} + \\ & - p_{sale}^{grid}(t, E_i^{int}, E_i^{with}) \end{aligned} \tag{7}$$

The electricity bill of each user is determined considering some fixed costs c_{fixed}, a cost c_{power} that depends on the power P_i employed by the users, and a variable cost c_{energy}^{grid} that depends on the energy withdrawn from the grid. The energy injected into the grid by active users is valued through a price $p_{sale}^{grid}(t, E_i^{int}, E_i^{with})$ that in the Italian framework can be:

- Zonal price
  The injected energy is sold at the zonal strike price :

$$\begin{aligned} p_{sale}^{grid}(t, E_i^{int}) &= p_{zonal}(m) \\ &= \sum_m E_i^{int}(h) * p_{zonal}(h) \end{aligned} \tag{8}$$

- Ritiro dedicato
  Ritiro dedicato assures the maximum price among the zonal price and a minimum granted price. A fee has to be paid to the GSE.

$$p_{RID}(h) = \max\left(p_{RID}^{mgp}; p_{zonal}(t)\right) \quad (9)$$

$$p_{sale}^{grid}(t, E_i^{int}) = p_{RID}(m) = \sum_m E_i^{int}(h) * p_{RID}(h) - \frac{c_{fee}^{GSE}}{12} \quad (10)$$

- Scambio sul posto
  This net metering mechanism takes into account the energy withdrawn and injected into the grid and it awards an annual grant C_{SSP} equal the sum of the exchange grant C_s, the valorisation of the surplus C_{rL} and the GSE fee C_{GSE}.

$$C_{SSP} = C_s + C_{rL} - C_{GSE} \quad (11)$$

The exchange grant is the sum of two members called respectively energy share, computed in Equations 13 and 14 and service share, computed in Equations 15 and 16.

$$C_s = \min[O_E; C_{EI}] + CU_{sf} * E_s \quad (12)$$

The energy share is the minimum value between the annual withdrawn energy valued at the national price (O_E) and the annual introduced energy valued at the zonal price (C_{EI}).

$$O_E = \sum_{m=1}^{12} \sum_{fi=1}^{3} [E^{with}(fi) * PUN_m(fi)] \quad (13)$$

$$C_{EI} = \sum_{h=1}^{8760} [E^{int}(h) * p^{zonal}(h)] \quad (14)$$

The service share is computed as the minimum value E_s between annual injected and withdrawn energy times the sum of the tariffs of variable items in the electricity bill CU_{sf}.

$$E_s = \min[E^{with}(y), E^{int}(y)] \quad (15)$$

$$CU_{sf} = CU_{sf}^{reti} + CU_{sf}^{org} \quad (16)$$

The valorisation of the surplus is instead computed as follows:

$$C_{rL} = \max[0, C_{EI,y} - O_{E,y}] \quad (17)$$

The monthly grant is then:

$$p_{sale}^{grid}(t, E_i^{int}, E_i^{with}) = p_{SSP}(m) = \frac{C_{SSP}}{12} \quad (18)$$

Community formation: self consumption priority
A community is formed, comprising active users, able to generate electricity, and passive users. In this configuration, active users prioritise self-consumption and only after share their energy. The energy fluxes are as described by Equations 2 to 4 for the stand-alone user, then the community is interposed between the members and the grid. The energy shared $E_{com}^{man}(t)$ in the community is computed as the minimum value of the total available energy $E_{com}^{av}(t)$ and the total required energy $E_{com}^{req}(t)$ of the members (Eq. 21).

$$E_{com}^{av}(t) = \sum_{i \in S} |E_i^{surplus}(t)| \quad (19)$$

$$E_{com}^{req}(t) = \sum_{i \in S} E_i^{need}(t) \quad (20)$$

$$E_{com}^{man}(t) = \min\Big(E_{com}^{av}(t), E_{com}^{req}(t)\Big) \quad (21)$$

The share of available energy is computed as in Eq. 22 and the share of required energy as in Eq 23:

$$k_{com}^{av}(t) = \frac{E_{com}^{man}(t)}{E_{com}^{av}(t)} \quad (22)$$

$$k_{com}^{req}(t) = \frac{E_{com}^{man}(t)}{E_{com}^{req}(t)} \quad (23)$$

These parameters are then used to compute for each user the interactions with the community and with the grid:

$$E_i^{off}(t) = E_i^{surplus}(t) * k_{com}^{av}(t) \tag{24}$$

$$E_i^{int}(t) = E_i^{surplus}(t) * \left(1 - k_{com}^{av}(t)\right) \tag{25}$$

$$E_i^{taken}(t) = E_i^{need}(t) * k_{com}^{req}(t) \tag{26}$$

$$E_i^{with}(t) = E_i^{need}(t) * \left(1 - k_{com}^{req}(t)\right) \tag{27}$$

The electricity bill for a community member can be computed as the standard energy bill as in Eq. 7, with the energy sold at the zonal price, plus a term that takes into account the saving determined by the shared energy saving index (SESi) and eventual redistributions:

$$C_i = C_i^{grid} + C_i^{com} \tag{28}$$

$$C_i^{com} = (c_{energy}^{grid} - SESi) * \sum_m E_i^{with} + \frac{\phi\,(i, v)}{12} \tag{29}$$

The redistribution term ϕ is the Shapley value computed as in 1 using the electricity bill as utility function. The term, computed annually is then divided for the monthly bill.

Community formation: shared consumption priority
In this configuration, the community members with a PV system on their roof, directly share the energy produced instead of prioritising self-consumption. The available energy and required energy at community level are computed as follows:

$$E_{com}^{av}(t) = \sum_{i \in S} |E_i^{gen}(t)| \tag{30}$$

$$E_{com}^{req}(t) = \sum_{i \in S} E_i^{load}(t) \tag{31}$$

The community fluxes are shared within the community and follow the scheme described from Equation 21 to 27. Also the electricity bill is computed using 28.

Community formation: PV and BESS
In this configuration a battery shared among the members of the community is added, to improve self-production in the community. It is assumed that in this configuration the priority will still be given to energy sharing instead of self-consumption. Thus the energy fluxes will be identical to the previous case, but considering also the following energy balance that takes into account the energy charging $E^{ch}(t)$ and discharging $E^{dis}(t)$ the battery:

$$E_{com}^{req}(t) + E_{com}^{with}(t) + E^{ch}(t) = E_{com}^{av}(t) + E_{com}^{int}(t) + E^{dis}(t) \tag{32}$$

The battery, with a capacity b, is described by a simplified model, with a charging logic that responds only on the battery's state of charge SOC. If the surplus energy is higher than the storable energy, the battery will be fully charged and the rest injected into the grid as in Eq. 33, otherwise the battery will be partially charged as in Eq. 34. On the contrary, if the requested energy is higher that the amount of energy the battery can release, the battery will be fully discharged up to the depth of discharge DoD and the rest withdrew from the grid, as in Eq. 35. Eq. 36 describes the case when the battery is not fully discharged. The charging and discharging is limited in any case by the maximum energy flowing energy limited by $\frac{b}{C_{rate}}$ and by the efficiencies of charge and discharge η_{ch} and η_{dis}.

$$\begin{aligned} &\text{if } E_{com}^{surpl}(t) \geq b - SOC(t-1) \\ &E^{ch}(t) = \min\left(\frac{b}{C_{rate}}; b - SOC(t-1) * \eta_{ch}\right) \\ &SOC(t) = b \end{aligned} \tag{33}$$

$$\text{if } E_{com}^{surpl}(t) < b - SOC(t-1)$$
$$E^{ch}(t) = \min\left(\frac{b}{C_{rate}}; E_{com}^{surpl}(t) * \eta_{ch}\right) \quad (34)$$
$$SOC(t) = SOC(t-1) + E^{ch}(t)$$

$$\text{if } E_{com}^{need}(t) \geq SOC(t-1) - DoD * b$$
$$E^{dis}(t) = \min\left(\frac{b}{C_{rate}}; SOC(t-1) - \frac{DoD * b}{\eta_{dis}}\right) \quad (35)$$
$$SOC(t) = DoD * b$$

$$\text{if } E_{com}^{need}(t) < SOC(t-1) - DoD * b$$
$$E^{dis}(t) = \min\left(\frac{b}{C_{rate}}; SOC(t-1) - \frac{E_{com}^{need}(t)}{\eta_{dis}}\right) \quad (36)$$
$$SOC(t) = SOC(t-1) - E^{dis}(t)$$

The electricity bill is computed as in Eq. 28.

2.2 MILP Optimization A further step of the tool is made towards implementing a MILP optimisation that maximises the NPV with respect to the PV capacity of every stand-alone and community configuration we have seen so far, by linearizing the energy fluxes of the users.

PV optimization for single user, RID The capacity of PV installed on the roofs of each user i represents the solution to the optimization problem, identified by the variable

$$x_i \, \forall \, i \in A \quad (37)$$

In which A is the set of the participants in the community.

The constraints define the energy fluxes interesting the users. The non-linear problem to define the self-consumed energy of Equations 2 to 4 is made linear by introducing a binary variable $y_i(t)$ defined as follows:

$$y_i(t) = \begin{cases} 1 & \text{if } E_i^{load}(t) < \sum_i E_i^{gen}(t) * x_i \\ 0 & \text{if } \sum_i E_i^{gen}(t) * x_i < E_i^{load}(t) \end{cases} \quad (38)$$

Then a set of four constraints is defined, in which M is a constant so that $\sum_i E_i^{gen}(t) * x_i, E_i^{load}(t) < M$ in any possible solution of the problem.

$$\begin{aligned} & E_i^{self}(t) \leq E_i^{load}(t) \\ & E_i^{self}(t) \leq \sum_i E_{t,i}^{gen} * x_i \\ & E_i^{self}(t) \geq E_i^{load}(t) - M * (1 - y_i(t)) \\ & E_i^{self}(t) \geq \sum_i E_i^{gen}(t) * x_i - M * y_i(t) \end{aligned} \quad (39)$$

Constraints 40 and 41 define the energy fluxes with the grid, while Constraints 42 and 43 limit the variable x_i with a non-null constraint and a maximum capacity that can be installed.

$$E_i^{int}(t) = \sum_i E_i^{gen}(t) * x_i - E_i^{self}(t) \quad (40)$$

$$E_i^{with}(t) = E_i^{load}(t) - E_i^{self}(t) \quad (41)$$

$$x_i \geq 0 \quad (42)$$

$$x_i \leq P_i^{max} \quad (43)$$

The objective function is the maximisation of the NPV for the useful life l of the PV.

$$\begin{aligned} & max\ NPV_i = \\ & = \sum_l \left(\frac{\sum_{t=1}^{8760}(E_i^{self}(t) * SCSi) + \sum_{t=1}^{8760}(E_t^{int} * p_{RID}(t))}{(1+k)^l} + \right. \\ & \left. + \frac{(C_i^{detrax} - C_i^{var}) * x_i}{(1+k)^l} - C_i^{fix} * x_i \right) \end{aligned} \quad (44)$$

Where C_i^{fix} are the fixed costs of the PV plant expressed in $\left[\frac{€}{KW}\right]$. C_i^{var} are the variable costs related to ordinary maintenance of the plant and C^{detrax} is the fiscal detraction. Their unit of measure is: $\left[\frac{€}{KWh\ yr}\right]$. k is the interest rate.

PV optimization for single user, SSP The SSP is modelled by adding some additional constraints that linearise the mechanism. An energy balance is described in Constraint 45, Constraint 46 linearises the "exchanged electric energy" of the SSP with a binary variable and four more equations as in 38 and 39. Constraint 47 defines the yearly SSP grant.

$$\sum_i E_i^{gen}(t) * x_i + E_i^{int}(t) = E_i^{with}(t) + E_i^{load}(t) \quad (45)$$

$$E_{s,i} = \min\left(\sum_{t=1}^{8760} E_i^{with}(t), \sum_{t=1}^{8760} E_i^{int}(t)\right) \quad (46)$$

$$p_i^{SSP} = E_{s,i} * CU_{sf} + \sum_{t=1}^{8760} (E_i^{int}(t) * p_{zonal}(t)) \quad (47)$$

The objective function is then similar to Equation 48 but with the SSP grant.

$$max\ NPV_i = \\ = \sum_l \left(\frac{\sum_{t=1}^{8760}(E_i^{self}(t) * SCSi) + p_{SSP}}{(1+k)^l} + \\ + \frac{(C_i^{detrax} - C_i^{var}) * x_i}{(1+k)^l} - C_i^{fix} * x_i \right) \quad (48)$$

PV community optimization: self - consumption priority
The optimization of the PV capacity of a community with users prioritizing their self-consumption has similar constraints to the PV optimization for the stand-alone user, plus a number of constraints describing the energy fluxes at the community level. The self-consumed energy is computed as Constraints 37 and 39. Constrains 49 and 50 define the surplus and needed energy for the individual users.

$$E_i^{surplus}(t) = \sum_i E_i^{gen}(t) * x_i - E_i^{self}(t) \quad (49)$$

$$E_i^{need}(t) = E_i^{load}(t) - E_i^{self}(t) \quad (50)$$

The following constraints describe the energy fluxes at community level:

$$E^{av}(t) = \sum_i E_i^{surplus}(t) \quad (51)$$

$$E^{req}(t) = \sum_i E_i^{need}(t) \quad (52)$$

$$E^{man}(t) = min\Big(E_i^{load}(t); \sum_i E_i^{gen}(t) * x_i\Big) \quad (53)$$

The previous constraint is linearised as in Constraints 37 and 39.

$$E^{int}(t) = E^{av}(t) - E^{man}(t) \quad (54)$$

The objective function is then:

$$max\ NPV = \\ = \sum_l \sum_i \left(\frac{\sum_{t=1}^{8760}(E_i^{self}(t) * SCSi + E^{man}(t) * SESi)}{(1+k)^l} + \\ + \frac{\sum_{t=1}^{8760}(E^{int}(t) * p_{zonal}(t))}{(1+k)^y} + \frac{(C_i^{detrax} - C_i^{var}) * x_i}{(1+k)^l} + \\ - C_i^{fix} * x_i \right) \quad (55)$$

PV community optimization: shared consumption priority
The optimization of the PV capacity of a community with the users sharing their whole energy is an extension of the optimization for the single user benefiting of RID. The variable, the constraints and the objective function are exactly the same, but the optimization is performed by considering the community as a whole. In particular, the shared energy will be valued with the SESi and the excess energy will be sold at the zonal price, rather than at the RID price. For sake of completeness, the objective function is:

$$max\ NPV = \\ = \sum_l \sum_i \left(\frac{\sum_{t=1}^{8760} t(E^{man}(t) * SESi + E^{int}(t) * p_{zonal}(t))}{(1+k)^l} + \\ + \frac{(C_i^{detrax} - C_i^{var}) * x_i}{(1+k)^l} - C_i^{fix} * x_i \right) \quad (56)$$

PV community optimization with BESS
In this advanced step of the optimization, let's consider the possibility to install a battery energy storage system (BESS) shared by the whole community. To the previous variables, the variable b will be also considered, which accounts for the capacity of the storage system in kWh. The objective function will slightly change to take this variable into account, while some constraints will be modified or added. The

first constraints concern the energy flows of the community:

$$\sum_i E_i^{gen}(t) * x_i + E^{with}(t) + E^{dis}(t) = \\ = E^{load}(t) + E^{int}(t) + E^{ch}(t) \quad (57)$$

$$E^{self}(t) = min\Big(E^{load}(t); \sum_i E_i^{gen}(t) * x_i\Big) \quad (58)$$

$$E^{int}(t) = max\Big(0; \sum_i E_i^{gen}(t) * x_i - E^{self}(t) - E^{ch}(t)\Big) \quad (59)$$

$$E^{with}(t) = max\Big(0; E^{load}(t) - Eself(t) - E^{dis}(t)\Big) \quad (60)$$

Constraints 58, 59 and 60 are linearised following the method already utilised. Constraints for non-negativity of the PV capacity 42 and 43 are also considered.

The following constraints limit the charging and discharging of the battery:

$$SOC(t) = \begin{cases} b * SOC_{initial} - \frac{E^{dis}(t)}{\eta_{dis}} + E^{ch}(t) * \eta_{ch} & \text{if } t = 1 \\ SOC(t-1) - \frac{E^{dis}(t)}{\eta_{dis}} + E^{ch}(t) * \eta_{ch} & \text{if } t \in (1; 8760) \\ b * SOC_{initial} & \text{if } t = 8760 \end{cases} \quad (61)$$

$$SOC \leq b \quad (62)$$

$$SOC \geq b * DoD \quad (63)$$

$$P_{stor}^{max} = \frac{b}{T_{ch/dis}^{max}} \quad (64)$$

$$E^{ch}(t) \leq P_{stor}^{max} * \Delta t \text{ and } E^{dis}(t) \leq P_{stor}^{max} * \Delta t \quad (65)$$

$$E^{ch}(t) \leq P_{stor}^{max} * \Delta t \text{ and } E^{dis}(t) \leq P_{stor}^{max} * \Delta t \quad (66)$$

$$C_{batt,rep} = \sum_t (E^{ch}(t) + E^{dis}(t)) * c_{batt,rep}^{unitary} \quad (67)$$

Where:

$$c_{batt,rep}^{unitary} = \frac{C_b^{replaceable}}{N^{cycles} * 2 * (1 - DoD)} \quad (68)$$

is the replaceable cost of the battery that accounts for the variable cost of cycling energy through the battery

$$b \leq B^{max} \quad (69)$$

Lastly, the objective function is:

$$max\ NPV = \\ = \sum_l \frac{\Big(\sum_{t=1}^{8760}(E^{load}(t) - E^{with}(t)) * SESi +}{(1+k)^l} \\ \frac{\sum_{t=1}^{8760}(E_t^{int} * p_{zonal}(t))}{(1+k)^l} + \\ + \frac{\sum_i (C_i^{detrax} - C_i^{var}) * x_i - C_b^{var} * b - C_b^{rep}}{(1+k)^l} + \\ - \sum_i C_i^{fix} * x_i - C_b^{fix} * b\Big) \quad (70)$$

Where C_b^{fix} is the part of the investment cost that has to be purchased only once for the BESS in $\left[\frac{€}{KWh}\right]$. C_b^{var} are the annual maintenance costs $\left[\frac{€}{KWh*yr}\right]$. C_b^{rep} the battery reposition cost (or wear cost) is the cost in $\left[\frac{€}{KWh*yr}\right]$ of cycling energy through the battery.

3 Application of the tools

3.1 Short-term analysis A short-term analysis investigates whether EC are economically convenient for stand-alone users that already own a domestic PV plant that was sized on their individual needs through the MILP optimisation. The algorithm compares the extended electric bill of stand-alone users with RID or SSP, with the three community configurations. If the community is convenient, profits are allocated via Shapley value. The algorithm is shown in Figure 1.

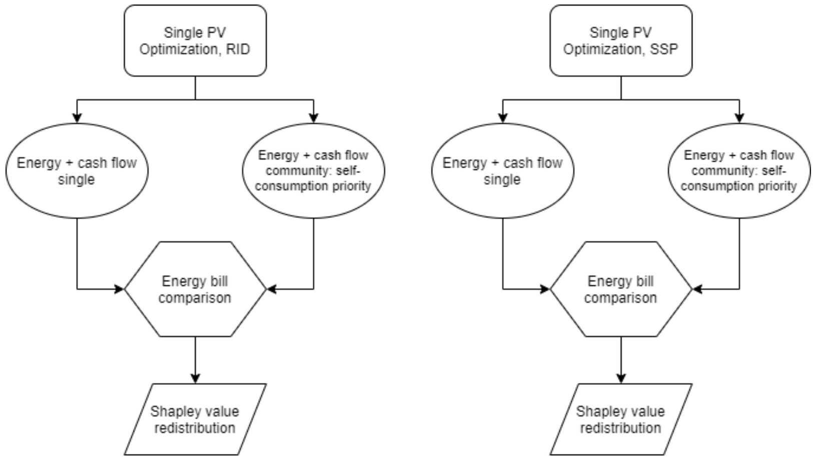


Figure 1. Short-term analysis

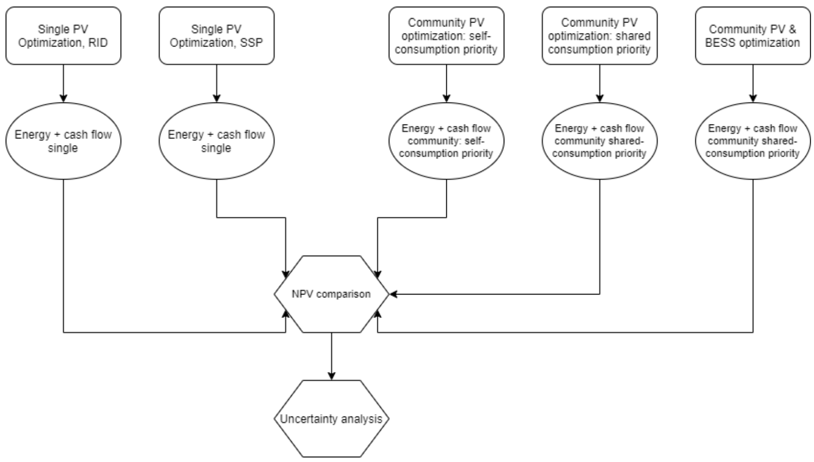


Figure 2. Long-term analysis

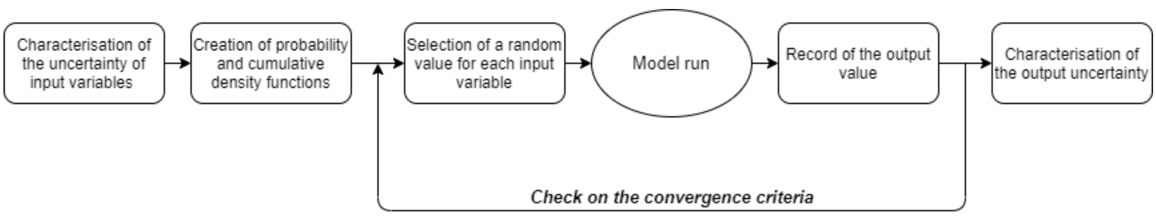


Figure 3. Uncertainty analysis process

3.2 Long-term analysis Long - term analysis investigates whether EC are convenient for users that want to invest in renewable energy. For the two stand-alone configurations and the three community configurations a MILP optimisation is performed and the energy fluxes are computed. The NPVs are then computed and compared. The algorithm is shown in Figure 2.

3.3 Uncertainty analysis To validate the results obtained through the long-term analysis, an uncertainty analysis is performed on the NPV to find the probability distributions created by the uncertainty of the price and efficiency inputs. A Monte Carlo sampling method is performed in which the model is run multiple times with random input variables taken from their probability distributions [17]. These are modelled as normal distributions and their value is taken from literature [18], [19], [20]. The outputs of the runs are collected to form an histogram that shows its uncertainty. The model is run until it satisfies a convergence criterion based on the mean $\bar{x}$ and the standard deviation $\bar{s}_x$ of the outputs of the runs. As presented in Equation 71, N+m is the number of iterations such that the absolute value of the relative differences between the mean and the standard deviation of the model outputs at the iteration N and at the iteration N+m (being m an arbitrary number), are smaller than a tolerance ϵ. In the UA, $m = 10$ and $\epsilon = 0,1\%$

$$N\ s.t.\ |\frac{\bar{x}(N) - \bar{x}(N+m)}{\bar{x}(N)}| < \epsilon\ and \\ |\frac{\bar{s}_x(N) - \bar{s}_x(N+m)}{\bar{s}_x(N)}| < \epsilon \tag{71}$$

The UA is performed for every stand-alone and community configuration and the results compared.

4 Case Study

The proposed methodology is demonstrated on a REC with PV systems. The community comprises 10 households with single-time band domestic contracts within the protected regime. Such an example has been adopted in order to have a compact and computationally efficient, but at the same time realistic, study case. Actual results could be easily scaled up to a bigger EC. Active users have the possibility to benefit of RID with minimum granted price or SSP. When they form a community the surplus energy is instead valued through the zonal price. Loads and generation curves are created using well-known tools as Load Profile Generator [21] and a PV GIS from the JRC [22]. Users characteristics are shown in Table 3. Table 2 summarises the technical and economical input parameters. The ones with the asterisk * are also subjected to the uncertainty analysis. Figure 4 shows the considered zonal price.

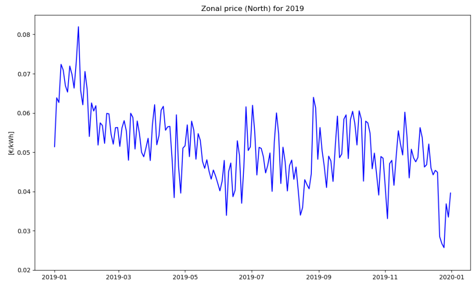


Figure 4. 2019 zonal price

	Parameters
PV efficiency %	14
*PV capex [€/kW]	1550
*PV opex [€/kW]	2% capex
*Battery charge efficiency %	90
*Battery discharge efficiency %	90
DoD %	20
Maximum battery cycles	3000
Max C-rate	3
*Battery investment cost [€/kWh]	200
*Battery electronic cost [€/kWh]	100
*Battery replacement cost [€/kWh]	100
*Battery Opex [€/kWh*yr]	1% capex
*Investment rate %	4
Service life [years]	20
Minimum granted price [€/kWh]	0,4

Table 2. Model parameters

Self-consumed energy is valued according to the current incentives: SCSi = 0,149 €/kWh. On the other hand, three cases are considered for the value of the shared energy within the community. In Case A, let's consider that EC are given an implicit incentive equal to the energy share (plus excises) minus the operating costs. In Case B, the shared energy is valued in the same way of the self-consumed energy, meaning that all the energy share is exempted, i.e. SESi = SCSi. In Case C, an

User	latitude	longitude	PV slope	PV orientation	Max. PV capacity [kWp]	Annual load [kWh]
User 1	45.699019	9.001100	10°	East	5,0	4370,33
User 2	45.698533	9.000239	10°	West	5,0	3529,89
User 3	45.698966	9.000496	10°	North	3,0	1816,74
User 4	45.698456	9.001077	10°	South	10,0	2200,92
User 5	45.698818	9.000378	35°	South	10,0	3021,28
User 6	45.698445	9.001062	35°	North	3,0	1088,83
User 7	45.698497	9.000415	35°	East	5,0	2712,39
User 8	45.698633	9.000952	35°	West	5,0	3345,88
User 9	45.698818	9.000099	35°	South	10,0	4257,18
User 10	45.698680	9.000319	10°	West	10,0	4560,17

Table 3. Characteristics of the users in the case study

explicit incentive is given that is higher that the one given in Case B. For simplicity let's consider this incentive equal to the SCSi plus the difference between the SESi of Case B and Case A. Taking everything into consideration, the three cases are:

- Case A: SESi = 0,108 €/kWh
- Case B: SESi = 0,149 €/kWh
- Case C: SESi = 0,190 €/kWh

4.1 Short-term analysis The PV capacity optimization of stand-alone users led to the results shown in Table 4. Both RID and SSP allow almost all stand-alone users to install some capacity on their roofs, due to the savings from self - consumption and profits from the valorisation of the energy injected into the grid. It is clear that SSP is an incentive that assures high revenues, given the almost double PV capacity found through the optimisation.

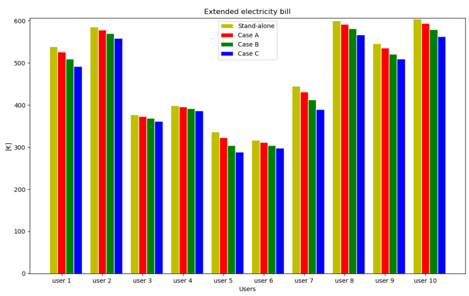


Figure 5. Short-term analysis for stand-alone users with RID

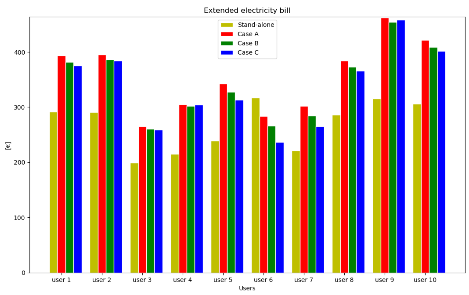


Figure 6. Short-term analysis for stand-alone users with SSP

The comparison of the sum of the electricity bills of all the users in stand-alone configuration and within the community led to the conclusion that community formation is always convenient if the users valued their surplus energy through RID, while it is not convenient if they valued it through SSP. In the case of RID, is then possible to allocate the profit through Shapley value. Figure 5 shows the electricity bills for stand-alone users with RID (yellow columns) and the savings from community formation with three SESi cases and Shapley redistribution. Figure 6 shows the electricity bills for stand-alone users with SSP (yellow columns) and the losses from community formation.

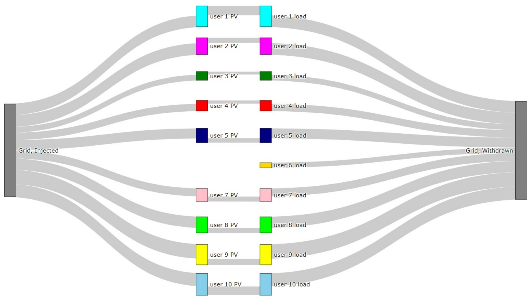
4.2 Long-term analysis The analysis allowed to compute and visualise the energy fluxes for each configuration as reported in Figure 7, in which can be ap-

	user 1	user 2	user 3	user 4	user 5	user 6	user 7	user 8	user 9	user 10
PV RID [kW]	2,30	1,03	0,43	0,66	2,35	0,00	1,07	0,63	2,14	2,05
PV SSP [kW]	3,88	3,12	1,83	1,76	2,16	0,00	2,58	3,15	3,05	4,04

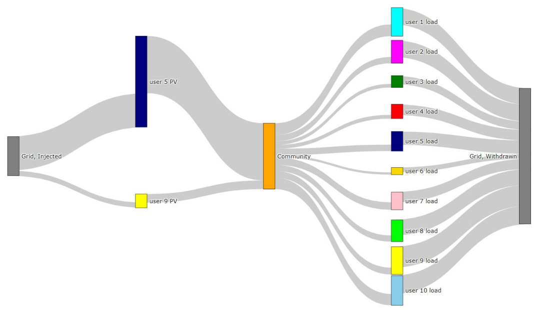
Table 4. Short-term analysis results - optimal capacity for each user

	RID	SSP	A			B			C		
			Shared	Self	BESS	Shared	Self	BESS	Shared	Self	BESS
Total PV installed [kW]	12,66	25,57	11,52	10,30	11,52	15,91	15,91	20,0	18,44	18,89	25,65
BESS capacity installed [kWh]	0,00	0,00	0,00	0,00	0,00	0,00	0,00	58,66	0,00	0,00	76,65
NPV [€]	5531,85	16904,57	5182,88	8147,79	5182,88	11968,88	11968,88	16389,05	17250,27	19066,24	30445,79

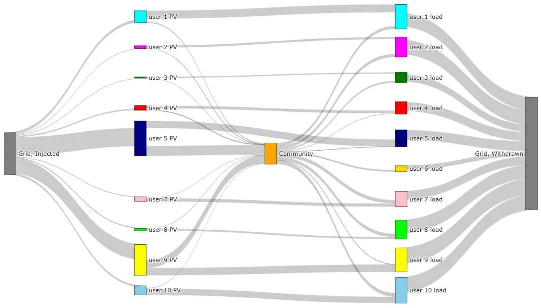
Table 5. Long-term analysis results



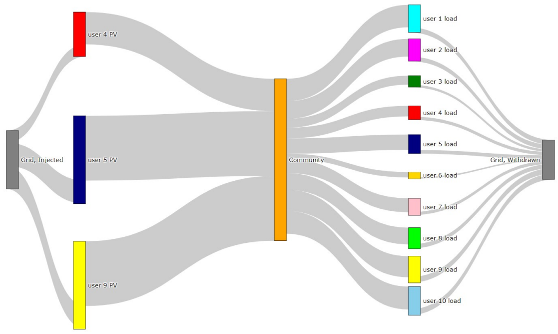
(a) Stand-alone users



(b) Community with shared consumption priority



(c) Community with self-consumption priority



(d) Community with BESS

Figure 7. Energy fluxes in different configurations

preciated the different energy strategies. On the left hand side of each Subfigure is represented the electricity generation of each user and on the right hand side the electricity consumption. The gray boxes represent the interactions with the grid and the orange boxes are the community, interposed between production and consumption.

The main results of long-term analysis are reported in Table 5. The comparison of the NPVs shows that the value of the incentive given to shared energy within the community, deeply influences the optimization process. In particular only with an incentive that is equal to the SCSi (Case B) the community configuration with BESS becomes almost competitive to the stand-alone configuration with SSP. The explicit incentive of Case C allows all the community configurations to be more profitable than the stand-alone case. The value of the SESi also increases

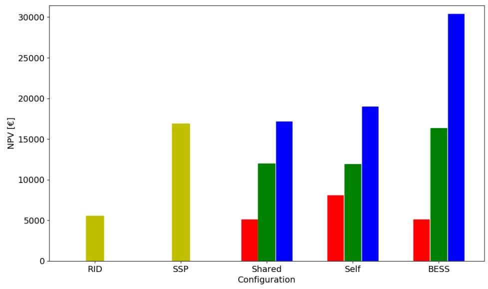
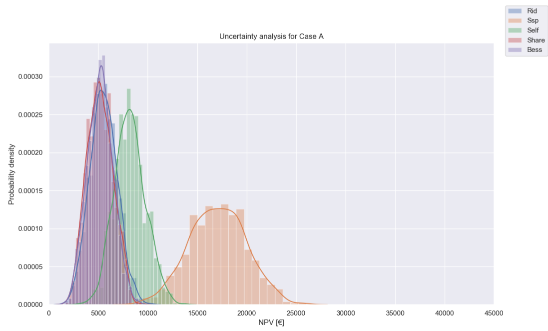


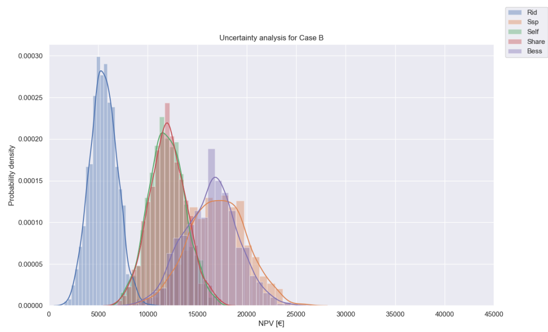
Figure 8. Long-term analysis results

the level of installed PV capacity, as the savings on shared energy will allow to repay the investment on PV. The analysis shows that the stand-alone case with SSP is the solution that makes to install the more PV capacity. That is due to a non-efficient utilisation of the latter that only satisfies the needs of the owner. The community on the other hand allows to install less PV, due to the sharing of the energy generated. The NPVs are shown in Figure 8, in which red bars are for Case a, green for Case B and blue for Case C.

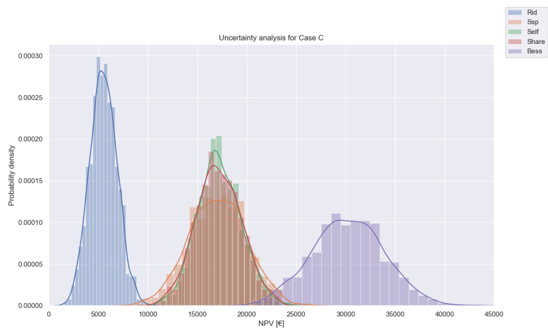
4.3 Uncertainty analysis The uncertainty analysis, performed on all the terms in Table 2 with an asterisk, allows to critically comment the long-term analysis. Figure 9 shows the outputs of the uncertainty analyses for every energy sharing strategy. The probability distributions of the NPVs are then confronted for every SESi case. The x-axis reports the NPV value and the y-axis the probability density. Subfigure 9a confirms the obtained results as no other distribution probability intersects the orange bell, meaning that even with price variability the stand-alone configuration with SSP is the most profitable with a low incentive on shared energy. Also Subfigure 9c for case C supports the results of the long-term analysis as the purple bell of the community with BESS is not intersected by any other. It is also interesting to see that for a high incentive in shared energy the other community configurations are comparable with the stand-alone SSP case. Lastly, subfigure 9b for Case B instead shows an overlapping of the probability distributions of the stand-alone SSP case and community with BESS configuration, meaning that when the variability of the input parameters is taken into account, the two solutions become comparable and the investment in an EC can be considered profitable even with an incentive on shared energy equal to the one given to self-consumed energy.



(a) Case A



(b) Case B



(c) Case C

Figure 9. Uncertainty analyses

Conclusions

The thesis proposed an innovative model to optimise the PV capacity and simulate the energy flows in an EC to evaluate its economic feasibility. When applied to a case study in the Italian framework, it was demonstrated that in a short-term analysis, i.e. when users already own a PV plant sized on their needs, the EC are convenient only in the case where stand-alone users benefit of RID and not of SSP. The long-term analysis showed that the value of the incentive on shared energy will be determining in the development of EC.

Future works include to extend the community also to non-domestic users such as local authorities and small businesses that have their load peak in the central hours of the day. From the implementation point of view, cooperative game theory could be used to describe the allocation of the cost of shared assets in a community. The model can be expanded by taking into account a more detailed model for the battery and other charging logics. The uncertainty analysis might be expanded by taking also into account the variability of the electricity production from PV and the price of electricity.

The proposed methodology presented in this thesis were all created from scratch by the author and programmed in Pyhton language. The optimisations were formalised with the Python-based modelling language Pyomo, using Gurobi as a solver. The model was run on a PC i7 5GHz 16GB and the highest computational time revealed to be 9 h for the optimisation and 19h for the Monte Carlo UA. Even though the computational cost is important, the approach proved to be computationally feasible.

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Sommario

Il Clean Energy Package, approvato tra il maggio 2018 e il maggio 2019, è una raccolta di politiche energetiche che saranno implementate negli Stati Membri europei e guideranno l'Unione Europea verso la cosiddetta transizione energetica. Le Comunità Energetiche (CE), riconosciute come entità giuridiche nel Pacchetto, saranno strumenti essenziali nell'avvicinare i cittadini agli ambiziosi obiettivi Europei, poiché sarà permesso a questi ultimi di unirsi come utenti finali e cooperare nella generazione, condivisione e distribuzione di energia elettrica e partecipare a servizi energetici come il miglioramento dell'efficienza energetica e gestione della domanda. Lo scopo di questa tesi è di sviluppare uno strumento che simuli i flussi energetici e valuti la fattibilità economica di una Comunità Energetica Rinnovabile contestualizzata al panorama italiano. La tesi analizza il processo di recepimento del Clean Energy Package in Italia per identificare possibili schemi di supporto per le CE, mentre una ricerca bibliografica su progetti di energia condivisa e micro-reti è mirata a identificare le caratteristiche principali delle future CE. Il modello sviluppato è in grado di descrivere i flussi energetici di utenti prosumer che interagiscono singolarmente con il sistema elettrico (modello attuale), ma anche di utenti che si uniscono in una CE e scambiano energia tra loro. E' stato implementato un ottimizzatore MILP che determina la capacità ottimale di generazione da PV in ciascun caso. Il modello è applicato a una analisi di breve termine, che calcola le bollette elettriche di utenti fuori o dentro una CE con capacità PV pre-esistente e a una analisi di lungo termine che valuta la convenienza economica degli investimenti nelle CE. L'applicazione dei modelli a un caso studio ha rivelato che nel breve termine le CE sono convenienti solo se l'utente singolo attualmente valorizza la propria energia in eccesso tramite Ritiro Dedicato, ma non convenienti nel caso in cui gli utenti singoli siano beneficiari di Scambio sul Posto. L'analisi di lungo termine ha mostrato che gli schemi di supporto sull'energia condivisa sono invece determinanti a sostenere futuri investimenti nelle CE. Considerati i numerosi sconti tariffari sull'energia autoconsumata in sito e il trattamento favorevole conseguibile con il meccanismo di Scambio sul Posto, la CE potrà diventare la soluzione più conveniente solo con un importante incentivo sull'energia condivisa nella comunità, che tenga conto non solo dei benefici portati dalle comunità sul sistema elettrico, ma anche del ruolo sociale che esse svolgeranno tra i cittadini.

Parole Chiave: Comunità energetiche, MILP, PV, Fonti di energia rinnovabile, regolazione, incentivi

Abstract

The Clean Energy Package, approved between May 2018 and May 2019, is a set of energy policies to be implemented in European Member States that will lead the EU towards the so-called clean energy transition. Energy Communities (EC), recognised as legal entities in the Package, will act as pivotal tools in bringing closer citizens to Europe's ambitious targets as they will be allowed to come together as final users and cooperate in the generation, distribution and supply of electrical energy and participate to energy services such as energy efficiency or demand side management. The goal of this thesis is to provide a tool that simulates energy flows and evaluates the economic feasibility of Renewable Energy Communities contextualized to the Italian framework. The thesis analyses the transposition process of the Clean Energy Package in Italy to identify possible support schemes for EC, while a literature review on community energy projects and micro-grids aims to identify the main characteristics of future EC. The tool is able to describe energy flows of prosumer users interacting individually with the electrical system (current model), but also of users who join together in an EC and share energy among themselves. It is also implemented a MILP optimisation that determines the optimal generation capacity from PV in each case. The tool is applied for a short-term analysis, computing the electricity bills of users inside or outside the EC with pre-existing generation capacity and a long-term analysis that evaluates the profitability of investments in EC. The application of the tool to a case study revealed that in a short-term, EC are convenient only if the stand-alone users are currently valuing their surplus energy through *Ritiro Dedicato*, but is less convenient for stand-alone users benefiting of *Scambio sul Posto*, regardless of the incentive given to shared energy. The long-term analysis showed that the support scheme on shared energy is instead pivotal to foster future investments of EC. Considering the numerous tariff exemptions on self-consumed energy and the favorable treatment that can be achieved with the *Scambio sul Posto*, the EC can become the most convenient solution only with an important incentive on energy shared in the community, which takes into account the benefits brought by the communities on the electrical system, as well as the social role that they will play among citizens.

Keywords: Energy Communitites, MILP, PV, RES, regulation, incentives

Introduction

The Clean Energy Package (CEP) is a set of Regulations and Directives that will shape the European energy policies up to 2030. Among the ambitious targets of increasing the renewable energy share and reducing the greenhouse gasses emissions, it is in the EU objectives to involve as much as possible its citizens in the clean energy transition. That is why Energy Communities (EC) are legally recognised in two Directives of the CEP with two different functions. EC will make European citizens active players in the energy field as they will be allowed to produce, share and distribute electrical energy and participate in energy services by performing energy efficiency projects or demand side management.

The deadline for the transposition of the CEP into the national laws of EU Member States is set to June 2021. While in Italy the transposition process has already started and set a milestone in February 2020 with the first law that establishes an experimental regime for EC, it is still an open issue whether EC will be economically convenient for Italian citizens with the current regulatory framework. As a matter of fact, EC will compete with active users already performing self-consumption, an activity that is receiving beneficial incentives for the energy used on-site. The nature and the amount of the support schemes recognised to EC is still under discussion and needs to be defined by the Italian energy Authority. It is therefore the scope of this thesis to develop a tool that reproduces the energy flows between users within a community and evaluates their economic feasibility in the Italian framework. The tool will be used in a short-term analysis, that evaluates the formation of an EC with users already possessing a generation plant optimised for their individual needs and in a long-term analysis that evaluates the profitability of investing in EC in three different configurations.

The thesis work is accordingly divided into two layers of research. A first layer deals with the study of the European norms that led to the definition of the two classes of EC: Renewable Energy Communities and Citizens Energy Communities. The transposition of the CEP into the Italian legal system and the current definition and regulation of self-consumption systems is then analysed. The second layer of research deals with the characterisation of the main features of EC: social benefits and business models are categorised taking into account existing experiences of community energy projects and energy co-ownership. A technical analysis is aimed to identify the main technologies present in an EC, while a taxonomic analysis of game theory applied to community energy projects is performed to understand the interactions among the members of an EC.

The thesis is therefore structured as follows: Chapter 1 contains the legislative and regulatory analysis of the first layer of research. Chapter 2 contains the socio-technical analysis of the second layer of research. Chapter 3 shows the proposed methodology for the tool that simulates the energy sharing in an EC and optimises the generation portfolio. In Chapter 4 a case study is set up to validate the tool and the results of a short-term, long-term and uncertainty analysis are reported, considering different support schemes for the EC.

Chapter 1

Energy communities in the European legislative framework

The commitment of the European Union (EU) towards climate and energy is embedded into the fundamental treaties that shaped the EU in its founding. Various articles of the Treaty of Functioning of the EU of 1957, later amended by the Lisbon treaty in 2007, gives to the EU agencies the legal competencies to take action towards climate change and sets a plurality of energy related objectives, including the pursue of energy efficiency and the development of renewable sources of energy. Furthermore, Article 3 of the Treaty on the EU of 1993 commits the EU to *"work for sustainable development"* and to a *"high level of protection and improvement of European environment"*.

Throughout the years the EU set objectives for increasing the shares of renewables and promoting energy efficiency. Moreover, it set up support mechanism to stimulate the development in the renewable energy sector, increase public awareness on climate change and promote a major role for regional or local entities. In the matter of community energy, the EU legal tools that enable its development include the Directive 2009/28/EC on the promotion and use of energy from renewable sources, Directive 2010/31/EU on improving energy performance in buildings, Directive 2012/27/EU on energy efficiency, and Directives 2009/72/EC and 2009/73/EC concerning common rules for the internal market in electricity and gas [23].

Lastly, the European Commission formed in 2019 and headed by Ursula von der Leyen announced the implementation of the "European Green Deal", 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 [24].

1.1 The clean energy package

In line with the green policies implemented in the past years, the EC proposed in 2016 an ambitious set of measures called "Clean Energy for all Europeans" or Clean Energy Package, CEP for short. The package includes four Regulations and four Directives discussed during the inter-institutional “trilogue” negotiations between the European

Council, representing the interests of the Member States, the European Parliament, on behalf of the European Citizens, and the European Commission. The negotiations ended up with the adoption of the eight legislative acts in May 2019. The Regulations and Directives that constitute the package are:

- Energy Performance of Buildings Directive (EU) 2018/844
- Renewable Energy Directive (EU) 2018/2001
- Energy Efficiency Directive (EU) 2018/2002
- Governance of the Energy Union and Climate Action Regulation (EU) 2018/1999
- Electricity Regulation (EU) 2019/943
- Electricity Directive (EU) 2019/944
- Regulation on Risk-Preparedness in the Electricity Sector (EU) 2019/941
- Regulation on the European Union Agency for the Cooperation of Energy Regulators (EU) 2019/942

The ambitious targets that the EU wants to achieve are part of the so-called *clean energy transition* towards a carbon-free economy. In particular, the CEP aims to fulfil by 2030 these targets:

- 40% reduction in greenhouse gasses emissions
- 32% of Renewable Energy Sources (RES) consumption
- 32.5% of energy efficiency

The importance of taking the clean energy transition as pioneers in the World and the positive impacts that the member states can benefit in terms of new jobs, GDP increase and investments are the central aspects identified by the European Commission during the development of the CEP [25].

The CEP deals with issues that were at the basis of the foundation of the *Energy Union* wanted by the Juncker administration of the European Commission from 2014 to 2019 [26]. These measures comprehend, in addition to the aforementioned improvement of energy efficiency and increase of the share of RES in the energy mix, a more flexible grid that takes into account their unpredictability, but nonetheless assures security of supply both from internal and external factors. The Regulations and Directives will also provide a consumer-centric market with rules that will fight energy poverty in risky regions, legal frameworks that will make easier for citizens to invest into renewables and take actively part into the energy transition. Moreover, the EU will ask its Member States to pledge to the clean energy transition by drafting a National Energy and Climate Plan for the decade 2021-2030.

1.2 Community energy potential in the EU

As it was mentioned in the previous section, one of the most 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 EC 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 [1].

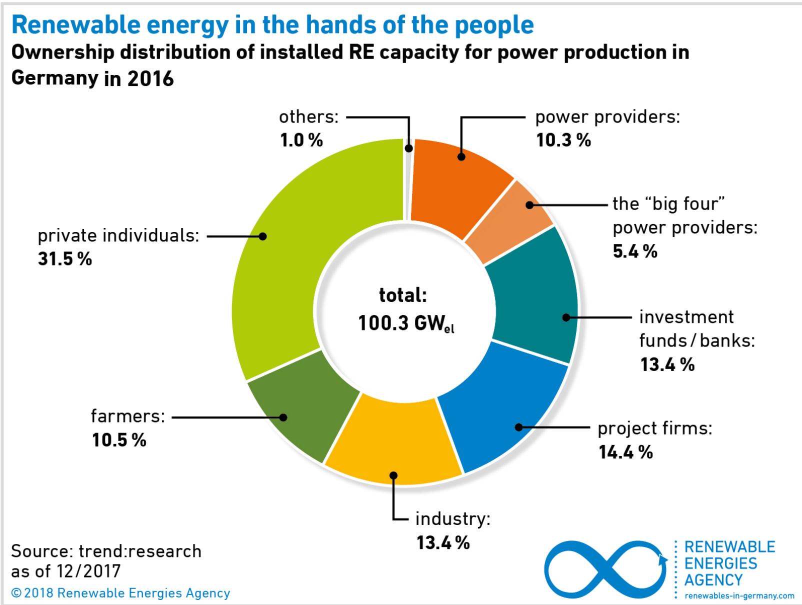


Figure 1.1. RES ownership in Germany in 2016 [27]

Even if 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 and consumption that still needs to be fully exploited. In countries where energy ownership or co-ownership is a diffuse phenomenon as in Germany, private users own more than 40% of the renewable energy capacity [28] as shown in Figure 1.1. Due to a long tradition of citizen participation, in 2015 a German cooperative resulted among the top 15 energy retailers in Europe, a ranking commonly dominated by large companies [29].

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 Federation and REScoop, showed promising results in the development of the participation of European citizens in the energy sector [30]. 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 other studies confirm the positive results obtainable in the future. The JRC computed the PV capacity that could be installed on roofs and the estimated energy production [27]. The calculations where performed at regional level as in Figure 1.2 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 [31].

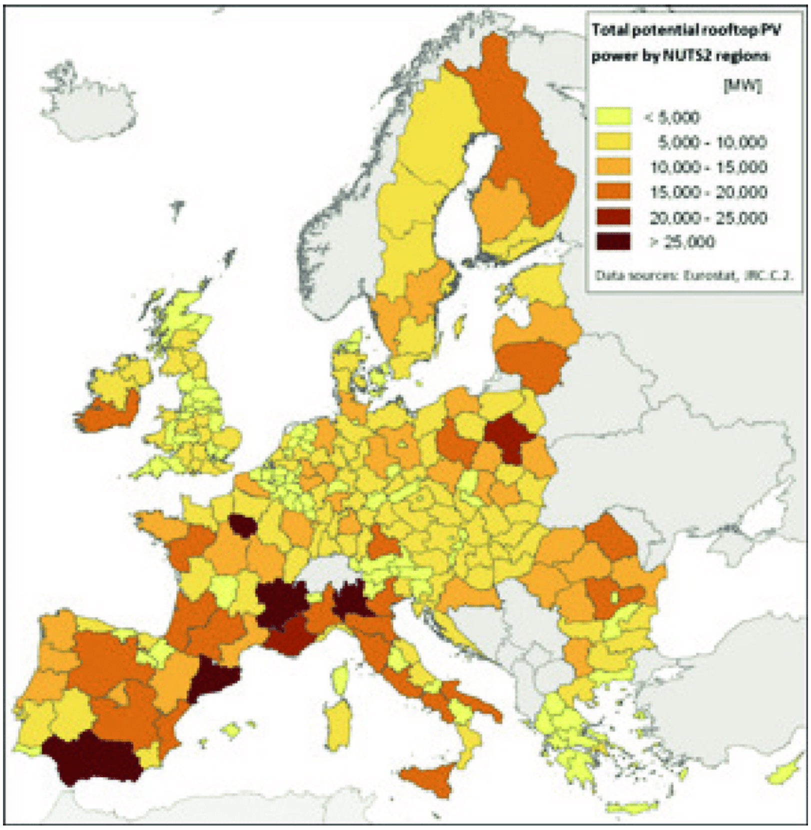


Figure 1.2. Potential PV capacity per NUTS2 region [27]

Taking these statistics into consideration, it is without any doubt that CEP sets a milestone in the formal recognition of the concept of Energy Community (EC) in the European legislation. EC, in their two declinations, will enable citizens to be protagonists of the energy transformation and to achieve it more faster, with social and economical fairness [32].

1.3 The energy communities

Community energy projects have been around Europe for decades, involving citizens generating energy collectively or providing management of small distribution infrastructures. The formalization of the EC as legal entities in the CEP will allow the 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 [9].

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 European Commission opted for the definition of two classes of energy communities with a distinct regulatory sense. In particular the definition of *Renewable Energy Communities* is contained in the recast of the Renewable Energy Directive (RED II), while the Electricity Market Directive describes the *Citizens Energy Communities.*

1.3.1 Citizen Energy Communities

The first kind of EC is the Citizens Energy Community (CEC), of which a general description is provided in the Article 2 (11) of the Electricity Market Directive [1]:

> *'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.*

From the description it is understood that a CEC can operate in the limits of the energy sector, but their purpose has to be the provision of environmental, economic or social community benefits to its shareholders. While electricity generation is not restricted to renewable sources, 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 [2]. 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.

[1] Directive (EU) 2019/944 of the European Parliament and of the Council on common rules for the internal market in electricity, amending Directive 2012/27/EU

[2] Article 16 (2a) of the Electricity Market Directive

1.3.2 Renewable Energy Communities

Article 2 (16) of the RED II [3] provides a preliminary representation of Renewable Energy Community (REC):

> *'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.*

Similarly to CECs, also RECs' purpose has to be the pursuit of the environmental, economic or social community benefits for their shareholders. On the other hand, RECs' activities are limited to generation of energy from renewable sources, and the consequent sale of that energy or its sharing among its shareholders. Also participation is more stringent as it is open and voluntary by natural persons, local authorities, including municipalities and micro, Small Medium Enterprises (SME). Participation in RECs is forbidden to large companies. A particular remark is made on the possibility to participate also for low-income or vulnerable households. Control is performed by those members in the proximity to the project owned by the community and decisions have to be taken democratically. RECs are allowed to exist only in contiguity to the renewable energy project, even though cross-border participation is foreseen. Member States are in charge of encouraging the development of RECs, by removing bureaucratic barriers that my hinder their formation and provide support schemes for their subsistence. Member States must inform citizens of the possibility of forming RECs when developing renewable projects [4].

1.3.3 Relationship between CECs and RECs

Generally speaking, RECs can be seen as a subset of CECs, because the eligibility criteria of the former are more stringent than the latter in all areas but in one. As a matter of fact, in order to consider true the previous sentence, a medium sized enterprise cannot control a RECs (CECs are more stringent in the effective control criteria). Table 1.1 highlights the main differences among the two types of energy communities.

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

[3]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, amending Directive 2009/28/EC

[4]Article 22 (7) of the RED II

Subject	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
Control	Medium and large companies are excluded	Members in proximity to the project
Geographic limitation	Cross-border participation is allowed	Proximity to the project
Activities	Electricity generation and consumption, energy efficiency services, EV charging, management of distribution networks	Production, consumption and sale of electricity from RES and energy sharing
Member States support	Create a level playing field in the market	Create a level playing field in the market, remove administrative barriers, enforce support schemes

Table 1.1. Differences among CECs and RECs

support to these communities through support schemes and facilitate their creation with national enabling frameworks [33].

1.3.4 Other definitions related to EC

The considered Directive also introduce some legal entities such as the *active customer*, the *renewables individual and joint self-consumers* that can be bounded to the two definitions of energy community. Both the Renewable Energy Directive and the RED II define the legal framework of the individual self-consumer. The Article 2 (8) of the RED II defines the "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":

> *'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 already considers the collective action of the customers (*active customer means a final customer, or a group of jointly acting final customers, . . .*). The Article 2 (15) if the RED II instead gives a separate definition of joint self-consumption:

> *'jointly acting renewables self-consumers' means a group of at least two jointly acting renewables self-consumers in accordance with point (14) who are located in the same building or multi-apartment block;*

The innovation brought with this characterization is that the Directive 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 meaning of collective renewable self-consumers and RECs might seem overlapping, but their definitions were given in two different articles because the former describes an action that could be performed outside an EC in any business model, while the RECs is more a way to organize and recognise users [33].

1.4 Energy communities in Europe

The Electricity Market Directive will have to be transposed into Member States' national laws before the 31st December 2020, and the Renewable Energy Directive before the 30th June 2021. While it is not the goal of this section to follow the legislative processes that will lead to the recognition of EC in each Country, it is definitely useful to investigate existing experiences and regulatory frameworks concerning bottom-up energy sharing in Europe. The concept of EC started to came out with the first proposals from the European Commission in 2016, however some Member States have a long tradition of energy co-ownership or community energy. On the other hand, other Member States have tried to anticipate the European Directives and supported with regulatory policies the establishment of business models that were similar to the definition of EC.

The research found that the Countries with a tradition in energy co-ownership such as Denmark, Germany and the Netherlands tend to follow their own path that has developed in the past through individual experiences and create entities that are not properly formalized as EC, but share the same scope and modalities. On the other hand, Countries like Greece or Slovenia are exploiting the momentum created by the CEP to emanate laws recognising EC in order to tackle national issues such as energy poverty or increase their RES share. Other countries are acting more gradually and use the concept of collective self-consumption as a base to promote EC in the next future. That is the case of Austria and Spain. Lastly, Poland and the UK are using the concept of community energy in a transitory and experimental regime to promote knowledge sharing among stakeholders and to study the experiences from a regulatory point of view. The most critical step of the experiences proved to be setting of the incentives (as it will also be shown for Italy) mainly because the impact of EC on the electrical system and distribution of the system costs have to be considered [35]. The following pages present the result of the research.

Austria - Extended collective self-consumption

Austria recognised in 2017 collective self-consumption in multi-apartment buildings for which support schemes are already in place in some federal States. It is intention of the Government to extend the scope of collective self-consumption to EC, starting from the existing cooperatives that produce, store and distribute renewable energy in limited areas. The support schemes are still into discussion, but if the EC will be bounded to the medium/low voltage transformer station, its members may pay only the distribution tariffs of the bill and not the transmission ones.

Belgium - EC in Wallonia

In Belgium, the autonomous Region of Wallonia promulgated a law that recognises renewable energy communities aimed to produce renewable energy for the benefit of their participants using a private or public grid. Participation is open and voluntary to natural persons, local authorities and SME, whose business core is not in the energy filed. Distribution System Operator (DSO) can intervene in the REC with the function of network managers. The local DSO has also the power to approve or refuse the establishment of a REC. While support schemes are still under discussion, they will have to encourage their formation while covering network costs. The most innovative characteristic of the Belgian RECs is the definition of its boundary, that is not limited to a spacial distance, but is determined by the same transformation station, considering the characteristics of the territory.

Denmark – Community participation

Denmark has long-established strategies for including the participation of the local people into renewable energy projects, especially for wind power. The Danish Government implements measures to achieve public acceptance of the projects through direct involvement of the communities into the financial part of the projects. According to the Danish Energy Agency, the main driver to establish energy cooperatives is economical remunerations for its members. The "option-to-purchase" scheme gives local citizens the right to buy up to 50% of the shares of a new onshore or near-to-shore project. If any share is left out, the priority to buy shares goes to the local municipalities. Moreover, project developers have to compensate the local citizens for any loss in property resulting from the implementation of the project, following the "value loss" scheme. The amount of the compensation is decided by an independent authority. The "Green" scheme allows municipalities that approve RES projects in their area to apply for national funds that will be used to finance activities that will bring social welfare to the community. Lastly, the Guarantee Fund provides local wind energy cooperatives a financial guarantee to the institutions that lend money for the project, in order to remove the planning barriers of financial nature that might arise in the early stage of the project [9]. Despite the many measures implemented by the Danish government to incentivize local participation in wind projects and in the creation of energy cooperatives, they do not fall into the definition of REC as the projects do not have to be owned totally by the cooperative and a profit is allowed.

Germany – The privileged auctions

Germany energy sector has been participated for a long time by community energy experiences as an active part of the Federal Energiewende, the German energy transition. As a matter of fact, more than 40% of the total installed capacity of RES in Germany is owned by private citizens or farmers [36]. The Renewable Energy Act written in 2000 provided a feed-in tariff to promote the implementation of RES projects by decreasing their high investment risks. In 2014 the feed-in tariffs scheme was replaced by a system of auctions in order to get a premium from the production. The communities were mainly left out from winning the auctions as they could not keep the pace of big energy companies in the pre-development of the projects. To solve this issue, in 2017 the German government developed an amendment to the 2014 act, by introducing substantial advantages in the auctions to the so-called "citizen energy communities", that consist of at least ten local private citizens. The advantages were lower requirements in the pre-development of the projects, longer implementation periods and a preferential price rules in the bidding process of the auction. This scheme resulted in almost a total win of communities in the auctions and as a consequence it was blamed of market distortion and unfair competition. Moreover, large energy companies created fictitious communities in order to benefit of the privileges. In response to these critiques, the advantages were modified to create a fair playing field [9]. The German experience of trial and error demonstrates how hard is to create a regulatory framework that incentivise a particular group of players without distorting the entire market.

Greece - Solidarity communities

Already in 2018, Greece established EC aimed to promote innovation and solidarity in the energy sector[5]. The Greek communities pursue the exploitation of the abundant renewable resources present in the territory, wind and sun, to promote actions of social economy and assure security of supply to the many Greek islands [37]. The allowed activities space from energy production to the operation of desalinators that use RES, the Greek EC configure more a CECs, considering the number of energy services provided. Participation is open to natural persons, municipalities and companies.

[5]Law 4513/2018

The Netherlands – The Dutch Experimentation Decree

In 2015 the Dutch government realised a Crown Decree for experimenting with decentralized renewable energy generation [6]. The Experimentation Decree creates exceptions in the concessions given to system operators. As a matter of fact, under certain constraints, the applicants provide proposal of integrated hybrid solutions between energy generation, distribution and consumption by linking various energy sources and allowing energy sharing among the users. The Experimentation Decree was written with the aim of increasing the RES and CHP at a local level; including the consumers in the energy production and of making a more efficient use of the already existing energy infrastructure [38]. The applicants must be associations, energy cooperatives funded by the developers of the project and fully controlled by its members. DSOs and energy suppliers must be left out from the effective control of projects. The association must asses the financial, technical and environmental feasibility of the project and must provide all the necessary funds to finance it. For the so-called "project grids" (i.e. projects with less than 500 connected users and one connection to the national grid), the associations become generators, suppliers and DSO of the local grid, with all the responsibilities that this entails, so that balancing methods and system security has to be provided as well.

The Dutch government is thus experimenting on bottom-up initiatives mainly involving microgrids and small-scale generation from RES. So-far a total of 17 projects have been implemented thanks to the Experimentation Decree, including RES generation in built environment also combined with smart grid, EV charging and storage [9]. Due to the inclusion of CHP as well as microgrids (also provided with internal tariffs) alongside RES generation, the Dutch experimental model is more similar to the CEC definition rather that the REC.

Poland – The energy clusters

The Polish Ministry of Energy introduced the energy cluster concept in the RES Amendment Act drafted in 2016. Energy clusters are civil law agreements between local governments, university and researchers, legal persons, end-users and prosumers which aim to pursue energy efficiency in the target region through a more effective RES utilization and to stimulate the economic development. The members of the cluster do not give up their existing businesses but aim to bring benefits and add value to the local community. The cluster can operate in the distribution network and in the area of maximum five municipalities. Each energy cluster has to be represented by a coordinator that has to manage the energy flow within the cluster, thus managing the energy trading, the relations between producers and end-users and grid services.

The best practice case is the Bioenergetic Cluster in Słupsk, including RES production (from wind, PV, CHP and traditional sources), heat recovery, DSO management and water management. The cluster has achieved a good interaction between the stakeholders, intermediated by the coordinator, with an overall benefit

[6] "Besluit van 28 February 2015, houdende het bij wege van experiment afwijken van de Elektriciteitswet 1998 voor decentrale opwekking van duurzame elektriciteit"

for the end-users and the society [39]. In a similar fashion as in the UK, the Polish government is using energy cluster to explore new regulatory developments, based on the energy community concept. The Polish clusters highlight the aspect of local proximity as in the concept of RECs, but the technology used within the cluster is not limited to RES, thus going beyond to the definition given in the RED II.

Slovenia - EC for domestic users

Slovenia is encouraging the formation of EC in order to tackle to issues in the country: the steady increasing of energy poverty and the lack of investment in RES [40]. The Slovenian law allowed in 2019 the establishment of so-called EC, in which collective self-consumption is allowed within its boundaries, defined by the transformation station. While these EC are aimed mainly to domestic users, the RES production unit can belong also to a third party, that agrees to take part in the community.

Spain - Nearby collective self-consumption

While EC per se are still not recognised in Spain, on April 2019[7] was allowed for active users to share their surplus energy among other users in the same building and nearby users connected by the low voltage network. The shared energy is exempted from charges and taxes.

United Kingdom – The regulatory sandbox

Even though the UK is no more a Member State of the EU, it was present during the drafting phase of CEP and followed the creation of EC. As a consequence, it is still notable of a mention. Ofgem (Office of Gas and Electricity Markets, the British regulatory authority) allows temporary regulatory sandboxes to innovators so that they can trial new business models with some exceptions in the rules applying. Ofgem grants the possibility to create a sandbox only if a licensed company is involved. The project has to be totally innovative, include a limited number of users and bring benefits and protection to them, and it has to be active for a maximum of two years. The innovators have to report the lesson learned to Ofgem in order to consider these results for future policies [41]. The projects implemented so far within the sandbox focus on P2P energy trading, community energy infrastructures to lower users' energy bill and prosumers development in general. Ofgem is satisfied of the lessons learned so far and will continue this trial approach [42].

1.5 Energy communities in Italy

The following Section will focus on the development of EC 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 EC. Self-consumption systems' definitions and incentives will be analysed in depth. In the second part of the Section, we will investigate the documents and

[7] Royal Decree 244/19

the laws recently written and concerning the reception of the CEP in the Italian legal system. A proposal for the possible regulation of the incentives for EC is then presented at the end.

1.5.1 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. This data shows how self-consumption is not still bounded to renewable energy, rather than a coexistence between producer and consumer. From another point of view, the Italian Gestore dei Servizi Energetici (GSE) can provide more accurate esteems for small PV generation. In 2018, 22,7% of the total production from PV was self-consumed mainly from small-medium sized plants owned by industries or domestic users. Almost 9.000 MW of PV capacity is installed for self consumption with a non-homogeneous distribution in the country: 57% in the North, 16% in the Center and 27% in the South [43].

Generally speaking, the configurations allowed by law for self-consumption can be divided into two main categories [2]: *Closed Distribution Systems*, in Italian Sistemi di Distribuzione Chiusi (SDC) and *Simple Systems of Production and Consuption*, in Italian Sistemi Semplici di Produzione e Consumo (SSPC).

As Figure 1.3 reports, 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 some to identify any possible similarity with the energy communities presented in the CEP.

The SDC are the result of the transposition into national law of the directive 2009/72/CE in the third energy package [8] and their definition has been recovered in the RED II of the CEP[9]. SDC are private grids distributing electric energy within a restricted geographical area. SDC can be located in industrial or commercial sites, railways, airports or hospitals but its extension cannot exceed the local level. This is motivated by the fact that for specific technical or safety reasons, the operations or the energy production system is integrated to the final consumers. Domestic users are not allowed to join SDC. It is important to highlight that currently in Italy the creation of new SDC is forbidden as their definition covers only systems that were already existing at the moment the definition itself came into effect. Due to this reason and due to their very narrow field of application that excludes domestic users, SDC are not compatible with energy communities.

SSPC are electric systems connected to the public grid, characterized by the direct connection of an electric power plant and a consumption unit, which can consist of one or more buildings. In SSPC the grid does not fulfill an activity of transmission

[8]see Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC, Article 28

[9]see Article 38

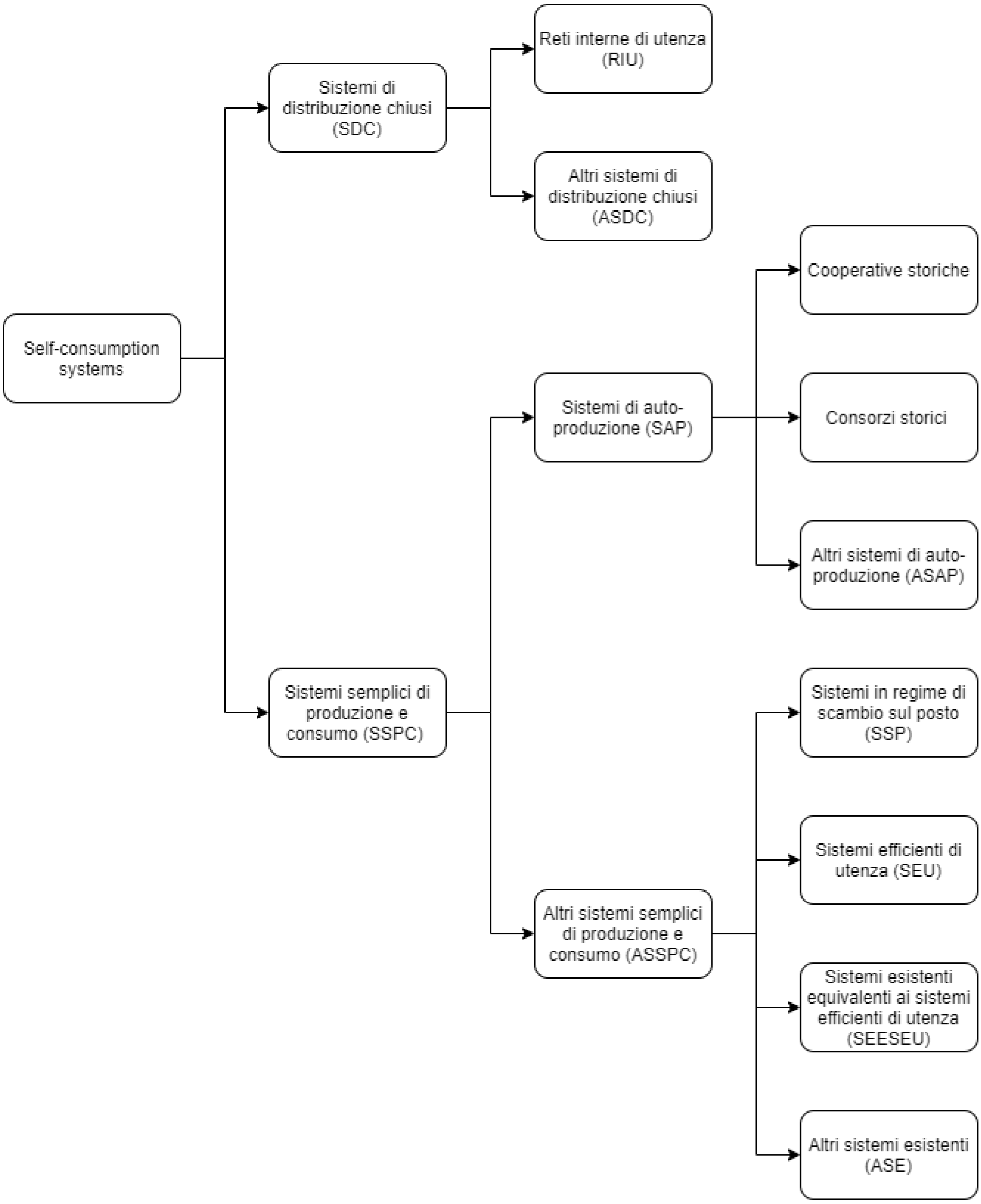


Figure 1.3. Classification of self-consumption systems in the Italian framework

or distribution, but it is considered as self-supply. The sub-category of the SEU is the more spread among the SSPC and consists in a *one-to-one* configuration, so that 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 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. only the payment of the price of energy, excluding transmission, distribution and system charges and excises) while the other users have to pay the full electric bill.

Historic cooperatives (*cooperative storiche*) are a sub-set of SSPC, result of a historical tradition that has survived the nationalisation of the electricity market, whose particular characteristics, different from the self-consumption systems seen so far, are similar to those presented in the CEP for energy communities.

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. Over the year, cooperatives explored other sources of renewable energy such as PV or, recently, wood biomass. Due to a massive utilization of non-programmable RES, they were ultimately connected to the national grid, to allow a continuous supply of electric energy.

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 "historic cooperatives" during the liberalization phase. Nowadays, historic cooperatives are defined as a kind of electric operator that represent an association with voluntary participation of members, aimed at the production and consumption of electric energy. Historic cooperatives are regulated by Autorità di Regolazione per Energia Reti e Ambiente (ARERA) with a resolution approved in 2012[10]. Historic cooperatives are allowed to exist in the national framework as energy producers and distributors both to members and non-members of the cooperative itself. As a matter of fact, due to the existence of the distribution grid owned by the cooperative, it would be technically as well as economically inefficient to build a duplicate of the grid in the same territory.

With respect to definitions seen so far, historic cooperatives cannot be categorized as SDC because they connect mainly domestic users and they are connected to the system in low/medium voltage. Moreover the generated electric energy is not essential to industrial processes. On the other hand, historic cooperatives connect a plurality of generators with a plurality of final users, represented by cooperatives and consortiums so that the configuration remains formally *one-to-one*. Furthermore, the grid of the historic cooperatives:

- can be owned by or at least under concession to the cooperative itself and provides energy to members and non-members;
- is connected to the national grid allowing continuity of supply even without

[10] see Testo integrato delle disposizioni dell'Autorità per la regolamentazione delle cooperative elettriche (TICOOP)

self-production.

Due to these characteristics, and the mainly renewable nature of their sources, historic cooperatives are really similar to the definition of energy communities.

For the sake of completeness, it is also right to mention the category of new electric cooperatives (*cooperative elettriche di nuova costituzione*), that were born after the nationalization of the energy sector and aim to provide its 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.

1.5.2 Incentives

In the Italian regulatory framework, are foreseen a plurality of mechanism to encourage self-consumption from RES that can lead mainly to three benefits [3]:

- *Exemption of the variable costs of electricity* for self-consumed energy.
- *Valorization of the energy injected into the grid* with mechanisms such as *Scambio sul posto* or *Ritiro dedicato.*
- *Fiscal benefits* with the detraction from taxes of 50% of the investment on the plant.

Before explaining in more detail the mechanisms of incentive for self-consumption, it is useful to describe the composition of the electricity bill in Italy and identify its items.

The Italian electricity bill

The cost of electric energy in the bill consits of a fixed share $\left[\frac{€}{year*POD}\right]$, a power share$\left[\frac{€}{year*kW}\right]$, which depends on the power employed in the contract, and a variable share $\left[\frac{€}{kWh}\right]$ that depends on the energy consumed.

The electricity bill can also be brokendown in items of costs:

- Wholesale cost of electricity (*Spesa per la materia energia*)
- Network costs (*Spesa per il trasporto, la distribuzione e la gestione del contatore)*
- Operating costs (*Oneri generali di sistema*)
- VAT and excises (*IVA e accise*)

Figure 1.4 represents the average breakdown of the energy bill for a typical domestic user with 3 kW of employed power and 2.700 kWh of annual demand. The esteem was evaluated by ARERA [44].

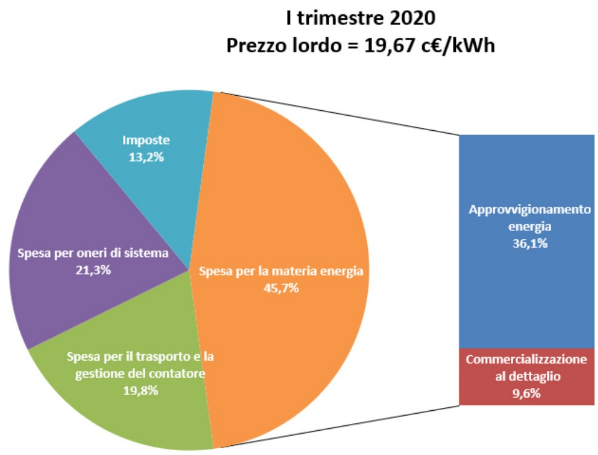


Figure 1.4. Average breakdown the energy bill for the domestic energy user [44]

The wholesale cost of electricity includes the cost of production of the electricity and its commercialization by the retailer. The effective cost of electricity can be further divided into time bands, depending on the type of contract. The composition of this item of cost depends if the user has a contract taken in the free market or in the protected regime (*regime di maggior tutela*). The network costs cover all the costs related to the activity of the Transmission System Operator (TSO) and the DSO. The operating costs consist in all the expenses for activity of public interest in the energy field, such as the incentives for renewables or high efficiency cogeneration.

The following Figure 1.5 is taken from the website of ARERA and shows the electricity bill of the first trimester of 2020 for a domestic user that has a contract in the protected regime [45].

1 gennaio - 31 marzo 2020	**Materia energia**			**Trasporto e gestione del contatore**	**Oneri di sistema**
	Monorario	Biorario			
	fascia unica	*fascia F1*	*fascia F23*		
Quota energia (euro/kWh)	0,07092	0,07666	0,06799	0,00833	0,041817
Quota fissa (euro/anno)	51,1409			20,4000	-
Quota potenza (euro/kW/anno)	-			20,8800	-
Sconto bolletta elettronica	*Ai clienti che ricevono la bolletta in formato elettronico e la pagano con addebito automatico è applicato uno sconto di 6 euro/anno.*				

Figure 1.5. Example of an electricity bill for a domestic user

Exemption of the variable cost of electricity

In case of an active user, the self-consumed energy is exempted from the variable costs in the electricity bill of the items of wholesale cost of electricity, network costs and operating costs[11]. As a consequence, the more energy is self-consumed, the more the user can save money in the bill. The amount of money that can be saved on the

[11] see DL 244/2016 (decreto milleproroghe 2016)

variable cost of energy has been addressed in literature as Self-consumption Saving index (SCSi) [4].

Valorisation of the injected energy into the grid

Scambio sul Posto (SSP), or in English *on-site exchange* is a self consumption mechanism that allows to value the electric energy produced on site. It is for all intent and purposes a net metering tool for "storing" in the national grid the electric energy produced, but not self consumed, and use it again in a different moment.

The mechanism is regulated by ARERA and was established from 2007 with the *deliberazione 28/06* but it was later innovated in 2013 with the *deliberazione 570/2012/R/efr*. The yearly grant that values the injected energy is instead recognised by the GSE. The technical rules [46] issued by GSE define the targeted users for the SSP and the equations needed to compute the energy and cash flows. The SSP can be provided to users able to self consume the energy in the same place where it is produced (in the Italian framework: *Altro Sistema Semplice di Produzione e Consumo*). The energy has to be produced by a renewable energy source with an installed capacity less or equal to:

- 20 kW if the plant came into operation before 1st of January 2007.
- 200 kW if the plant came into operation before 1st of January 2014.

In 2018, 656.717 plants benefited SSP with a total capacity of 5.6 GW and an energy flow of 2.4 TWh. Almost all the plants were PV systems of which 83% owned by domestic users connected to low tension [47].

Ritiro dedicato (RID) or in English *dedicated withdrawal* is a simplified mechanism of commercialization of energy that interposes the GSE between the energy producers and the electric system with uniform and transparent rules on the whole Country. It is regulated by ARERA with the *Deliberazione 280/07*, starting from January 2008.

With the RID, the energy producers can sell the electricity to the GSE as an alternative to bidding it in the energy market. Any plant with a maximum power below 10 MVA and any plant working with RES (if it is not already benefiting of other incentives, such as feed-in tariffs or SSP) can access to the RID. The GSE buys the energy at the hourly zonal price and resells it in the market. A special minimum granted price (*prezzo minimo garantito*) is recognised to the first 1,5 GWh of electricity produced in a year by a plant running on RES with a nominal capacity below 1 MW. The minimum granted price of 2020 is adjusted every year and it is different for every RES.

In 2018, the GSE withdrew with the RID 10,5 TWh of electric energy, produced by 49.264 plants with a total power of 8,7 GW. The minimum granted price was recognised by 1,9 TWh of electric energy 73% of which coming from PV plants [47].

Fiscal benefits

The installation of a PV on a domestic roof and an eventual storage system connected to it is contemplated in the context of building renovation works for efficiency for which are available fiscal benefits regulated by the Italian Tax Agency[12] (*Agenzia delle entrate*). The benefit consists in a fiscal detraction of the income tax (*imposta sul reddito delle persone fisiche or IRPEF*) equal to 50% of the initial investment spread over 10 years. The current law allows also entire apartment building to benefit this detraction, if on its roof a PV system is built, that powers the common appliances of the block.

1.5.3 Transposition of the CEP into national law

Italy, as the other European Member States, has time until the 30th June 2021 to transpose the Directives of the CEP into its national law. EC are being debated by different organisms in the Italian legal system. The Government mentioned their interest in EC in their Energy strategy report published in 2017 during the drafting phase of the CEP and committed itself in establishing EC in the Integrated National Energy and Climate Plan of December 2019 asked by the EC. The National interest culminated in the writing of the first law that recognises EC in February 2020. At a lower level, three Regions promulgated Regional laws establishing EC in 2019. Meanwhile in March 2019, the energy Authority expressed its opinion regarding EC and incentives.

The National strategy

The *Strategia Energetica Nazionale* (SEN) and the *Piano Nazionale Integrato per l'Energia e il Clima* (PNIEC) are two documents born from different necessities, which delineates 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 [48]. On the other hand, the PNIEC is required from the Regulation 2018/1999[13] 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 measures in the matter of energy aligning with the EU policies [49]. 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 (remember that 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 the matter of incentives for self-consumption, the SEN judges the aforementioned exemptions of the variable

[12] see art.16 bis D.p.r 917/86, Testo unico delle imposte sui redditi

[13] see Governance of the Energy Union and Climate Action Regulation (EU) 2018/1999

cost of electricity for self-consumed energy 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 bill as they will cover less the costs of transmission and more the cost to assure security of supply for distributed generation systems.

The PNIEC reiterates the concepts expressed by the SEN by classifying the energy communities in the framework of the development of distributed generation, 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 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 [50]. The energy Authority ARERA published then a report, stating its opinion on the consultation, in order to be transmitted to the Government [14]. 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 warns 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 Regional laws

After that the CEP came into force, three Italian Regions anticipated the National legislator and are promulgating Regional laws for the establishment of EC on their territory. The concerned Regions are Piedmont[14], Apulia[15] and Sardinia[16]. The three laws are very similar in the form and highlight the interest of local authorities for EC. As a matter of fact, Regions 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 [51].

The laws recognise EC as legal entities in the modalities delineated by the European Directive, even if there is not yet 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. The definition of support schemes is left to further laws.

The National law

On first March 2020 came into force the first law that transposes Article 21 and Article 22 of the RED II, concerning self-consumption and Renewable Energy Communities [17]. In particular the law allows to establish collective self-consumption and RECs in a transitional regime that, with the same intents of the British *sandbox*, will be useful to obtain lessons from the regulatory point of view and study the reactions of the various stakeholders, such as citizens and network operators.

Focusing on RECs, the law confirms the social purpose of the entity and the ownership limited to citizens, local authorities and SMEs. Moreover, electric energy must be produced only by plants powered by RES that came into force after 1st March 2020. 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 transitory regime as a tool for creating new RES capacity [52]. 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. From the energy point of view, users share energy through the existing distribution network and regulate their internal sharing via private contracts. The energy withdrawn from the grid will be charged with the individual contracts between the members and their retailers. ARERA holds the job to regulate and define the tariffs of the components while the Ministry of Economic Development will identify an incentive tariff to reward instantaneous

[14]see *Legge regionale 3 agosto 2018, n. 1223*

[15]see *Legge regionale 9 agosto 219, n. 45*

[16]see *Proposta di legge del 4 settembre 2019*

[17]see Legge 28 febbraio 2020, n. 8 *Conversione in legge, con modificazioni, del decreto legge 30 dicembre 2019 n.162 recante "Disposizioni urgenti in materia di proroga di termini legislativi, di organizzazione delle pubbliche amministrazioni, nonché di innovazione tecnologica", Articolo 42bis: Autoconsumo da fonti rinnovabili*

self-consumption and to ensure return of investment.

General provisions	RECs are established in an experimental regime
Modalities	RECs are formed by citizens, local authorities and SME whose participation is not the main commercial activities. Only new RES plants can generate electricity in a REC
Rights and duties	RECs' member detain their rights as end customers.
Energy treatment	Energy must be shared using the existing distributing network and it is regulated by private contracts among members.
Regulating regimes	ARERA will regulate tariffs components for shared energy.
Supporting regimes	The Ministry of Economic Development will define incentive tariffs to reward internal consumption.

Table 1.2. Summary of law 8/2020

Possible future tariffs for EC

Taking the whole legislative process into consideration, it is clear that the incentives granted to EC will be a pivotal issues that might encourage or hinder their development in the energy system. Even though self-consumption system and EC are strictly related from the technological and legislative point of view, a decoupling will be seen in their regulation as stated by ARERA.

So while it is possible that EC will initially follow self-consumption system in the application on implicit incentives on shared energy with exemptions of variable energy's item on the electric bill, in a second moment EC will receive their dedicated explicit incentives, seen as a feed-in tariff on the energy internally consumed. In the matter of implicit incentives, ARERA expressed itself negatively on leaving a complete exemption on variable energy items, saying that while it is reasonable to exempt network costs due to a lack of use of the networks, operating costs are not cost reflective of the benefits brought by decentralised energy. If this exemption is left as it is, the market might be distorted and the other users of the system will be forced to pay higher operating costs in their bills. In any case it will be necessary to define an incentive that will be cost reflective of the benefits that EC bring to the electric system. On this matter, explicit incentives are easier to keep track of and can be differentiated depending on the technology used. These incentives can be appropriately controlled and modified to lead these technology towards market parity.

In this thesis, we will take into account the possibilities foreseen by the Authority on short-term and long-term. We will therefore consider implicit incentives similar to the ones granted to self-consumption systems and independent explicit incentives.

ARERA consultation document of 1st April 2020

On 1st April 2020 ARERA published a consultation document that defines the energy Authority's guidelines for the economic regulation of EC, taking into account the aforementioned law published on the 28th February 2020 that establishes the transitory regime for REC [53]. The guidelines of ARERA on regulation of EC contained in the consultation document, define with precision the level of exemptions that an EC should get and the explicit incentive given by the Ministry of Economic Development.

First of all, the Authority sets up a so-called "virtual" regulatory model, meaning that the formation of a REC is not physical but relies on abstract agreements. The virtual model avoids to build new distribution grids, enhances the freedom of choice of the configuration for the final users and allows these new configurations to be implemented in a short time, in line with the objectives of the transitory and experimental regime set by law 8/2020. In particular the virtual model allows users to keep their connection to the public grid and their electricity retailer, but allows them to access a REC anyhow. Moreover, it foresees the restitution of the exempted voices of the electric bill and the release of the explicit incentives from the GSE.

As already mentioned in this thesis, the exemptions of shared electricity on the bill should be cost reflective of the benefits brought by EC on the electrical system. In particular the Authority founds reasonable to exempt the variable components in the electricity bills of the items of transmission and distribution. This is thanks to the local dimensions of REC (remember that law 8/2020 limits REC under the same transformation station of low/medium voltage) that allows to avoid the majority of transportation losses. However the exemption granted to REC is lower to the one recognised to collective self-consumers, because the former use the distribution grid (thus creating some sort of loss), while the latter are confined to the same block or multi-block. On the matter of explicit incentives recognised by the Ministry of Economic Development, it is the Authority's opinion that the incentive should be a premium on the energy internally consumed within the community, equal to the difference, on an hourly basis, of an incentive tariff recognised by the Ministry and the zonal price. This incentive should make profitable the investment on a REC and encourage the energy sharing within communities.

Even though this document was published at the end of the writing process of this thesis, its content confirms the line of reasoning adopted throughout this research work.

Chapter 2

Socio-technical analysis of energy communities

The previous Chapter showed that, while EC will bring in the European panorama new opportunities and benefits, experiences of community energy or co-owned energy projects are not new among European Member States. This Chapter will focus on presenting the benefits of existing community energy projects that will be for extension the benefits of EC. Business models of existing projects are also presented, to have an idea of the size and the current type of organization that is present in Europe nowadays and that will lead to the future EC. Moreover, an overview of the technology that characterises distributed generation and micro-grids is presented. Lastly, we will classify elements of game theory applied to community energy projects to understand how cost and profit could be allocated within members.

2.1 Social benefits

The diffusion of energy communities will have a great impact in bringing closer the European citizens to renewable energy projects. It was already mentioned that the development of energy communities will achieve the democratization of energy. This means that the people that are affected in some way by the implementation of an energy related project, will be able to take part in the decision-making process, own a share of the project and enjoy its economical profit and environmental achievements [5].

Past experience taught that social acceptance could be hardly achieved if the community is involved at a late stage of development of the project. In [6] it is stated that many renewable projects that had issues with the local population, confronted both the well known NIMBY ('Not in my backyard') syndrome, as well as an opposition born from the feeling of exclusion felt by the locals towards the project designers during the decision-making process and the feeling of being 'forced' to passively accept the project. On the other hand, community owned energy enables citizens to have decision-power over the investments and become co-owners of the renewable project. Moreover, their involvement can overcome the resistance to any inconvenience the project might create [23].

Moreover, being part of a community devoted to clean energy and social justice favours the development of a positive feeling that encourages participation and volunteerism [7]. In the matter of the engagement, being in an EC awakes the awareness of the member towards energy consumption and might lead to a change in the behavioural lifestyle with action such as load shifting, lower consumption, improvements in energy efficiency or the will install new renewable generation capacity [7]. Furthermore, being part of a community that promotes RES, install in its members the consciousness of exercise the right to chose where and how they get their energy from.

In many projects, new jobs are created to manage and operate the plant. In addition, communities may choose to use local manpower and local technology when possible, thus creating additional value by investing in the resources in the area and indirectly creating new jobs in other sectors of the supply chain [5]. The investment is shared among the members of the community, creating a local scale economy. The surplus generated by revenues is seen less as an exploitation of the territory and it can be use to foster educational and innovative activities that benefit the members [8].

Lastly, but very importantly energy communities have the power to address the issue of energy poverty due to their non-profit nature. A global definition of energy poverty is the lack to the access to modern energy services and it is often used as a development indicator. In developed countries such as the Member States of the EU, the term describes the situation happening to low-income households that do not have enough money to cover their energy needs [8], such as keeping their house warm or paying the electricity bills. EC can undertake this problem by performing energy efficiency measures to decrease consumption, reduce energy supply tariffs for vulnerable households or establish a fund within the community to help needing neighbourhoods.

2.2 Business models for energy communities

There are many forms that an EC can assume, depending on the level of involvement of the stakeholders in the project, the initial capital, the characteristics of the area taken into account. Existing projects of community energy felt the need to be recognised in a range of different legal forms that define the ownership model, individual liabilities and the rights of each shareholder. The following classifications will first take into account the legal form of community energy project then they will be classified by size.

The most common ways to organize community energy are hereby presented as reported in [54] and [23]:

Co-operatives: membership is open and voluntary. Control is in the hand of the members and based on the democratic principle of *one member-one vote*. The purpose of the co-operatives is to benefit the local community as a whole or just their members. Members have the right to receive education and training, especially if they play an active role within the organization. Profits are re-invested to improve the activities of the co-operatives.

Partnerships: a partnership is an enterprise with the purpose to profit, while generating energy. The governance, and consequently the vote power, is determined on each partner's stake. Members receive a revenue from the profits of selling energy and management is delegated to a board of executives.

Community trust and foundations: this organization is based on the charitable non-profit model, with the purpose of achieving social benefit for the community rather than a profit. In this way, less advantaged citizens that cannot afford to participate can still receive the welfare created by the foundation.

Non-profit customer-owned enterprises: these business models are considered ideal for community projects in which a small distribution grid is owned by the organization itself, for example in the case of remote and quasi-isolated areas. The members of these enterprises are the users connected to the micro-grid and the revenues are used to benefit the local community by maintaining a reliable and affordable distribution system.

Municipal ownership: in some European countries, public utility companies are allowed to participate to energy services activities. Potentially, municipalities can have a strong role in the diffusion of community energy as they are the result of a democratic mechanism that led to their creation. However, transparency and accountability should always be assured.

Public-Private Partnership: this business model is considered optimal to balance the efficient use of local resources and promote community benefits. Public entities can create formal partnership with community groups, private enterprises or NGOs with the purpose of achieving common good.

A study made by REScoop, the federation of European energy cooperatives, classifies the cooperatives within its network based on the size of the project and number of the members working on it [55]:

Local group of citizens it is a group born from the necessities of a local community and it is managed from the members of the community itself, usually in a voluntary form, as it has no paid employees. The projects have a limited size, with a local impact and can consist of the installation of PV on roofs or micro-hydro power plants.

Regional-national renewable energy cooperative: it can be seen as the natural evolution of the previous category when it develops in a mix of energy-related activities or an articulated portfolio of plants from renewable sources. This implies that the cooperative is spread in a regional or national area.

Fully integrated renewable energy cooperative: energy production, distribution and supply are done by the same cooperative that can operate in autonomy, thanks to a large amount of self-production. These cooperatives are the heritage of old energy companies that survived the first nationalization and the liberalization and unbundling of the market.

Network of renewable energy cooperatives: this business model is based on a main, big cooperative that creates spin-offs communities by sharing capital and experience. Scale economy and expertise allow these spin-off to grow and become competitive. Once they become autonomous, an extensive network of cooperatives is created.

Multi-stakeholder governance model: the cooperative plays the role of aggregator for all the companies involved in the energy sector, from the producer to the consumer or the expert of energy services. The geographical scale can be local as well as national, through a pyramidal scheme.

2.3 The technology dimensions in energy communities

The technological components existing in an EC will vary depending on the characteristic of the area, social background and laws and regulations of the Member States. However, technology availability and readiness will be essential to allow communities to perform energy services activities as foreseen in the CEP.

Technology assets can be divided into three layers that are common to the most kinds of energy community [9]:

- Physical energy assets
- Information and communication technologies (ICT)
- Grid connection

2.3.1 Physical energy assets

Physical energy assets comprehend the means for distributed energy generation, such as PV panels, wind turbines, cogeneration plants and means to provide energy services such as batteries, electric vehicles and so on. As the analysis of this thesis will focus on REC with photovoltaic systems and storage, a more detailed review of these technologies is hereby presented.

Photovoltaic systems

Photovoltaic (PV) technology allows to directly convert the irradiance of the sun into electric energy through the so-called photovoltaic effect, a property possessed by certain semiconductor materials. A PV system is composed by elementary PV cells, grouped in modules and then in arrays and auxiliary components such as inverters and controls. PV cells are classified in "generations" depending on their basic material and commercial development [10]. *First generation* PV cells are well rooted in the market and rely on wafer-based single or multiple crystalline silicon technology. *Second generation* PV cells are in early commercial development phase and rely on thin film technology and can potentially be cheaper than the dominant silicon technology. The main disadvantage is the steady reduction in efficiency over time. *Third generation* PV cells are still under development and yet to be fully commercialized, comprising concentrating PV and organic solar cells. The maturity of the technology and the modularity of PV system, combined with the abundance of silicon and low maintenance costs are the reason of their fast development of first generation PV within the energy sector.

Energy storage systems

The unpredictability embedded in the electricity generation from RES, will lead EC to equip with energy storage systems that will allow to meet the local demand. The research presented in [11] provides an extensive overview for hybrid systems comprising solar photovoltaic and electrical energy storage technologies for the use in buildings. Among the mechanical storage technologies, flywheels, thanks to their high power density and discharge rate, could smooth the production curve from PV in the central hours of the day and release electricity during peak loads hours. However, the large space required for the installation and cooling system, combined to a large investment cost may hinder its use in EC. On the other hand, pumped hydro storage and compressed air storage are reliable and mature technologies that can store a large amount of power, however their presence in EC is too location-specific. Supercapacitors could act as complementary to other storage systems thanks to their fast charging time and efficiency. Battery Energy Storage Systems (BESS) are the most common among building integrated storage technologies. While lead-acid technology were popular thanks to their low investment and maintenance costs and high efficiency, lithium-ion batteries are taking an higher share of the market due to their high depth of discharge and long operational life time. The main barrier for lithium-ion battery was its investment cost, that is reducing of almost 20% per year [20] making it the most competitive technology.

2.3.2 ICT

Are part of the ICT layer all the components, physical and virtual, that allow to measure and manage the energy flows in and out the community. The smart meter for example is an important tool for the ICT platform that allows consumers and network managers, DSO or aggregators, to keep track almost instantaneously of production and consumption in the community. The smart meters roll-out is at different levels among Member States, with Italy being the first European country to perform a large-scale roll-out for low voltage users and its the first Country in the World for the number of smart meters installed [12].

The ICT layer also groups all those hardware and software that allow communication between the users of the community and allow energy trading among members in the cases the community is organised with an internal market. The internal market might take the shape of [56]:

- Full Peer-to-peer (P2P) market
- Community market
- Hybrid P2P market

In full P2P markets, members agree to establish a transaction in exchange for a certain amount of energy without a third-party supervision. A market ruled by the law of demand and supply is established within the community in which members act to maximise their individual profit. The behaviour of the community members can be described by non-cooperative game theory as it will be done in the first part of

Section 2.4. The main advantage of full P2P markets is the full democratisation of energy found in the freedom of choice of community members. On the other hand, a great computational burden is asked to keep track and perform real time transactions. In community markets on the other hand, members are supervised by an aggregator or community manager that menages the tradings within the community. As in this case, energy and infrastructures can be shared, the economical transactions are cost or profit allocations within the members. A community of this kind can be described by cooperational game theory as in the second part of Section 2.4. The hybrid configuration is created when there are different layers of energy markets. An example might be an electric system in which communities, ruled by community market, interact with the other actors of the system through P2P market.

2.3.3 Grid connection

The access to the national or a private grid is an essential prerequisite for the development of EC, that can become a true barrier if it is costly, lengthy and complicated. A CEC can own its distribution network or it can just use the public one, when present. This is not a threat for DSOs, for which new opportunities arise in fulfilling new roles such as three-party intermediaries between community members, network and market operators [13].

The development of EC will bring various disruptions in the daily operations of distribution and transmission networks. At a system level, the electricity produced on site within EC reduces its flows on the network, thus decreasing the network and transformation losses. Moreover, less investments on new networks or on network revamping could be done by DSOs as the distribution networks are designed on the maximum power at the connection points. Nevertheless, dispaching costs are not necessary reduced as the TSO has maintain some reserve capacity, in order to safely operate the system even when the production in EC is null [14]. At a local level, EC can offer balancing services and increase the demand flexibility, with the use of storage systems and the future use of electric vehicles. Moreover citizens involved in EC are expected to take an active part in demand response activities, as they are more engaged within the energy field [8].

2.4 Taxonomic analysis of game theory

The formation of EC is considered a potential tool to promote and increase the utilization of renewable energy at a decentralized level. The disruption of the centralized electrical infrastructure will lead to a direct communication between active and passive users within the energy system as interested consumers will be able to purchase cheaper energy (i.e. sold at a reduced price) from a prosumer that has a surplus in its renewable energy self production.

The engagement of the users without any intermediaries raises the need to model the decisions of each participant in order to achieve the greatest benefit of the community, but also taking into account human aspects such as personal interest, selfishness, environmental awareness and motivations. These factors can eventually lead the participating users into conflict, or in the will to form a coalition to achieve the desired objectives, such as minimization of costs, maximization of profit or utilization of renewable energy [57].

Taking this challenge into consideration, game theory is an effective tool to address the interactive nature of energy sharing. In order to outline a clear and synthetic description of game theory, the book *Game Theory, analysis of conflict* by R.B. Myerson was mainly used as reference [58]. The same book provides an initial definition of the game theory:

> *The study of mathematical models of conflict and cooperation between intelligent rational decision-makers. Game theory provides general mathematical techniques for analyzing situations in which two or more individuals make decisions that will influence one another's welfare.*

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*. It has to be said that the utility function has not to be purely monetary, as the utility can be seen by the player as something not measured in coins. The players are also said to be *intelligent*, ad 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 that define 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 [59].

The next paragraphs will present a synthetic but comprehensive classification of the various declinations in game theory. An overview of such classification is shown in Figure 2.1. In parallel with the main categories present in game theory, the applications of such models and frameworks in the energy management of small scale power systems are also offered.

2.4.1 Non-cooperative games

In non-cooperative games the players are independent and choose their strategy, the maximization of the 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. Non-cooperative games are categorised into *static* and *dynamic* games.

Static games are characterized by the fact that the players can make their decisions only one time in the game (at the same time or at different moments), while in

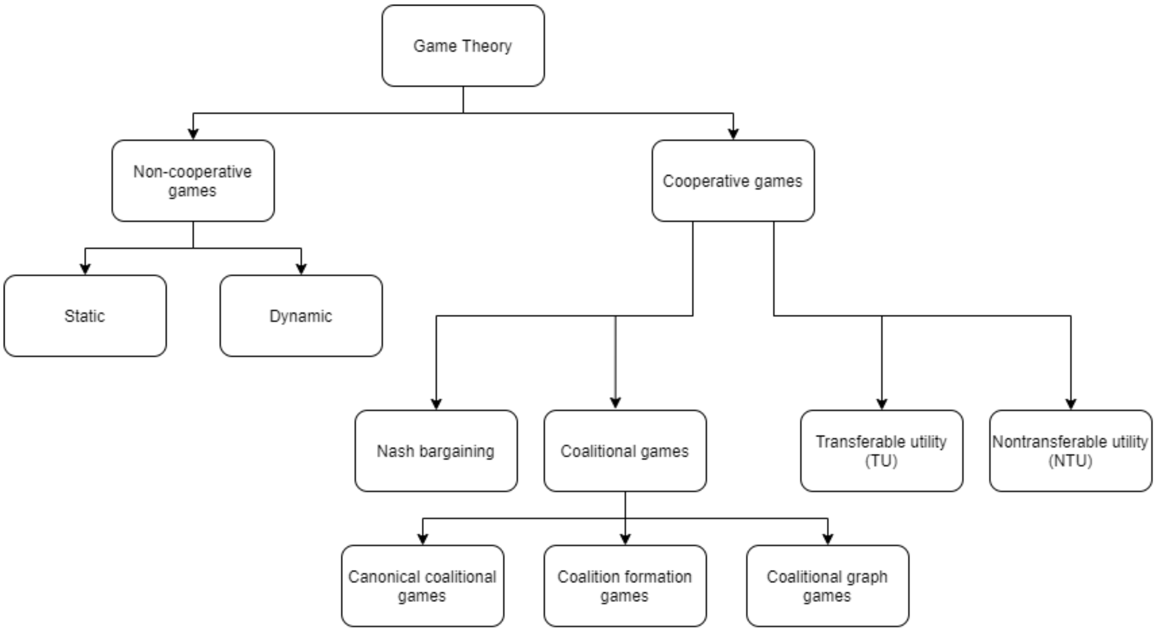


Figure 2.1. Overview of the classification made by the author

dynamic games the players act more than once and can acquire information about the moves of their opponents. 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 players have to select an appropriate action in the set $a_i \in A_i$ so that its utility function will be maximised $u_i(a_i, \mathbf{a_{-i}})$. Nevertheless the utility function does not only depend from the individual action of the player a_i, but also from the array of actions of the other $N \backslash \{i\}$ players $\mathbf{a_{-i}}$.

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 $\mathbf{a^*_{-i}}$:

$$u_i(a_i^*, \mathbf{a^*_{-i}}) \geq u_i(a_i, \mathbf{a^*_{-i}}) \quad \forall\, a_i \in A$$

2.4.2 Non-cooperative games applications in community energy

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.

Nash equilibria are found to find a stable state between the users, so that they all individually improve their utility. In [60] 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 Nash equilibrium takes into account the fact that if too many batteries are present, the system might become too much unpredictable, thus making ineffective the spreading of storage devices.

[61] provides 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 adeguating their power to the actions of the other players. The Nash equilibrium is found when no player has an incentive to change its power control strategy.

Moreover, some specific declinations of non-cooperative game theory are also considered in literature, in order to better analyze some particular situations. As an example, [62] studies an isolated microgid 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.

[63] proposes a mechanism to encourage users in a smart grid to actively participate in energy trading with a central power station. 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).

2.4.3 Cooperative games

Cooperative games are characterized by the possibility of communication between the players. In particular, the players decide to form coalitions between them 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 a 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, in *coalition games* is studied 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. It can also happen that the utility function cannot be described by a finite number, as in the case of games with *nontransferable utility* (NTU). The side-payment of each player is not determined by a rigid allocation rule, but it depends on the internal strategies used by the players inside the coalition [64].

Within the domain of coalitional games, it has been proposed a novel application-oriented classification [15]. The first class, *canonical coalitional games*, is the most understood, and hence formalized, and utilized in real applications. The latter two classes, even though their implementation and solutions are limited, are reported for the sake of completeness and for the interest they may have in future developments. The classes are summarised in Figure 2.2.

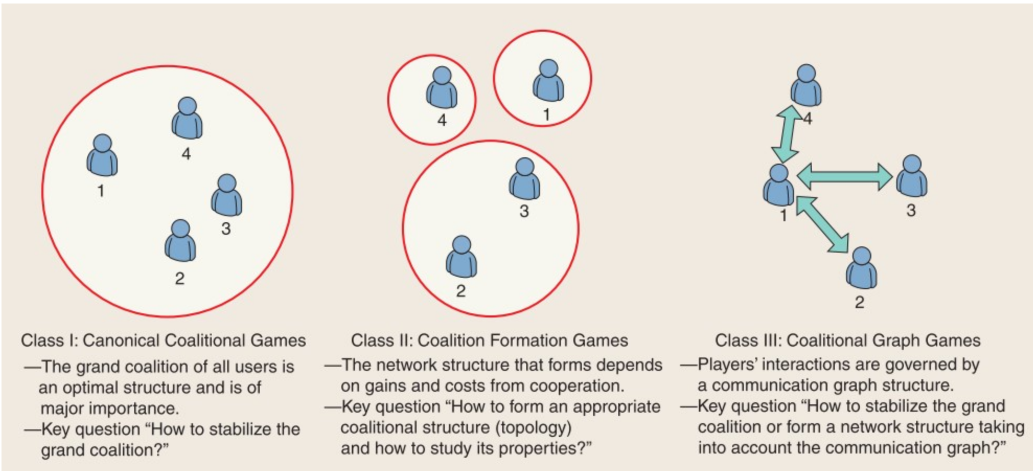


Figure 2.2. The classification of coalitional games as proposed in [15]

- *Canonical coalitional games*: in these games the costs of forming the grand coalition (the coalition comprehending all the players) are null or negligible, thus these games benefit the property of superadditivity (see 2.4.5. The objective of studying canonical cooperational games is to find a fair allocation rule that gives an adequate payoff to the players so that no one is incetivised to leave the coalition. The grand coalition is said to be stable and fair.
- *Coalition formation games*: these games are not superadditive as it may happen that the formation of a coaltion brings additional costs. Therefore, the aim is to study which coalition will be formed, with which size and with which characteristics.

- *Coalitional graph games*: this games are characterized by particular communication structures between the players, that will ultimately influence the formation of a certain coalition. The goal of this class is to study the architecture of these communication graphs, i.e. who is connected with who and at which level, and study the stability and efficiency of the formed coalitions.

Given the widespread use of canonical coalitional games in energy sharing application, this particular class deserves an in-depth description so to understand its characteristics. The coalitional game is uniquely defined by the pair $(\mathbf{N}, v(\mathbf{S}))$, where $\mathbf{N}$ denotes again the set of players and $v(\mathbf{S})$ is the value of the coalition $S \subseteq \mathbf{N}$. The payoff x_i of the player $i \in \mathbf{S}$, part of the coalition, is determined by an allocation criterion.

The *core* is a classical solution of the stability of a canonical game and delineates a space of solutions (i.e. payoffs) $\mathbf{x}$ for the members of the grand coalition $\mathbf{N}$, for which no player can receive any greater payoff in any other subset of the grand coalition $\mathbf{S} \subset \mathbf{N}$. In mathematical therms for a TU game:

$$C_{TU} = \Big(\mathbf{x} : \sum_{i \in \mathbf{N}} x_i = v(\mathbf{N}) \text{ and } \mathbf{x} : \sum_{i \in \mathbf{N}} x_i \geq v(S)\Big)$$

Nevertheless, a solution based on the core may comprehend many possible values for each players and these payoff may not reflect the most fair way to allocate the grand coalition's value.

In order to solve these problems the *Shapley value* was introduced, that reflects the most fair payoff for the players in the grand coalition, taking into account the marginal contribution of each player. In other words, in order to fairly allocate the coalition's value, the Shapley value takes into account the added value that each player brings to the coalition. Shapley value ϕ is expressed as:

$$\phi_i(v) = \sum_{S \subseteq \mathbf{N} \setminus \{i\}} \frac{|S|!(N - |S| - 1)!}{N!} [v(\mathbf{S} \cup \{i\}) - v(\mathbf{S})]$$

in which the marginal contribution $[v(\mathbf{S} \cup \{i\}) - v(\mathbf{S})]$ of the player i in the coalition $\mathbf{S}$ 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 $\mathbf{S}$.
The Shapley value definition is bounded to four axioms [65]:

1. *Pareto efficiency*: $\sum_{i \in \mathbf{N}} \phi_i(v) = v(\mathbf{N})$, the total value of the grand coalition is redistributed among the players.

2. *Symmetry*: if $v(\mathbf{S} \cup i) = v(\mathbf{S} \cup j)$ 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 $v(\mathbf{S}) = v(\mathbf{S} \cup i)$ then $\phi_i(v) = 0$, a player that does not contribute to the coalition, receives no payoff.

The Shapley value does not necessary lies in the core. Nevertheless, that might happen in some particular applications thus combining the stability of the core and the fairness of the Shapley value. One of the major drawbacks of the Shapley is its computational burden as the number of players inside the coalition increases.

Lastly, the *nucleulus* is another solution concept proposed to allocate the coalition value. Differently from the other concepts the nucleulus finds that payoff ripartition that minimises the dissatisfaction occurred in the player from such allocation.

2.4.4 Cooperative games applications in community energy

In the domain of cooperative games, Nash bargaining is employed to provide incentives to individual users to share their excess energy. In [66] 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 [67] 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 [68] is to form coalitions of microgrids comprising energy producers and energy buyers which 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. [16] 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. [65] 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 [69] 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.

2.4.5 Convex cooperative games

When applying the Shapley value to a cooperative game, it is important to verify that the game is *convex*, so that the Shapley value lies in the core and assures the most fair allocation of payoff. A game is convex if and only for each player $i \in \mathbf{N}$ the value of the coalition with the player is higher than without the player. In other words, a game is convex if the marginal contribution of each player is positive [15]. In mathematical terms, being $\mathbf{S_1}$ and $\mathbf{S_2}$ two coalitions so that $\mathbf{S_1} \subseteq \mathbf{S_2} \subseteq \mathbf{N}$:

$$v(\mathbf{S_1} \cup \{i\}) - v(\mathbf{S_1}) \leq v(\mathbf{S_2} \cup \{i\}) - v(\mathbf{S_2})$$

Convex games assures superadditivity, meaning that given a set of players the grand coalition will always form. Moreover, the core is non-empty and the Shapley value is in its center of gravity.

Chapter 3

Proposed methodology

The purpose of this thesis is to develop a methodology able to simulate energy fluxes of different configurations of users, comprising the single prosumer case and EC, and to compare the economic profitability of EC, with three different energy sharing strategies.

The implemented approach aims to describe in a reliable way the introduction of EC in the Italian scenario, thus the interactions of the users with the electric grid were simulated taking into account the Italian electric market and the support schemes currently regulated by the Italian energy Authority, as described in Chapter 1. In particular, stand-alone users benefit of support mechanisms such as *Ritiro Dedicato* or *Scambio sul Posto*, while EC will value their surplus energy by selling it in the market at the zonal price. Also, the valorisation of self-consumed energy and shared energy, that will eventually lead to the convenience of EC, is based on the domestic electricity bill.

Energy sharing in EC is modelled in three different ways: prioritising self-consumption, prioritising shared consumption, and utilising a battery. When considering the formation of EC from stand alone users, the allocation criterion of profits is based on the analysis of Game Theory of Chapter 2. In particular, cooperative games are used to describe interactions in EC and Shapley value is chosen to redistribute profit.

In order to optimally size PV and BESS plants, Mixed Integer Linear Programming (MILP) optimization algorithms were developed. MILP approaches are widely considered in literature and are appreciated for the formalisation in strict mathematical terms of the constraints, even at the expense of calculation time. Moreover,a plurality of MILP solvers is available. In the research of [70] a business model on optimized PV and wind system is considered. A formalization of the constraints for an energy mix optimization is provided in [71], while a sizing of a PV and BESS system is performed in [72]. In the model, the capacities are optimised to maximise the total Net Present Value (NPV).

As a last analysis is then useful to validate the assumptions made so far and compute their influence on the final outputs of this research, i.e. the NPVs of the different energy sharing strategies. For this purpose, an Uncertainty Analysis is developed, that creates the probability distribution of the output of the model, starting from the uncertainty of the input parameters. A Monte Carlo sampling method is used to select random values of input variables for many runs of the model, in order to create the probability density functions of the final results.

3.1 Energy sharing strategies

This section presents the energy balances and the relative cash flows for the determination of the monthly electricity bill for different configurations of users. Generally speaking, the section summarises the possible choices available to any user that aspires to become an "energy citizen". First, the stand-alone configuration is investigated, in which the user can only exchange energy with the grid. Different ways of valuing the energy introduced into the grid are considered, such as selling at the zonal price, *Ritiro dedicato* and *Scambio sul posto*. Then are identified different logics of energy sharing once the community is formed: first it is considered the prioritization of self-consumption by the user, while in another model it is assumed that the energy is completely shared with the community. This will lead to different savings in the electricity bill of the energy self-consumed and the energy shared.

3.1.1 Stand-alone configuration

Energy flows

Figure 3.1 shows that the stand-alone users have only energy exchange with the grid.

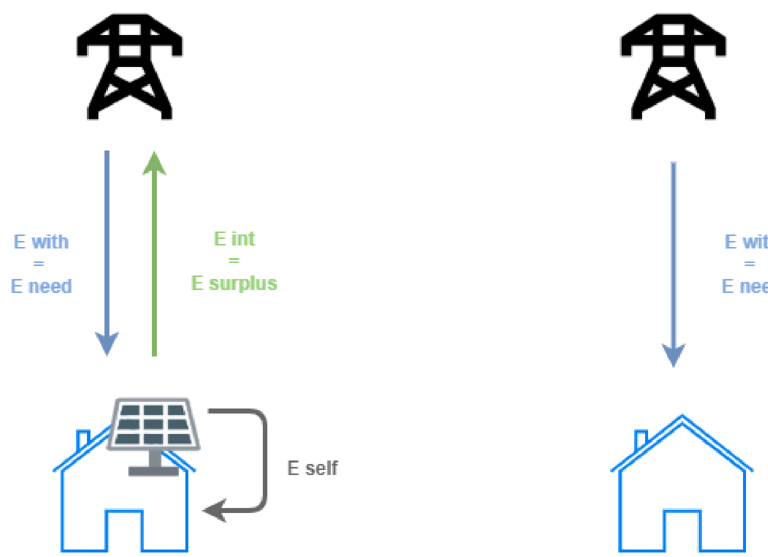


Figure 3.1. Stand-alone users

In particular, in every instant active users first give priority to self-consumption by consuming $E^{self}_{active}(t)$ and then the surplus energy $E^{surplus}_{active}(t)$ is injected into the grid as $E^{int}_{active}(t)$. In case the produced energy is null or not enough to satisfy the energy need

$E_{active}^{need}(t)$ of the user it is taken from the grid as $E_{active}^{with}(t)$. On the other hand, passive users satisfy their energy needs $E_{passive}^{need}(t)$ by collecting energy $E_{passive}^{with}(t)$ from the grid.

Generally speaking, for every user i, given at any instant its load profile $E_i^{load}(t)$ and its eventual generation profile $E_i^{gen}(t)$ we can compute its energy balance as:

$$E_i^{need}(t) = \begin{cases} E_i^{load}(t) - E_i^{gen}(t), & \text{if } E_i^{load}(t) \geq E_i^{gen}(t) \\ 0, & \text{otherwise} \end{cases}$$

$$E_i^{surplus}(t) = \begin{cases} E_i^{gen}(t) - E_i^{load}(t), & \text{if } E_i^{gen}(t) > E_i^{load}(t) \\ 0, & \text{otherwise} \end{cases}$$

$$E_i^{self}(t) = E_i^{gen}(t) - E_i^{surplus}(t)$$

In this simple reference case the energy exchanges with the grid are then:

$$E_i^{with}(t) = E_i^{need}(t)$$

$$E_i^{int}(t) = E_i^{surplus}(t)$$

Cash Flows

The electricity bill of each user is determined considering some fixed costs c_{fixed}, a cost c_{power} that depends on the power P_i employed by the users, and a variable cost c_{energy}^{grid} that depends on the energy withdrawn from the grid. The energy injected into the grid by active users is valued through a price $p_{sale}^{grid}(t, E_i^{int}, E_i^{with})$ that can eventually be a function of time and/or the energy exchanged with the grid, depending on the national legislation. The fluxes are shown in Figure 3.2. In Italy the valorisation mechanism are:

- Zonal price
- Ritiro dedicato
- Scambio sul posto

The total *monthly* bill received by user i, is thus computed as:

$$C_i = c_{fixed} + c_{power} * P_i + c_{energy}^{grid} * \sum_m E_i^{with} - p_{sale}^{grid}(t, E_i^{int}, E_i^{with})$$

Zonal price

In the most simple of cases and without any incentives, an active user can decide to sell its surplus energy directly into the energy market at the strike price of the geographic area of relevance, i.e. the so-called zonal price. The zonal price is decided on the day-ahead market and it varies every hour of the day, on the basis of the available supply of electricity and the demand.

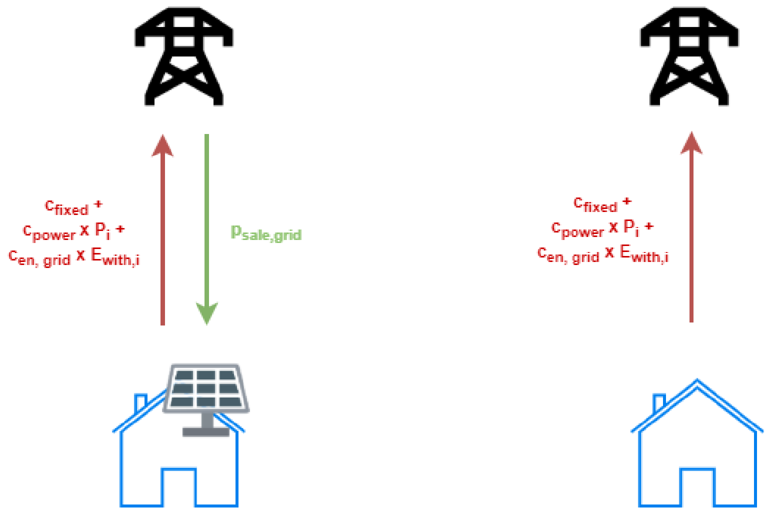


Figure 3.2. Cash flows of an active and passive user in a stand-alone configuration

In this case $p^{grid}_{sale} = p^{zonal}$ is a function of time and depends on the energy injected into the grid. Thus the monthly revenues from the sale in the market are:

$$p^{grid}_{sale}(t, E^{int}_i) = p_{zonal}(m) = \sum_m E^{int}_i(h) * p_{zonal}(h)$$

Ritiro dedicato

Another option to value the injected energy into the grid is the *Ritiro dedicato* (RID), in which the Italian energy service company, the GSE, interposes between the active user and the market. A more complete description of the mechanism is given in Chapter 1. As a form of incentive for small-scale RES, the GSE allows a minimum granted price p^{mgp}_{RID}, meaning that the user will receive this value if the zonal price is lower. As an example, the minimum granted price of 2020 for PV is 40,0 €/MWh [1].

$$p_{RID}(h) = \max\left(p^{mgp}_{RID}; p_{zonal}(t)\right)$$

The GSE requests an annual fee c^{GSE}_{fee} to benefit of RID that depends of the nominal power of the plant. There is a maximal fee of 10.000 €/year[2]. The fees are reported in Table 3.1:

kW	Solar $\left[\frac{€}{kW*yr}\right]$	Wind $\left[\frac{€}{kW*yr}\right]$	Hydro $\left[\frac{€}{kW*yr}\right]$	Other RES $\left[\frac{€}{kW*yr}\right]$
$3 < P \leq 20$	0,7	0,9	1,1	1,2
$20 < P \leq 200$	0,65	0,8	0,9	1,0
$P \geq 200$	0,6	0,7	0,8	0,9

Table 3.1. Definition of the GSE fee for RID

[1]Prezzi minimi garantiti per l'anno 2020. https://www.arera.it/it/comunicati/20/200127.htm
[2]D.M. 24/12/2014

Eventually, the monthly revenues of the active user, when choosing the RID are:

$$p_{sale}^{grid}(t, E_i^{int}) = p_{RID}(m) = \sum_{m} E_i^{int}(h) * p_{RID}(h) - \frac{C_{fee}^{GSE}}{12}$$

Scambio sul posto

The GSE, also allows active users to benefit of a net metering mechanism called Scambio sul posto (SSP) for "storing" in the national grid the electric energy produced, but not self consumed, and use it again in a different moment. A more in-dept description of the tool is given in Chapter 1. Among the many cases considered by the GSE, we will take into account a domestic user connected to the low voltage grid, whose energy is measured hourly. The necessary data of the user needed to determine the total amount obtainable with the SSP C_{SSP} are the measurements of the electric energy withdrawn from the grid E^{with} and of the electric energy introduced into the grid E^{int}.

The total annual amount SSP is the result of the sum of three elements:

$$C_{SSP} = C_s + C_{rL} - C_{GSE}$$

Where C_s is the so-called exchange-grant (*Contributo in conto scabio*), C_{rL} is the so-called valorisation of the surplus (*valorizzazione delle eccedenze*) and C_{GSE} is the fee to pay to the GSE for the service of SSP.

The exchange grant is the sum between two terms; the first member in the summation is called energy share (*quota energia*) while the second member is called service share (*quota servizi*):

$$C_s = \min[O_E; C_{EI}] + CU_{sf} * E_s$$

The energy share is computed as the minimum value among the so-called energy charge (*onere energia*) and the so-called electricity countervalue (*controvalore energia elettrica*).

The energy charge is the annual sum determined on time bands of the monthly energy withdrawn from the grid for every time band multiplied for the arithmetic mean of the PUN of the month in that time band:

$$O_E = \sum_{m=1}^{12} \sum_{fi=1}^{3} [E^{with}(fi) * PUN_m(fi)]$$

On the other hand, the energy countervalue is the hourly sum of the energy introduced into the grid times the zonal hourly prices:

$$C_{EI} = \sum_{h=1}^{8760} [E^{int}(h) * p^{zonal}(h)]$$

The service share is computed as the product between the electric energy exchanged E_S and the so-called unitary fee CU_{sf} (*corrispettivo unitario di scambio forfettario*). The electric energy exchanged is the minimum value between the annual energy introduced into the grid and the annual energy withdrawn from the grid:

$$E_s = \min[E^{with}(y), E^{int}(y)]$$

The unitary fee is the sum between two terms:

$$CU_{sf} = CU_{sf}^{reti} + CU_{sf}^{org}$$

Where CU_{sf}^{reti} is the unitary fee related to the grid and it is computed as the sum of the variable terms of the transmission and distribution tariffs, the dispatching fees and the components of the electricity bill UC3 and UC6. The CU_{sf}^{ogs} is the unitary fee related to the general charges of the system and it is computed as the sum of the variable terms of the electricity bill A_{SOS} and A_{RIM}.

In case at the end of the considered year y, $O_{E,y} < C_{EI,y}$ happens,the difference $C_{EI,y} - O_{E,y}$ can be reimbursed as a credit for the next years or can be repaid in clearance. For the sake of simplicity, we assume that the user chooses to avail of the clearance mechanism. Thus the clearance valorization of the surplus is computed as:

$$C_{rL} = \max[0, C_{EI,y} - O_{E,y}]$$

The fee to pay to the GSE to benefit of the service of SSP depends on the nominal power of the system that produces energy[3]. The fee consists of a fixed and a variable part as it is reported in Table 3.2.

kW	Fixed fee $\left[\frac{€}{kW*yr}\right]$	Variable fee $\left[\frac{€}{kW*yr}\right]$
$P \leq 3$	0	0
$3 < P \leq 20$	30	0
$20 < P \leq 500$	30	1

Table 3.2. Definition of the GSE fee for SSP

Considering that the SSP is a yearly grant, in order to account it in the monthly bill, we simply divide it for the number of months:

$$p_{sale}^{grid}(t, E_i^{int}, E_i^{with}) = p_{SSP}(m) = \frac{C_{SSP}}{12}$$

3.1.2 Community formation: self consumption priority

Energy flows

The formation of an energy community introduces the possibility for the users to exchange energy among each other. The formation of a community does not necessarily

[3]D.M. 24/12/2014

implies an additional electrical connection, as the energy flows can be intended as virtual flows. As shown by Figure 3.3, $E_{active}^{off}(t)$ is the surplus energy given to the community by an active user, while $E_i^{taken}(t)$ is the energy taken by any user from the community.

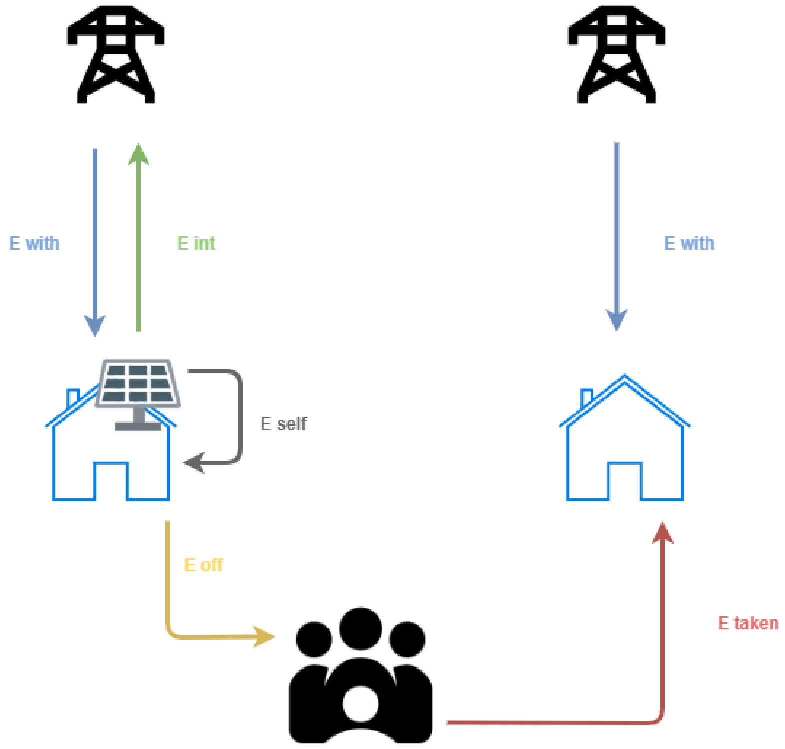
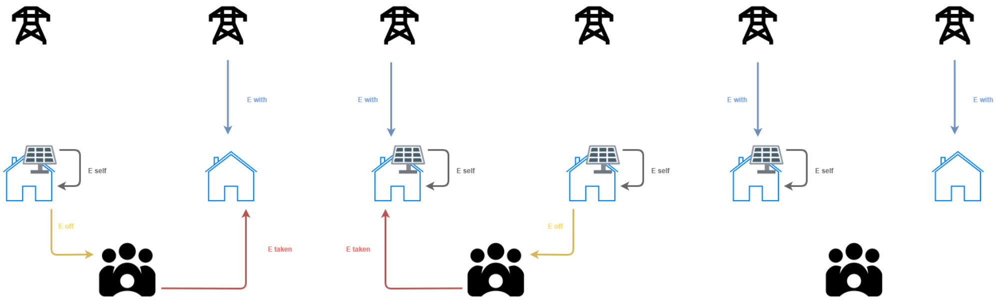


Figure 3.3. Example of energy community with an active and a passive user

The active users maintain as priority their self consumption $E_{active}^{self}(t)$, whose magnitude does not change from the stand-alone case. Their second priority is then to inject energy into the community and only then to inject energy into the grid. The energy to satisfy the demand can be taken both from the community or from the grid, according to the energy surplus available to the active users in that moment. Depending on the conditions of the load and generation curve of the users at a certain instant t, three scenarios of energy sharing can occur:

- An active user has surplus energy that is injected into the community and taken by a passive user as in figure 3.4a.
- An active user has surplus energy that is injected into the community and taken by an active user whose generation is not enough to satisfy its energy needs as in figure 3.4b.
- Both active and passive users take energy from the grid due to lack of energy self-generation as in figure 3.4c

From the implementation point of view, let's first compute some quantities at a community level, which take into account the overall energy offered to the community by the users and the energy taken by the users from the community.



(a) Active user surplus (b) Exchange between active users (c) No surplus

Figure 3.4. Energy sharing in a community

$$E^{av}_{com}(t) = \sum_{i \in S} |E^{surplus}_i(t)|$$

$$E^{req}_{com}(t) = \sum_{i \in S} E^{need}_i(t)$$

The energy flowing within the community is equal to the minimum value between the energy offered from the producers and the energy requested from the consumers:

$$E^{man}_{com}(t) = \min\Big(E^{av}_{com}(t), E^{req}_{com}(t)\Big)$$

Once the energy flowing within the community is determined, we can compute the share of energy that can be given to the community with respect to the energy made available by the active participants:

$$k^{av}_{com}(t) = \frac{E^{man}_{com}(t)}{E^{av}_{com}(t)}$$

In a similar way, we can identify the share of energy that is taken from the community that satisfies the energy needs of the community participants:

$$k^{req}_{com}(t) = \frac{E^{man}_{com}(t)}{E^{req}_{com}(t)}$$

$k^{av}_{com}(t)$ is then a quantity that splits the energy that the active users can inject into the community and the energy injected into the grid.

$$E^{off}_i(t) = E^{surplus}_i(t) * k^{av}_{com}(t)$$

$$E^{int}_i(t) = E^{surplus}_i(t) * \Big(1 - k^{av}_{com}(t)\Big)$$

In a similar fashion, $k^{req}_{com}(t)$ makes a division between the energy taken from the community and the energy taken from the grid.

$$E^{taken}_i(t) = E^{need}_i(t) * k^{req}_{com}(t)$$

$$E_i^{with}(t) = E_i^{need}(t) * \left(1 - k_{com}^{req}(t)\right)$$

Once we have identified these quantities we can identify three borderline cases that might happen during the operation of the energy community:

1. When $E_{com}^{av}(t) < E_{com}^{req}(t)$, inside the community there is less energy available than the one requested by the participants.That implies $E_{com}^{man}(t) = E_{com}^{av}(t)$ and subsequently $k_{com}^{av}(t) = 1$. By entering these values into the equations of $E_i^{off}(t)$ and $E_i^{int}(t)$ we get
$$E_i^{off}(t) = 1 \text{ and } E_i^{int}(t) = 0$$
meaning that all the energy surplus from the active users is injected into the community and non into the grid.

2. When $E_{com}^{av}(t) > E_{com}^{req}(t)$, the energy requested by the consumer is less that the energy that the active users can give to the community. That implies $E_{com}^{man}(t) = E_{com}^{req}(t)$ and subsequently $k_{req}^{av}(t) = 1$. By entering these values into the equations of $E_i^{taken}(t)$ and $E_i^{with}(t)$ we get
$$E_i^{taken}(t) = 1 \text{ and } E_i^{with}(t) = 0$$
meaning that all the energy surplus from the active users is injected into the community and not into the grid.

3. When $E_{com}^{av}(t) = 0$, the active users are not able to inject energy into the community. It implies that $E_{com}^{man}(t) = 0$ and subsequently $k_{com}^{req}(t) = 1$ and $k_{com}^{req}(t) = 1$, meaning that there is no interaction between the users and the community as $E_i^{off}(t) = 0$ and $E_i^{taken}(t) = 0$.

Cash flows

This case was considered behind the assumption that the self-consumed energy by the single user and the energy shared within the community will be value differently in the energy bill. As it was mentioned in Chapter 1, the saving obtainable with self-consumption can be expressed by the *Self-consumption saving index* (SCSi), while the ones coming from community energy are expressed by the *Shared energy saving index* (SECi). These indexes summarize what is exempted from the payment in the energy bill if a user self-consumes or takes energy from its energy community in the case of an implicit incentive. On the other hand, in case of explicit incentives the SECi coincides with the value of the incentive itself plus the exemptions.

Let's call *extended electricity bill* of user i the sum of a *conventional* electricity *bill*, that takes into account the monetary flows between the user and the energy provider, and a *community electricity bill*, which instead considers money exchange between the community participants. The total cost for the user i will be expressed as the sum of the costs of the conventional electricity bill and the community electricity bill:
$$C_i = C_i^{grid} + C_i^{com}$$

The conventional energy bill is computed as showed in the stand-alone case taking into account the energy flows with the grid in the presence of the energy community:

$$C_i^{grid} = c_{fixed} + c_{power} * P_i + c_{energy}^{grid} * \sum_m E_i^{with} - p_{sale}^{grid}(t, E_i^{int}, E_i^{with})$$

Moreover, it is reasonable to assume that once in a community, the users will not be able to benefit of additional incentives for the valorisation of the energy sold to the grid. As a consequence, RID and SSP will not be considered and the excess energy will be sold at the zonal price:

$$p_{sale}^{grid}(m) = p_{zonal}(m) = \sum_m E_i^{int}(h) * p_{zonal}(h)$$

The community energy bill values the energy exchanges between users. As a consequence, the fixed costs and the power costs are omitted because the services they cover have ideally already been paid in the conventional electricity bill. On the other hand, the community members enjoy of reduced rates for the variable component of the energy taken from the community c_{energy}^{com}, whose magnitude is determined by the level of the support schemes of the Member States mentioned in the European Directives. Generally, it can be said that:

$$c_{energy}^{com} = c_{energy}^{grid} - SECi$$

Consequently the energy bill of the community will be:

$$C_i^{com} = c_{energy}^{com} * \sum_m E_i^{with}$$

Redistribution via Shapley value
As the active users renounce to sell their surplus energy the grid and give it to the community instead, they are entitled to receive a remuneration for the energy injected. Consequently, an internal price of the energy p_{sale}^{com} can be introduced, implying a remuneration for the active users and an additional cost for passive users. It can be nevertheless demonstrated that the definition of the internal price does not affect the overall performance of the community, since this transaction is bounded within the community. Moreover, p_{sale}^{com} could be determined by an auction based local energy market, in which prosumers could trade their energy with each other. However, the price curves of the energy demand and energy supply are totally inelastic, as it was initially assumed that the community is formed among the users without any change of technology, i.e. batteries, nor behaviour, that could lead to demand flexibility. As a consequence, p_{sale}^{com} could take any value between the grid purchasing cost and the grid selling price.

In order to overcome this deadlock, the payment calculation scheme is based on a game theoretic approach. In particular, as already discussed in Chapter 2, the *Shapley value redistribution* will be used to fairly allocate the generation costs inside the community. It can be said that the allocation made according to the Shapley value is the best achievable result from an aggregator with the task of fairly redistributing the community's earnings.

When applied to this model, the Shapley value redistribution can assume negative or positive values depending on the condition of the user i, in particular:

- $\phi(i, v) > 0$ when the user i is active, as it is rewarded for its energy injection into the community.
- $\phi(i, v) < 0$ when the user i is passive, as it pays the active users for the energy received from the community.

As the Shapley value redistribution is computed on an annual basis, in order to fit it into the monthly bill, it is divided by the number of months in a year.

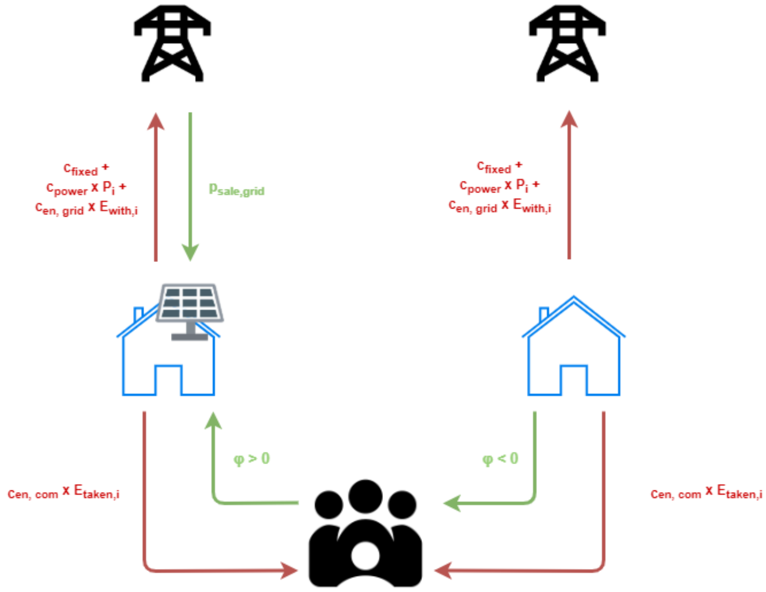


Figure 3.5. Cash flows of an active and passive user in a community configuration

As a result, the cost structure within the community electricity bill will be the following:

$$C_i^{com} = c_{energy}^{com} * \sum_m E_i^{with} + \frac{\phi(i, v)}{12}$$

3.1.3 Community formation: shared consumption priority

Energy flows

In this configuration, active users act collectively in the community as it is assumed that the plant it is owned by all members and installed on a particular roof due to better conditions such as exposition or space availability.

Unlike the previous case, the energy generated by the user i is given available to the whole community as shown in Figure 3.6. It will not be of importance to who the energy will be directed or who will have to buy it from the grid, as the community

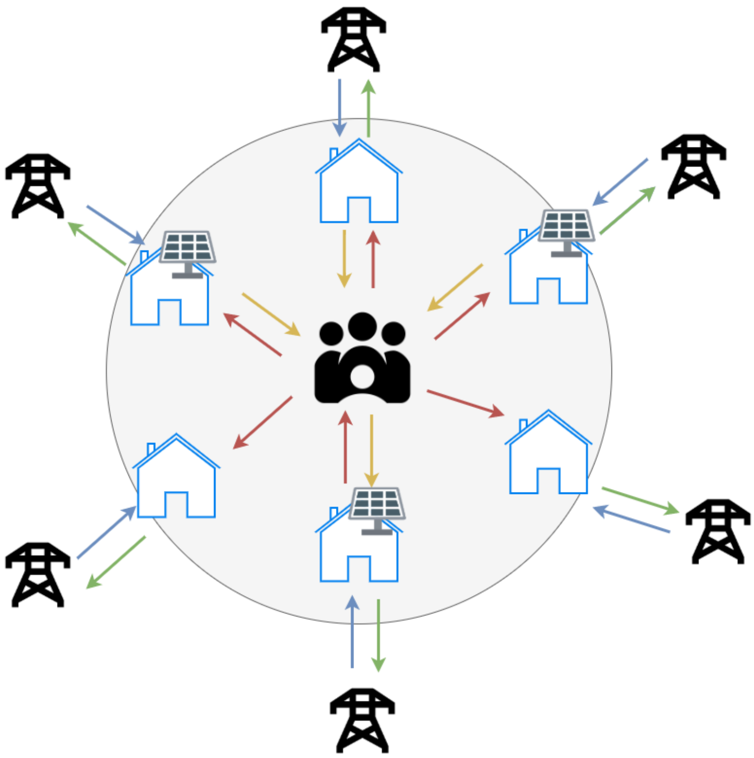


Figure 3.6. Example of energy community with active users prioritizing sharing

will act as one entity redistributing the cost of the bills among its members. As a consequence, the flows in the community are similar to the previous case with the difference that the available energy for the community is the sum of the energy generated by the users and the energy required by the community is the total demand of the members:

$$E_{com}^{av}(t) = \sum_{i \in S} |E_i^{gen}(t)|$$

$$E_{com}^{req}(t) = \sum_{i \in S} E_i^{load}(t)$$

The determination of the energy flows is then completely equal to the one seen in Subsection 3.1.2.

Cash flows

Even in this case, is useful to divide the energy bill between the conventional and community bill. The way of computing the cash flows is again the same as in Subsection 3.1.2, with the only difference that the self-consumed energy is null and the user will only benefit if the SESi.

3.1.4 Community formation: PV and BESS

Energy flows

In this configuration, the users act as in the previous model, without prioritizing the shared-consumption and sharing all the energy they might produce. As a further step, a battery energy storage system (BESS) is added, to store the surplus energy that remains after shared-consumption and avoid to take it from the grid. In this exercise, the BESS is commonly owned by the community and is charged and discharged following the energy needs of its members. Figure 3.7 shows the scheme.

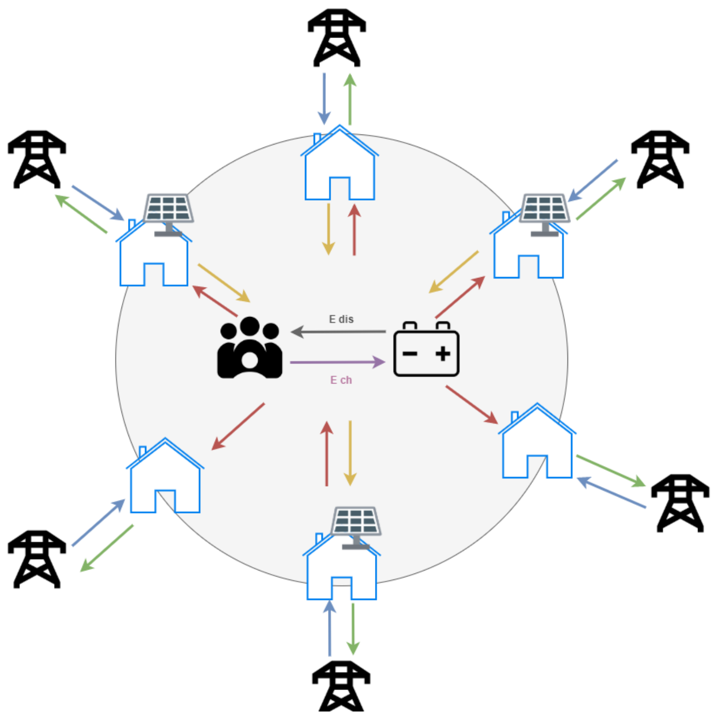


Figure 3.7. Example of energy community with shared BESS

The energy generated and the energy demand of the members are accounted as measures of the whole community:

$$E_{com}^{av}(t) = \sum_{i \in S} E_i^{gen}(t)$$

$$E_{com}^{req}(t) = \sum_{i \in S} E_i^{load}(t)$$

It is then possible to compute the energy shared within the community and the energy need and surplus at the instant t:

$$E_{com}^{man}(t) = \min\Big(E_{com}^{av}(t), E_{com}^{req}(t)\Big)$$

$$E_{com}^{need}(t) = E_{com}^{load}(t) - E_{com}^{man}(t)$$

$$E_{com}^{surpl}(t) = E_{com}^{gen}(t) - E_{com}^{man}(t)$$

It is now time to define the charging logic of the battery. The energy flows of the battery are the energy flowing into the battery $E^{ch}(t)$, the energy flowing out of the battery $E^{dis}(t)$ and the state of charge of the battery $SOC(t)$, bounded between the maximum capacity b and the minimum dept of discharge $DoD * b$. When there is some surplus energy $E_{com}^{surpl}(t)$, the battery will charge it, taking into account its physical limits such as the C_{rate} and its maximum capacity b. If some energy cannot charge the batter, it will be injected into the grid. From the mathematical point of view:

$$\text{if } \; E_{com}^{surpl}(t) \geq b - SOC(t-1)$$

$$E^{ch}(t) = \min\left(\frac{b}{C_{rate}}; b - SOC(t-1) * \eta_{ch}\right)$$

$$E_{com}^{int}(t) = E_{com}^{surpl}(t) - E^{ch}(t)$$

$$SOC(t) = b$$

$$\text{if } \; E_{com}^{surpl}(t) < b - SOC(t-1)$$

$$E^{ch}(t) = \min\left(\frac{b}{C_{rate}}; E_{com}^{surpl}(t) * \eta_{ch}\right)$$

$$E_{com}^{int}(t) = 0$$

$$SOC(t) = SOC(t-1) + E^{ch}(t)$$

On the other hand, if the community requires energy $E_{com}^{need}(t)$, the battery will try to satisfy it, limited by the already mentioned $C - rate$ and its minimum discharging point $DoD * b$. If the community still demands energy, it will be withdrawn from the grid. In formulas:

$$\text{if } \; E_{com}^{need}(t) \geq SOC(t-1) - DoD * b$$

$$E^{dis}(t) = \min\left(\frac{b}{C_{rate}}; SOC(t-1) - \frac{DoD * b}{\eta_{dis}}\right)$$

$$E_{com}^{with}(t) = E_{com}^{need}(t) - E^{dis}(t)$$

$$SOC(t) = DoD * b$$

$$\text{if } \; E_{com}^{need}(t) < SOC(t-1) - DoD * b$$

$$E^{dis}(t) = \min\left(\frac{b}{C_{rate}}; SOC(t-1) - \frac{E_{com}^{need}(t)}{\eta_{dis}}\right)$$

$$E_{com}^{with}(t) = 0$$

$$SOC(t) = SOC(t-1) - E^{dis}(t)$$

3.2 Capacity optimization

Once the energy flows in the different configurations are clear, it is possible to make a further step by optimizing the PV capacity for the single user with RID and SSP, for the community with and without self-consumption priority. Lastly, a joint PV and BESS optimization was performed, considering complete sharing of energy within the community.

3.2.1 PV optimization for single user, RID

Variable

The capacity of PV installed on the roofs of each user i represents the solution to the optimization problem, identified by the variable

$$x_i \, \forall \, i \in A$$

In which A is the set of the participants in the community.

Constraints

Self-consumed energy
$E_i^{self}(t)$ is defined as the minimum value between the energy demand and the energy generated by the user i.

$$E_i^{self}(t) = min\Big(E_i^{load}(t); \sum_i E_i^{gen}(t) * x_i\Big)$$

The constraint is then linearized by adding a set of additional constraints. It particular, a binary decisional variable depenting on time and on the user is defined as:

$$y_i(t) = \begin{cases} 1 & \text{if } E_i^{load}(t) < \sum_i E_i^{gen}(t) * x_i \\ 0 & \text{if } \sum_i E_i^{gen}(t) * x_i < E_i^{load}(t) \end{cases}$$

M is a constant so that $\sum_i E_i^{gen}(t) * x_i, E_i^{load}(t) < M$ in any solution of the problem.

At last, the following constraints define the linearized minimum problem:

$$E_i^{self}(t) \leq E_i^{load}(t)$$

$$E_i^{self}(t) \leq \sum_i E_{t,i}^{gen} * x_i$$

$$E_i^{self}(t) \geq E_i^{load}(t) - M * (1 - y_i(t))$$

$$E_i^{self}(t) \geq \sum_i E_i^{gen}(t) * x_i - M * y_i(t)$$

Energy injected into the grid
The energy introduced into the grid is equal to the difference between the energy generated and the energy self-consumed for every user i:

$$E_i^{int}(t) = \sum_i E_i^{gen}(t) * x_i - E_i^{self}(t)$$

Energy withdrawn from the grid
The energy withdrawn from the grid is the difference between the demand and the energy self-consumed for every user i:

$$E_i^{with}(t) = E_i^{load}(t) - E_i^{self}(t)$$

Non-negative solution
The capacity installed for each user has to be greater or equal to zero:

$$x_i \geq 0$$

Available space on the roofs
The dimensions of the roofs limit the number of PV panels and consequently the maximum power that can be installed by each user:

$$x_i \leq P_i^{max}$$

Objective function

The objective function requires that the NPV of each user is optimized over a time period l equal to the useful life of the plant:

$$max\ NPV_i =$$
$$= \sum_l \left(\frac{\sum_{t=1}^{8760} (E_i^{self}(t) * SCSi + E_t^{int} * p_{RID}(t))}{(1+k)^l} + \frac{(C_i^{detrax} - C_i^{var}) * x_i}{(1+k)^l} - C_i^{fix} * x_i \right)$$

where:

- C_i^{fix} are the fixed costs of the PV plant expressed in $\left[\frac{€}{KW}\right]$.
- C_i^{var} are the variable costs related to ordinary maintenance of the plant. Their unit of measure is: $\left[\frac{€}{KWh\ yr}\right]$.
- C^{detrax} is the fiscal detraction that a user can benefit by law. It is equal to the 50% of the investment cost of the plant, spread in 10 years. Their unit of measure is: $\left[\frac{e}{KWh\ yr}\right]$.
- $SCSi$ includes the variable price of electricity discounted for the energy shared in an energy community.
- $p_{RID}(h)$ is the hourly price of electricity with the RID.

3.2.2 PV optimization for single user, SSP

In order to model the SSP in the LP, we have to change the objective function and add some additional constraints. To simplify the SSP in the LP and remove a non-linear passage, only the electric exchanged energy is computed in the *Contributo conto scambio* as the difference between the electric exchanged energy and the energy charge would be given at the end of the year as valorization of the surplus.

Constraints

Energy balance
An energy balance is added to define the energy flows for each user:

$$\sum_i E_i^{gen}(t) * x_i + E_i^{int}(t) = E_i^{with}(t) = E_i^{load}(t)$$

Exchange energy SSP
The exchanged energy is an annual value that represents the minimum between the energy injected and the energy withdrawn from the grid:

$$E_{s,i} = \min\big(\sum_{t=1}^{8760} E_i^{with}(t), \sum_{t=1}^{8760} E_i^{int}(t)\big)$$

The constraint is linearized by introducing the binary variable s_i:

$$E_{s,i} \leq \sum_{t=1}^{8760} E_i^{with}(t)$$

$$E_{s,i} \leq \sum_{t=1}^{8760} E_i^{int}(t)$$

$$E_{s,i} \geq \sum_{t=1}^{8760} E_i^{with}(t) - M(1 - s_i)$$

$$E_{s,i} \geq \sum_{t=1}^{8760} E_i^{int}(t) - M * s_i$$

SSP grant
Finally the annual grant is computed as the sum between the energy share and the service share:

$$p_i^{SSP} = E_{s,i} * CU_{sf} + \sum_{t=1}^{8760} E_i^{int}(t) * p_{zonal}(h)$$

Objective function

The objective function is changed, taking into account the SSP grant that each user receives:

$$max\ NPV_i =$$
$$= \sum_l \left(\frac{\sum_{t=1}^{8760}(E_i^{self}(t)*SCSi)+p_i^{SSP}}{(1+k)^l} + \frac{(C_i^{detrax}-C_i^{var})*x_i}{(1+k)^l} - C_i^{fix} * x_i \right)$$

3.2.3 PV community optimization: self-consumption priority

The optimization of the PV capacity of a community with users prioritizing their self-consumption has similar constraints to the PV optimization for the single user in 3.2.1, plus a number of constraints describing the energy fluxes at the community level.

Constraints regarding the single user

Self-consumed energy

$$E_i^{self}(t) = min\Big(E_i^{load}(t); \sum_i E_i^{gen}(t) * x_i\Big)$$

The constraint is then linearized:

$$E_i^{self}(t) \leq E_i^{load}(t)$$

$$E_i^{self}(t) \leq \sum_i E_{t,i}^{gen} * x_i$$

$$E_i^{self}(t) \geq E_i^{load}(t) - M(1 - y_i(t))$$

$$E_i^{self}(t) \geq \sum_i E_i^{gen}(t) * x_i - M * y_i(t)$$

Surplus energy

$$E_i^{surplus}(t) = \sum_i E_i^{gen}(t) * x_i - E_i^{self}(t)$$

Needed energy

$$E_i^{need}(t) = E_i^{load}(t) - E_i^{self}(t)$$

Constraints regarding the community

Available energy in the community

$$E^{av}(t) = \sum_i E_i^{surplus}(t)$$

Requested energy in the community

$$E^{req}(t) = \sum_i E_i^{need}(t)$$

Managed energy in the community

$$E^{man}(t) = min\Big(E_i^{load}(t); \sum_i E_i^{gen}(t) * x_i\Big)$$

The constraint is then linearized:

$$E^{man}(t) \leq E^{av}(t)$$

$$E^{man}(t) \leq E^{req}(t)$$
$$E^{man}(t) \geq E^{av}(t) - M * (1 - s(t))$$
$$E^{man}(t) \geq E^{req}(t) - M * s(t)$$

Energy introduced into the grid

$$E^{int}(t) = E^{av}(t) - E^{man}(t)$$

Objective function

The NPV of the community is computed adding an element that takes into account the savings coming from the energy shared in the community.
$max\ NPV =$
$$= \sum_l \sum_i \left(\frac{\sum_{t=1}^{8760}(E_i^{self}(t)*SCSi + E^{man}(t)*SESi + E^{int}(t)*p_{zonal}(t))}{(1+k)^l} + \frac{(C_i^{detrax} - C_i^{var})*x_i}{(1+k)^l} - C_i^{fix} * x_i \right)$$

3.2.4 PV community optimization: shared consumption priority

The optimization of the PV capacity of a community with the users sharing their whole energy is an extension of the optimization for the single user benefiting of RID presented in 3.2.1. The variable, the constraints and the objective function are exactly the same, but the optimization is performed by considering the community as a whole. In particular, the shared energy will be valued with the SESi and the excess energy will be sold at the zonal price, rather than at the RID price. For sake of completeness, the objective function is:
$max\ NPV =$
$$= \sum_l \sum_i \left(\frac{\sum_{t=1}^{8760}(E^{man}(t)*SESi + E^{int}(t)*p_{zonal}(t))}{(1+k)^l} + \frac{(C_i^{detrax} - C_i^{var})*x_i}{(1+k)^l} - C_i^{fix} * x_i \right)$$

3.2.5 PV community optimization with BESS

In this advanced step of the optimization, let's consider the possibility to install a battery energy storage system (BESS) shared by all the community. To the previous variables, a new one will be considered, which accounts for the capacity of the storage system. The objective function will slightly change to take this variable into account, while some constraints will be modified or added.

Variables

PV capacity
No changes from the previous formulation.
Capacity of the battery
In this first step, only a single battery system will be taken into account, whose capacity is b expressed in kWh.

Constraints

Energy balance
The energy balance is written considering the boundary of the energy community as the control volume. $E^{ch}(t)$ and $E^{dis}(t)$ are respectively the energy charging and discharging the battery:

$$\sum_i E_i^{gen}(t) * x_i + E^{with}(t) + E^{dis}(t) = E^{load}(t) + E^{int}(t) + E^{ch}(t)$$

Self-consumed energy
The self-consumed energy by the whole community. The formulation and linearization of the minimum problem does not change:

$$E^{self}(t) = min\Big(E^{load}(t); \sum_i E_i^{gen}(t) * x_i\Big)$$

Energy sold to the grid
The definition of the energy introduced to the grid is slightly changed from the previous formulation. The quantity is defined as the maximum value between 0 and the difference between the total generated energy, the self-consumed energy and the energy charging the battery:

$$E^{int}(t) = max\Big(0; \sum_i E_i^{gen}(t) * x_i - E^{self}(t) - E^{ch}(t)\Big)$$

The problem is linearized introducing the binary decisional variable $z(t)$:

$$E^{int}(t) \geq \sum_i E_i^{gen}(t) * x_i - E_t^{self} - E^{ch}(t)$$

$$E^{int}(t) \geq 0$$

$$E^{int}(t) \leq \sum_i E_i^{gen}(t) * x_i - E_t^{self} - E^{ch}(t) + M * (1 - z(t))$$

$$E^{int}(t) \leq M * z(t)$$

Energy withdrawn from the grid
In a similar fashion the energy withdrawn is the maximum value between 0 and the difference between the total demand, the self-consumed energy and the energy discharging the battery:

$$E^{with}(t) = max\Big(0; E^{load}(t) - Eself(t) - E^{dis}(t)\Big)$$

The problem is linearized introducing the binary decisional variable $q(t)$:

$$E^{with}(t) \geq E^{load}(t - E_t^{self} - E_t^{dis}$$

$$E^{with}(t) \geq 0$$

$$E^{with}(t) \leq E^{load}(t) - Eself(t) - E^{dis}(t) + M * (1 - q(t))$$

$$E^{with}(t) \leq M * q(t)$$

Non-negative solution for PV solution
No changes from the previous formulation.
Available space on the roofs
No changes from the previous formulation.

BESS constraints

Definition state of charge
This constraint calculates the State of Charge (SOC) for each period of analysis. The SOC in the period 't' is equal to the SOC in period 't-1' plus the energy flow into the battery, minus the energy flow out of the battery weighted for the energy of charging and discharging. At time t=8760 the SOC is the same as at the beginning of the analysis.

$$SOC(t) = \begin{cases} b * SOC_{initial} - \frac{E^{dis}(t)}{\eta_{dis}} + E^{ch}(t) * \eta_{ch} & \text{if } t = 1 \\ SOC(t-1) - \frac{E^{dis}(t)}{\eta_{dis}} + E^{ch}(t) * \eta_{ch} & \text{if } 1 < t < 8760 \\ b * SOC_{initial} & \text{if } t = 8760 \end{cases}$$

Maximum charge
his constraint keeps the state of charge of the battery equal or under the size of the battery

$$SOC \leq b$$

Minimum discharge
This constraint maintains the level of charge of the battery above the deep of discharge

$$SOC \geq b * DoD$$

Maximum power in charge and discharge
This constraint calculates the Maximum power of discharge of the battery.

$$P^{max}_{stor} = \frac{b}{T^{max}_{ch/dis}}$$

Maximum energy in charge and discharge
This constraint maintains the energy in to the battery, below the maximum power of charge and discharge

$$E^{ch}(t) \leq P^{max}_{stor} * \Delta t$$

$$E^{dis}(t) \leq P^{max}_{stor} * \Delta t$$

Battery reposition cost
Calculation of the reposition of the battery after a stated time of use:

$$C_{batt,rep} = \sum_{t} (E^{ch}(t) + E^{dis}(t)) * c^{unitary}_{batt,rep}$$

Where:

$$c^{unitary}_{batt,rep} = \frac{C^{replaceable}_{b}}{N^{cycles} * 2 * (1 - DoD)}$$

Maximum capacity of BESS
The battery has a maximum capacity due to lack of available space:

$$b \leq B^{max}$$

Objective function

The objective function is modified to take into account the costs of the BESS. The new o.f. is

$$max\ NPV =$$
$$= \sum_l \left(\frac{\sum_{t=1}^{8760}((E^{load}(t)-E^{with}(t))*SESi+E_t^{int}*p_{zonal}(t))}{(1+k)^l} + \frac{\sum_i(C_i^{detrax}-C_i^{var})*x_i-C_b^{var}*b-C_b^{rep}}{(1+k)^l} + \right.$$
$$\left. - \sum_i C_i^{fix} * x_i - C_b^{fix} * b \right)$$

The added elements are:

- C_b^{fix} is the part of the investment cost that has to be purchased only once for the BESS in $\left[\frac{€}{KWh}\right]$
- C_b^{var} are the annual maintenance costs $\left[\frac{€}{KWh*yr}\right]$
- C_b^{rep} the battery reposition cost (or wear cost) is the cost in $\left[\frac{€}{KWh*yr}\right]$ of cycling energy through the battery.

3.3 Application of the tools

The energy sharing mechanism and the MILP optimization are designed from scratch by the author of this thesis and are programmed with the high-level programming language *Python*, that has a simple, clear and object oriented syntax. The optimizations were performed with *Pyomo* [73] and *Gurobi* [74] as a solver. *Pyomo* is an acronym for Python Optimization Modeling Objects and, as the name suggests, is a Pyhton-based open-source optimization modeling language for formalizing optimization problems, including MILP. The advantage is Pyomo is the possibility to express optimisation problems with Python in a way that resembles the mathematical formulation. The optimisation models developed in this thesis are called "concrete", meaning that they are defined with data, initialised as parameters from other Python files or external spreadsheets and database. *Gurobi* is a powerful software used to solve the MILP written with Pyomo. It distinguishes for its pre-solving capabilities of nodes, different classes of plane cuts and heuristics to quickly found feasible solutions.

The methodology implemented in the Python code is used in a short-term analysis and in a long-term analysis of EC described below.

3.3.1 Short-term analysis

This first algorithm will investigate whether energy communities will be economically convenient for users that already invested in the past in a PV plant and, when the national law in the field of energy communities comes into force, are interested in forming one. The optimizations are performed assuming that the excess energy is valued with RID or SSP. Then a comparison of the annual extended electric bills is implemented considering the user in stand-alone configuration or in community with

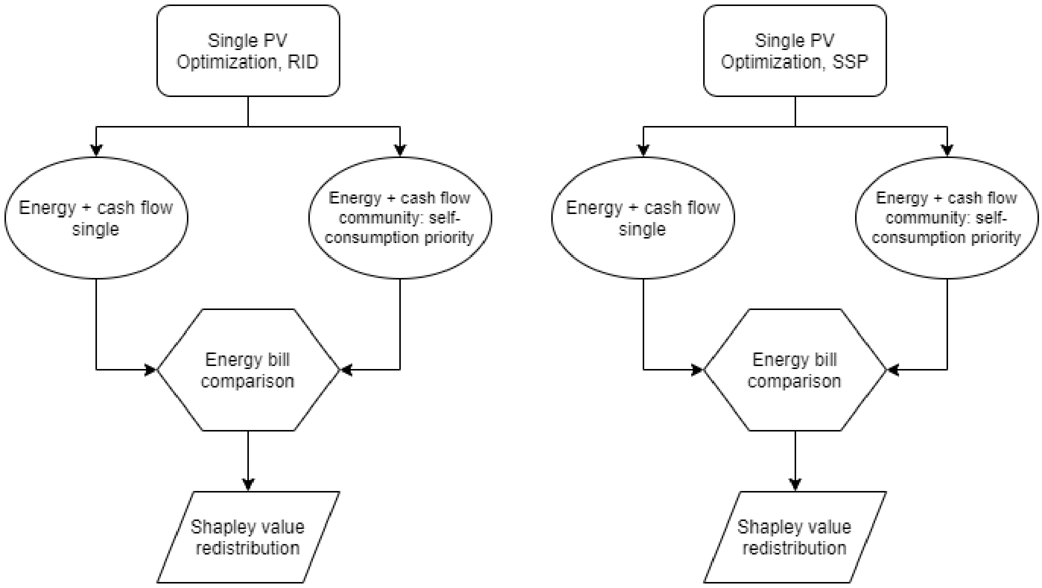


Figure 3.8. Short-term analysis

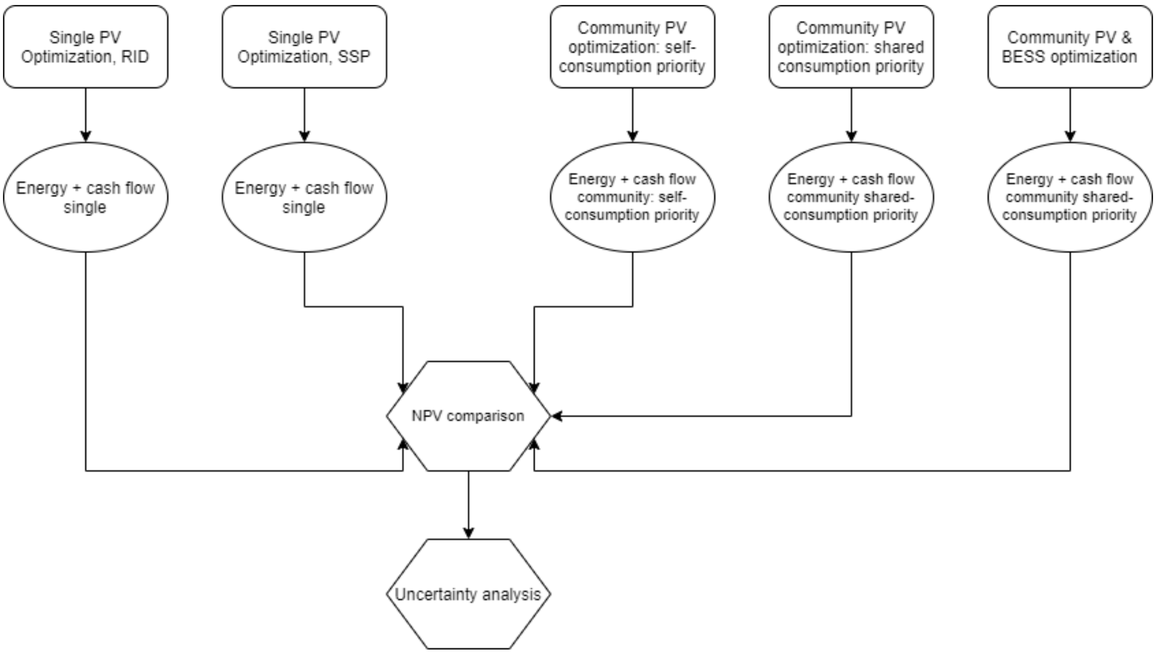


Figure 3.9. Long-term analysis

self-consumption priority. In the case of community, if the overall extended electricity bill is positive, the benefit is redistributed via Shapley value. An overview of the algorithm is presented in Figure 3.8.

3.3.2 Long-term analysis

The algorithm hereby presented aims at comparing different business models for users that are considering in investing in a domestic PV system at the time the CEP will be transposed into national law. The investors will have to decide between being stand-alone active users and valuing their energy with RID or SSP, or forming a community with other users. In the case of the community, the investors will have to evaluate the modalities that rule the energy flow, i.e. with or without self-consumption prioritization. Lastly, it is also explored to add a shared battery inside the community, to improve the self-supply of energy. Lastly, an uncertainty analysis, described in the next Section, is performed on the output NPVs. An overview of the algorithm is presented in Figure 3.9.

3.4 Uncertainty analysis

The versatility of any model is highly dependant on the accuracy and in the reliability of its output data. The uncertain nature of output variables is born from ambiguous information and assumptions as well as from the variability of the process the model aims to describe. Uncertainty can be classified into three categories [17]:

- *Natural variability* is embedded in the phenomenon the model is describing and in the accuracy the input data are measured. Moreover, the measured inputs might be suitable for a certain time period or space location, but they might not describe with precision what happens in another place and in another time.
- *Knowledge uncertainty* is related to the structure of the model and the uncertainties related to the parameters of the model. The latter may arise due to an uncertain estimates of the parameters used to calibrate the model and to the imprecise definition of the boundary conditions of the model. The uncertainty of the structure of the model lies in its embedded approximation of numerical method compared to the physical phenomenon the model is representing.
- *Decision uncertainty* lies in the sudden changes of policies, demands, human habits and decisions that the model aims to simulate. This class takes into account the inability of the modeller to take everything into account and predict future happenings.

Many modellers aim to identify uncertainty in order to understand if it is worth to spend more time and money on improving the precision of the model, or if the uncertainty of the output is acceptable for the model's goal. The propagation of the aforementioned three kinds of uncertainties into the model and the creation of an uncertainty for the outputs can be assessed in two ways, with sensitivity analysis and with uncertainty analysis. Even though the two are closely related, they bear some differences. Sensitivity analysis aims to identify the impacts of the variations of the inputs data on the outputs and it is used to asses the most influential input parameters and diminish the associated uncertainty. On the other hand, uncertainty analysis derives probabilistic distributions of model outputs from probabilistic distribution of inputs. Figure 3.10 represents the difference between the two analyses.

Sensitivity analysis methods can be divided into three main categories [75]:

- Local methods let vary one parameter at the time, keeping the others fixed.

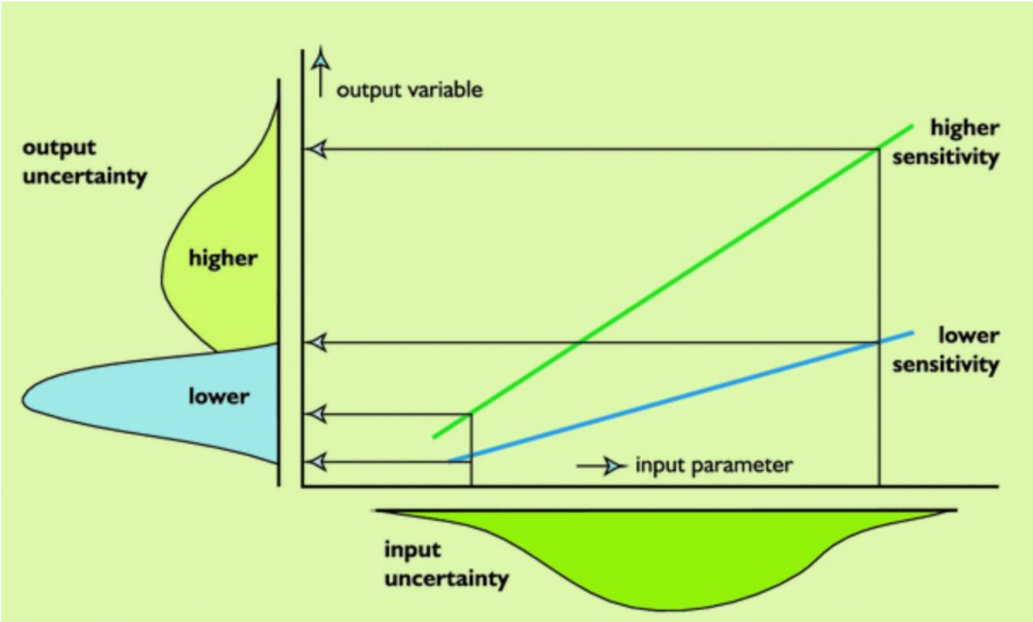


Figure 3.10. Uncertainty analysis ans sensitivity analysis from [17]

- Global methods take into account a set of input variables that are considered important and their combined influence is studied.

- Screening methods all the inputs are let to vary, in order to quantify the most influential.

In the same fashion, also uncertainty analysis method are divided into two main categories [75]:

- Local approximations: in which the statistics are often decomposed with Taylor expansions in order to have lighter computations. A linear model is preferred to have accurate results.

- Sampling methods: consists in running the model multiple times to build a probabilistic distribution at the output, using different ways to create the samples at the input. Monte Carlo method produces random numbers, while Latin Hypercube divides the input probability into layers and chooses a value from each section.

3.4.1 Implemented approach

As a last step of our investigation on EC, an Uncertainty Analysis (UA) will be performed to the energy flows models, in order to identify possible propagation of uncertainty of the input data. UA is chosen to identify and compare the probability distributions of the outputs, in our case they will be the NPVs of each configuration, to better understand the effect of the uncertainties of the input variables.

Monte Carlo sampling method of performing UA is chosen due to its spread use in literature and universality, even though its computational times are relevant [17].

Monte Carlo sampling method takes, for every input value, a random number to be taken from the probability distributions describing the inputs uncertainties. The values are then used in the model to obtain the output variables. The method is then repeated as many times as possible to obtain a distribution of the output variables that is significant from the statistical point of view. The final result of the Monte Carlo sampling method is a probability distribution that describes the uncertainty associated with the output variable. The implementation process [76] of the UA is hereby presented and visualized on Figure 3.11.

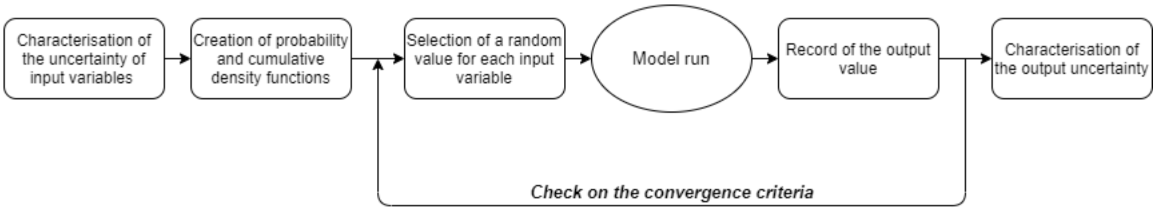


Figure 3.11. Uncertainty analysis process

1. Choice of an output variable of interest.
   The analysis will consider the NPV of each case as variable of interest in order to choose the most profitable business model taking into account also its uncertainty. The outputs of the analysis will be distributions of probability of the NPVs.

2. Identification of the (uncertain) inputs of the model.
   For this analysis, only non-time dependant input variable were chosen comprising price inputs and efficiencies.

3. Characterization of the uncertainty of the inputs.
   The uncertainty is identified through probability density functions and cumulative density functions. The curves are built with data found in literature.

4. Repeated run of the model (Monte Carlo process for uncertainty propagation).
   The model is run for a number of iterations that satisfies a convergence criterion based on the mean $\bar{x}$ and the standard deviation $\bar{s}_x$ of the outputs of the runs. As presented in the equation below, N+m is the number of iterations such that the absolute value of the relative differences between the mean and the standard deviation of the model outputs at the iteration N and at the iteration N+m (being m an arbitrary number), are smaller than a tolerance ϵ.

$$N\ s.t.\ |\frac{\bar{x}(N)-\bar{x}(N+m)}{\bar{x}(N)}| < \epsilon\ and\ |\frac{\bar{s}_x(N)-\bar{s}_x(N+m)}{\bar{s}_x(N)}| < \epsilon$$

In the presented UA, the chosen parameters are $m = 10$ and $\epsilon = 0.1\%$. For every run of the model and for each input variable, a random number between 1 and 0 is chosen that fed to the cumulative distribution function, represents a random value of the input variable. The model is then run, taking into account the random inputs generated.

5. Record of the results of each run.
   The output of every run is recorded and it is use to build an histogram that will reveal the probability distribution of the NPV.

6. Interpretation of the results.
   Once we have obtained the results for each run, it is possible to compare the uncertainties of each NPV and identify possible overlapping.

Chapter 4

Simulations and results

4.1 Case study

In order to validate the models and the procedures developed in Chapter 3, a reference case study is built, simulating a small scale REC formed by a local group of domestic users. The models will be used to evaluate the economic feasibility of forming a REC with pre-existing PV plants or with plants built ex-novo. The case study is set in Northern Italy, in the Northern outskirts of Milan. Ten households are then considered, with available space on their roof as in Figure 4.1.

Figure 4.1. Reference map for the case study

The households have domestic, single-time band electricity contracts within the protected regime. When they become active users, they have the possibility to benefit of incentives such as RID with minimum granted price or SSP. When they form a community the surplus energy is instead valued through the zonal price (in the case study: the North zonal price). The price of technologies and the values of the energy markets are updated to December 2019. Table 4.1 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

User	latitude	longitude	PV slope	PV orientation	Maximum PV capacity [kW]
User 1	45.699019	9.001100	10°	East	5,0
User 2	45.698533	9.000239	10°	West	5,0
User 3	45.698966	9.000496	10°	North	3,0
User 4	45.698456	9.001077	10°	South	10,0
User 5	45.698818	9.000378	35°	South	10,0
User 6	45.698445	9.001062	35°	North	3,0
User 7	45.698497	9.000415	35°	East	5,0
User 8	45.698633	9.000952	35°	West	5,0
User 9	45.698818	9.000099	35°	South	10,0
User 10	45.698680	9.000319	10°	West	10,0

Table 4.1. Characteristics of the users in the case study

The following Subsections will describe the tools used for the delineation of the case study. The algorithms for the computation of the extended electricity bill and the evaluation of the investments are then applied. At the end, the uncertainty analysis will be applied to compare the results. The computational time of the models is reported in Appendix A.

4.1.1 Definition of the loads

The households for the case study were 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) [77]. The average families will not be indicative of a particular place in Italy, but are a starting point in order to build a case study. 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 were modelled using a tool named Load Profile Generator (LPG) [21]. 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 were 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 [78]. In particular, the appliances were changed to a Mediterranean Country, with the introduction of air-conditioning and gas heating instead of electric heating. The average energy consumption per m^2 in dwellings was shifted to Italian standards and the space heating was adapted to the Italian climate. Lastly, public holidays and school vacations were contextualized to the Italian calendar.

The users' typologies and annual demands are summarized in Table 4.2:

User	Typology	Annual Load [kWh]
User 1	Working couple, no kids	4370,33
User 2	Working couple with one kid	3529,89
User 3	Single with work	1816,74
User 4	Student	2200,92
User 5	Senior couple	3021,28
User 6	Single with one kid	1088,83
User 7	Senior single	2712,39
User 8	Working couple with two kids	3345,88
User 9	Working couple with three kids	4257,18
User 10	Couple with kid, one parent at home	4560,17

Table 4.2. Users' typology and annual demand

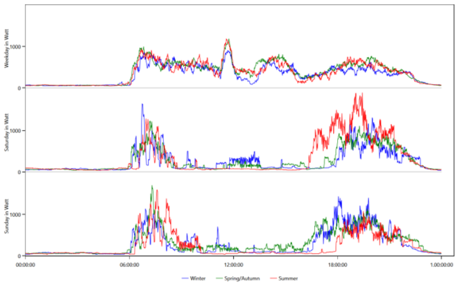
Figure 4.2 reports the outputs of the LPG. The three subplots represent the average load curve in a weekday, on a Saturday and on a Sunday. The three colors identify the season, blue for Winter, green for Spring/Autumn and red for Summer.

4.1.2 Simulation of the PV

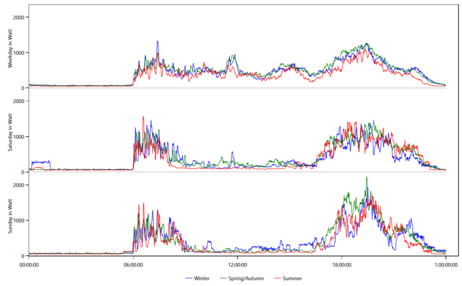
The households have the possibility to install some PV capacity on the top of their roofs. Each roof is characterised by specific inclination and orientation, that influences the electricity production from the panels. The slope of the PV modules, i.e. the angle between the horizontal plane and the PV module, and the azimuth (orientation) of PV modules, i.e. 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, are summarized in Table 4.1 in the introductive paragraph of this Section.

The production curves from PV were generated using the *Photovoltaic Geographical Information System (PV GIS)* of the EC Joint Research Center [31]. The tool allows to compute the yearly energy production of a PV system connected to the grid, taking into account the location, the solar radiation, the temperature, the wind speed and the configuration of the PV module. The PV GIS web interface is shown in figure 4.3.

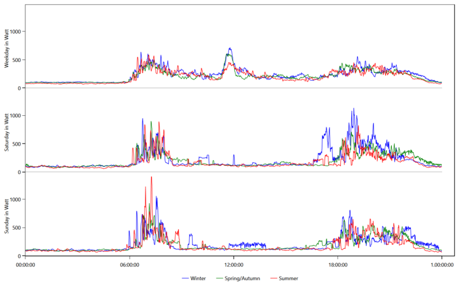
For the definition of the case study, the selected database was the PVGIS-SARAH, the reference database for Europe. Polycrystalline silicon was chosen as PV technology



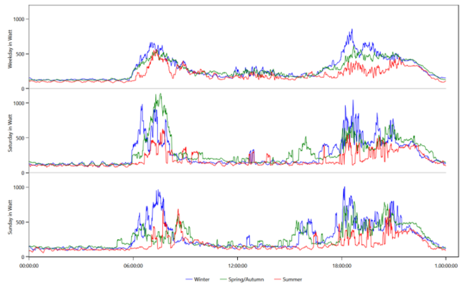
(a) User 1: Working couple, no kids



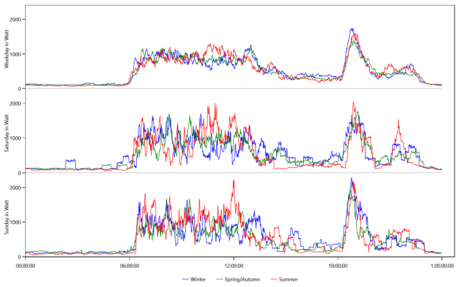
(b) User 2: Working couple with one kid



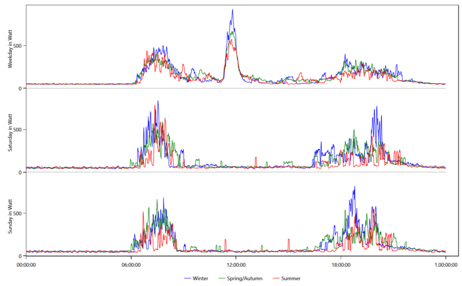
(c) User 3: Single with work



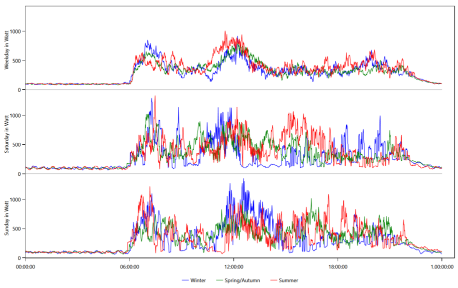
(d) User 4: Student



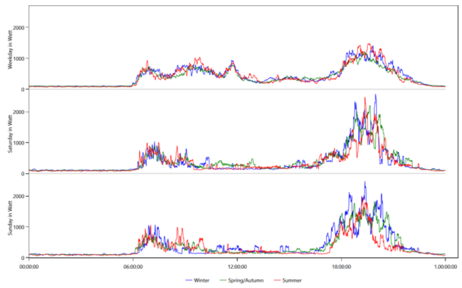
(e) User 5: Senior couple



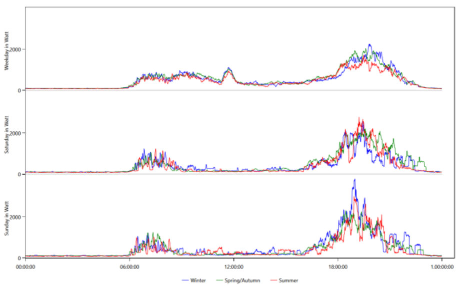
(f) User 6: Single with one kid



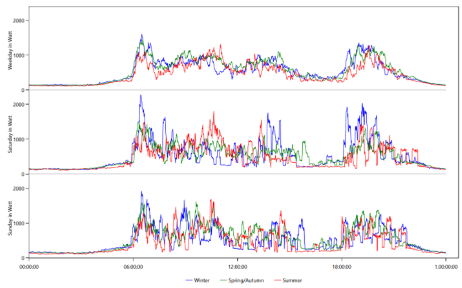
(g) User 7: Senior single



(h) User 8: Working couple with two kids



(i) User 9: Working couple with three kids



(j) User 10: Couple with kid, one parent at home

Figure 4.2. Average daily load curves per season of the case study

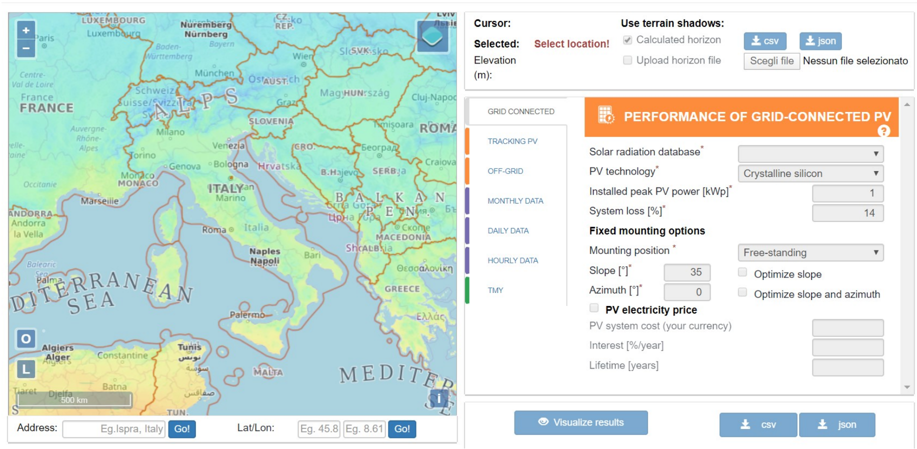


Figure 4.3. Web interface of the PV GIS

taking into account the GSE's outlook on solar power in 2018 [43] that identifies this technology as the most common in Italy. For crystalline silicon, the PV GIS can take into account temperature and irradiance losses. The nominal power of the PV system was selected to 1 KWp, in order to have a unitary generation curve and scale it to higher capacities during the optimization phase. System losses were set at the reference value of 14% and a fixed, free-standing mounting position was chosen. The lifetime of the solar panels was set to 20 years.

PV economics

The average investment cost for domestic PV systems between 2 and 10 kW settles around 1,55 €/W (including VAT) with observed thresholds of 1,33 and 1,74 €/W, 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].

From the investment perspective, it was investigated that for residential installation, the average rate of loans is between 3,5% to 5,0% [18]. Inflation rate was equal to $i = 0,3\%$ from ISTAT data [77] and it was embedded in the interest rate. As a matter of fact, being $k*$, the basic interest rate, the real interest rate k is computed as follows [79]:

$$k = \frac{k* - i}{1 + i} \cong k* - i \quad \text{when } i \ll 1$$

4.1.3 Simulation of the BESS

A simplified model of a lithium-ion battery is used to simulate the energy storage inside the community. Charge and discharge efficiency are equal and are considered constant throughout the lifetime of the battery. The same assumption was made for the depth of discharge (DoD) and the C-rate. The battery investment costs are taken from a cost analysis of BNEF [20] and are divided into a one-off price, the electronic investment cost, and a replacement cost that will be used to compute the wear cost of the battery. The parameters are summarized in Table 4.3:

	Li-ion battery parameters
Charge efficiency %	90
Discharge efficiency %	90
DoD %	20
Maximum battery cycles	3000
Max C-rate	3
Battery investment cost [€/kWh]	200
Battery electronic investment cost [€/kWh]	100
Battery replacement cost [€/kWh]	100
Battery Opex [€/kWh*yr]	1% Capex

Table 4.3. Technical specifications of the Li-ion battery

4.1.4 Simulation of the energy market

The market is simulated when taking into account the electricity exchanges between active users and the grid. As already been discussed in the previous chapters, an active user or a community can exchange its surplus energy at the zonal price or benefiting of supporting schemes such as RID with minimum granted price or SSP. The trends of the Northern zonal price and RID are taken from the website of the GME (Gestore Mercati Energetici) [80] and are reported in Figures 4.4 and 4.5. From the last Figure it can be seen the effect of the minimum granted price of the RID, that was 0,04 €/kWh in 2019 and imposes a lower limit on the zonal price.

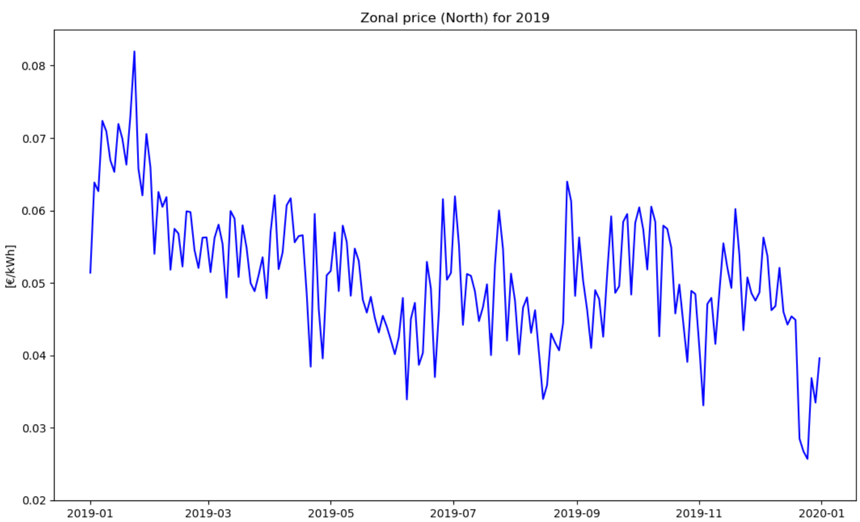


Figure 4.4. 2019 North zonal price

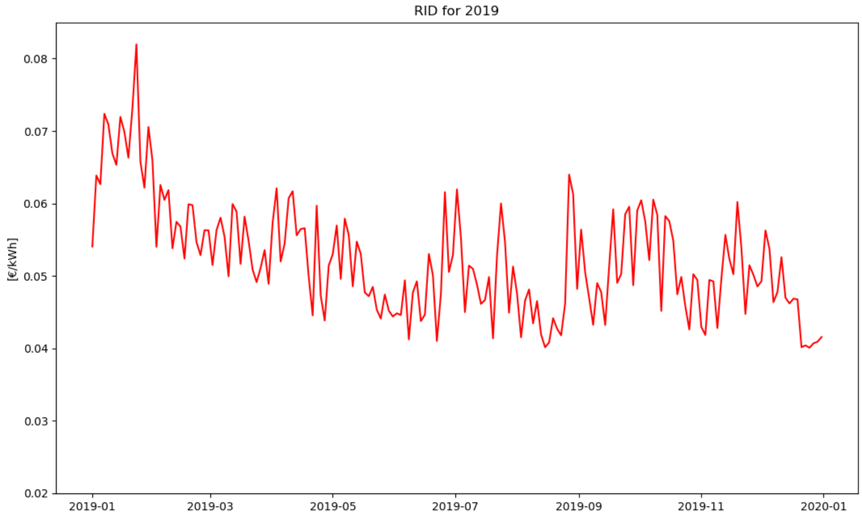


Figure 4.5. 2019 RID

The valorisation of the energy consumed internally, being the boundaries defined by the POD of the user or by the EC, deserves a separate speech. In the case study, the households are classified as domestic users with a single time band contract in protected regime. For the sake of simplicity, in order to have a uniform incentive tariffs applied throughout the year, let's consider the average electricity bill composition taken from ARERA [45] and presented in Table 4.4.

Electricity bill	Wholesale cost	Network costs	Operating costs	Excises
Fixed share $\left[\frac{€}{year*POD}\right]$	48,007	20,28	-	-
Power share $\left[\frac{€}{year*kW}\right]$	-	21,2934	-	-
Energy share $\left[\frac{€}{kWh}\right]$	0,0762625	0,00798	0,041817	0,0227

Table 4.4. PV capacity for stand-alone domestic users with RID

While the fixed share and power share are always paid by the user, the energy share may be subjected to exemptions when an implicit incentive is applied. As we had already seen, self-consumed energy benefits of a total exemption of the variable items of the wholesale cost of electricity, of network costs and of operating costs plus the excises. Consequently, the quantity that defines the value of self-consumed energy is:

- *SCSi (Self-consumption saving index)*=0,149 €/kWh

The incentive given to the energy shared inside an EC is still a matter of discussion and will be decided by the Authority. In the case study, three different cases will be analysed that might take into account the future developments of the incentive.

The quantity that defines the value of shared energy is called *SCSi (Shared energy saving index)*. In the first case, Case A, let's consider that EC are given an implicit incentive equal to the energy share (plus excises) minus the operating costs. In Case B, the shared energy is valued in the same way of the self-consumed energy, meaning that all the energy share of the bill is exempted, i.e. SESi = SCSi. In Case C, an explicit incentive is given that is higher that the one given in Case B. For simplicity let's consider this incentive equal to the SCSi plus the difference between the SESi of Case B and Case A. Taking everything into consideration, the three cases are:

- Case A: SESi = 0,108 €/kWh
- Case B: SESi = 0,149 €/kWh
- Case C: SESi = 0,190 €/kWh

Throughout the case study the *extended* electricity bill concept will be applied as presented in Chapter 3 and it will be used as synonym for electric bill. The extended energy bill is the sum of the conventional electricity bill, plus the valorisation of the surplus electricity through the presented mechanism, plus the possible profit redistribution within the community and possible explicit incentives.

4.1.5 Input data for the uncertainty analysis

The output variable of interest in our analysis is NPV, used for the comparison of the different business models. The input variables are all the investment related quantities for which it was possible to build a probability density function. As it was not possible to access to datasets containing statistical data, the probability density functions have been accordingly built assuming a normal distribution. The input variables, their means and standard deviation are reported in Table 4.5:

Input variable	Mean	Standard deviation	Source
PV capex [€]	1550	110	[18]
PV opex [%]	2	0,2	[19]
k [%]	4	0,4	[18], [77]
BESS capex [€]	200	20	[20], [10]
BESS opex [%]	1	0,1	[20], [81]
BESS efficiency [%]	90	3	[82]

Table 4.5. Uncertainty of input data

4.2 Results of the short-term analysis

The first part of the analysis will investigate whether the formation of an energy community is economically convenient for users that had already invested into a PV system on their roof, sized on their individual needs. The pre-existing PV system size is obtained through the MILP optimization. The analysis will be done considering the yearly electricity bill as proxy of the economic feasibility of the formation of the energy community. As already described in the previous chapters, the surplus energy can be valued via RID or SSP.

4.2.1 Stand-alone users, RID

The optimized PV capacity for stand-alone users valuing their surplus electricity via RID are reported in Figure 4.6 and Table 4.6.

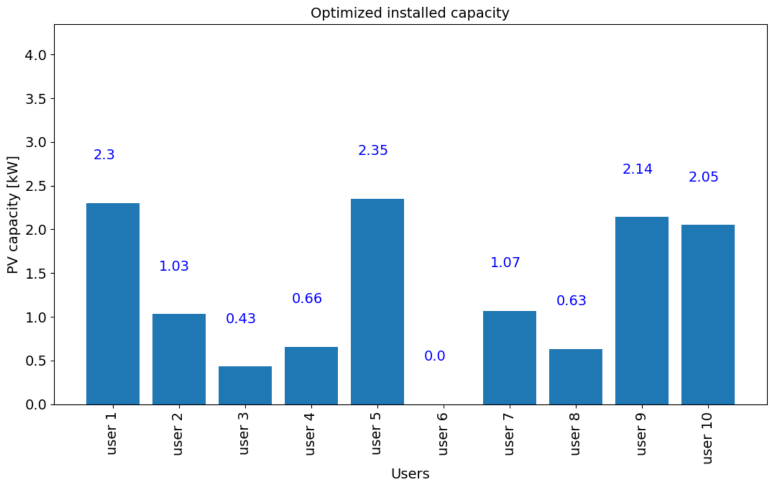


Figure 4.6. PV capacity for stand-alone users with RID

	user 1	user 2	user 3	user 4	user 5	user 6	user 7	user 8	user 9	user 10
Optimized PV [kW]	2,30	1,03	0,43	0,66	2,35	0,00	1,07	0,63	2,14	2,05

Table 4.6. PV capacity for stand-alone users with RID

The RID allows users to afford to invest in some PV capacity as a minimum profit can be obtained by selling the energy at least at the minimum granted price. That explains why also low demanding users get a minimum capacity of PV, that in reality would not be installed. User 6 sees no capacity installed due to its low consumption and bad orientation of the roof. In any case self consumption is encouraged as shown by Figure 4.7. As a matter of fact most users reach a high level of self consumption, 8 active users over a total of 9 self-consume more that 50% of the energy they produce.

The yearly electricity bill of each stand-alone user is reported in Table 4.8. The individual cost of each user is then summed to form the total cost, that is 4752,42 €.

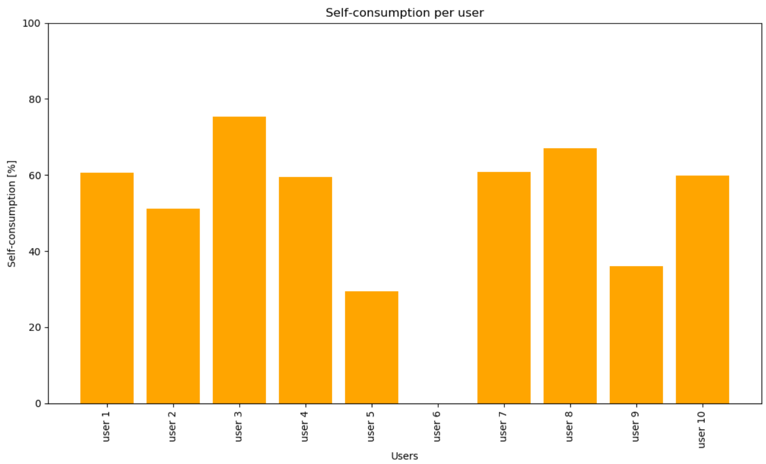


Figure 4.7. Share of self-consumption for stand-alone users with RID

When forming the EC with the same infrastructures, under the conditions of Case A, the total electric bill of the community is 4663,80 €. That means that sharing the excess energy of the active users among the other community members, led to a total saving in the bill equal to the difference between the two total costs, in Case A 88,60 €. Considering Case B, the total cost is 4544,96 € with an overall saving of 207,4 €. Lastly for Case C, the total electric bill for the community is 4415,69 € and a saving of 336,71 €. For a complete outlook of the electricity bills breakdown per users and per item, please see Appendix B.

The savings hereby found can be seen as a profit, a margin for the community. Depending on the purpose of the EC, the margin could be both kept by the community itself to promote social activities as well as it can be redistributed among the members to award them of their participation in the EC. As seen in Chapter 2, the EC can be modelled as a cooperative game that fulfils the concept of superadditivity, thus the grand coalition will form [83]. This is true if and only the game is said to be convex, and this condition can be checked by looking at the sign of each member's marginal contribution. In order to demonstrate this property, let's check the marginal contributions of the members in Case A, that is the least advantageous for the community, due to its low value of shared energy. The results are reported in Table 4.7. All the marginal contributions are negative, meaning that each members brings a benefit to the coalition, thus the game is proved to be convex.

	user 1	user 2	user 3	user 4	user 5	user 6	user 7	user 8	user 9	user 10
Marginal contribution [€]	-26,61	-14,07	-7,86	-7,20	-30,17	-11,08	-29,98	-16,39	-22.50	-22,73

Table 4.7. Marginal contributions of users in Case A

As the game is convex, the Shapley value that results to be the most fair method to allocate profit among the players of a cooperative game, that is to say the members of an EC. The Shapley value takes into account the marginal contribution of each user, meaning that the users that gave a lot of energy to the community will receive a compensation, while users that received large amounts of energy from the community will have to pay a contribution. Shapley value is seen as an amount that goes to be added or subtracted to the electricity bill of each user. Please note that in this case the Shapley value-reward will take a negative sign, as it is subtracted by the electricity bill, while the contribution will be added to the bill. Table 4.8 shows the Shapley values and the final electricity bills for each user in the three cases.

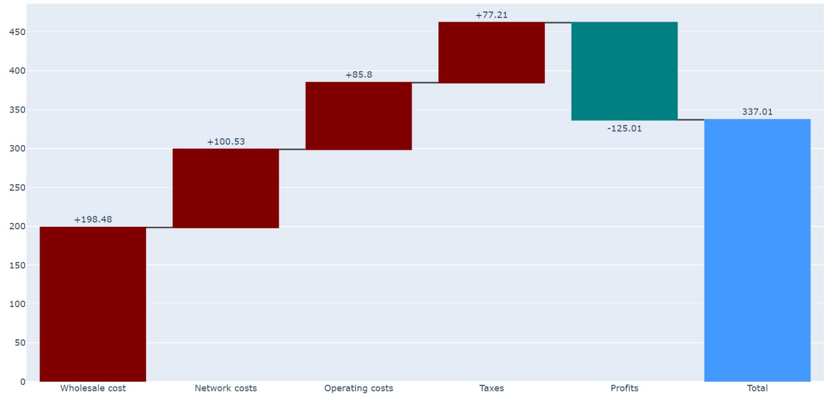
	user 1	user 2	user 3	user 4	user 5	user 6	user 7	user 8	user 9	user 10	Total
Electricity bill stand-alone [€]	539,21	585,91	377.33	399,46	337,01	316,95	445,28	600,06	546,17	605,02	4752,42
Case A											
Shapley redistribution [€]	-2,44	10,41	10,73	0,22	-45,1	15,64	16,38	21,43	-33,91	6,63	
Electricity bill in community [€]	526,95	578,96	373,45	396,11	323,24	311,5	431,12	591,91	535,94	594,62	4663,80
Savings	2,27%	1,19%	1,03%	0,84%	4,09%	1,72%	3,18%	1,36%	1,87%	1,72%	1,86%
Case B											
Shapley redistribution [€]	-4,18	14,61	14,03	0,27	-57,51	19,75	18,9	28,25	-42,73	8,6	
Electricity bill in community [€]	509,94	570,44	368,68	391,54	303,83	304,77	412,30	582,03	521,43	580,02	4544,96
Savings	5,43%	2,64%	2,29%	1,98%	9,85%	3,84%	7,41%	3,00%	4,53%	4,13%	4,37%
Case C											
Shapley redistribution [€]	-5,89	18,73	17,27	0,32	-69,68	23,78	21,37	-34,94	-51,38	10,54	
Electricity bill in community [€]	491,93	558,62	361,55	386,42	288,97	298,32	389,92	567,26	510,07	562,63	4415,69
Savings	8,77%	4,66%	4,18%	3,26%	14,26%	5,88%	12,43%	5,47%	6,61%	7,01%	7,09%

Table 4.8. Electricity bills and Shapley redistribution

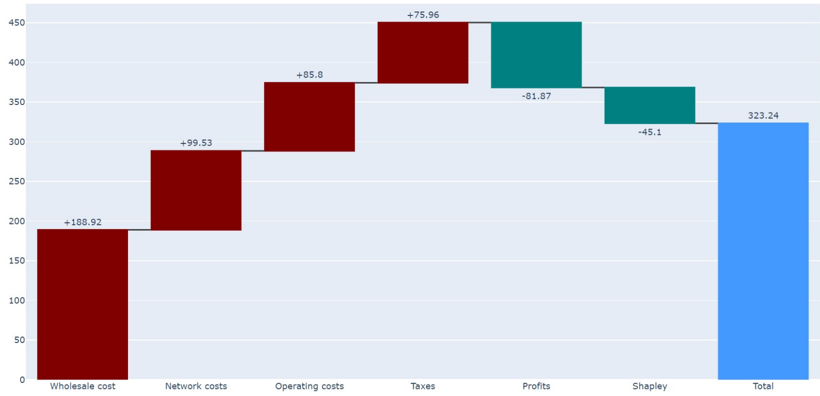
In order to better understand the extended electricity bill composition and the Shapley redistribution, let's consider the case for user 5, shown in Figure 4.8. (the extended bills for all the users are reported in Annex B). The Subfigures show the breakdown of the extended electricity bill, divided into costs and gains. The costs, red columns, represent the conventional electricity bill, divided into wholesale cost of electricity, network costs, operating costs and taxes. The gains, in the green columns, are represented by the profits from selling the energy to the grid, Shapley value redistribution (that is an incoming cash flow for user 5) and the possible explicit incentive.

Comparing the stand-alone case, represented in Subfigure 4.8a with community Case A and Case B, Subfigures 4.8b and 4.8c, we see that the implicit incentive on shared energy reduces the costs proportionally to the granted exemptions. The profits in Case A and B are reduced, due to a lower injection of electricity into the grid, the energy is first shared in the community and then injected, and a lower valorisation of injected energy. Nonetheless, as the shared energy is more valued, the Shapley redistribution increases due to an higher marginal contribution by user 5. If we also take into account Case C in Subfigure 4.8d, we see that there is no difference in the costs, as there are no exemptions in the energy bill, but the user receives an explicit incentive that values the shared energy.

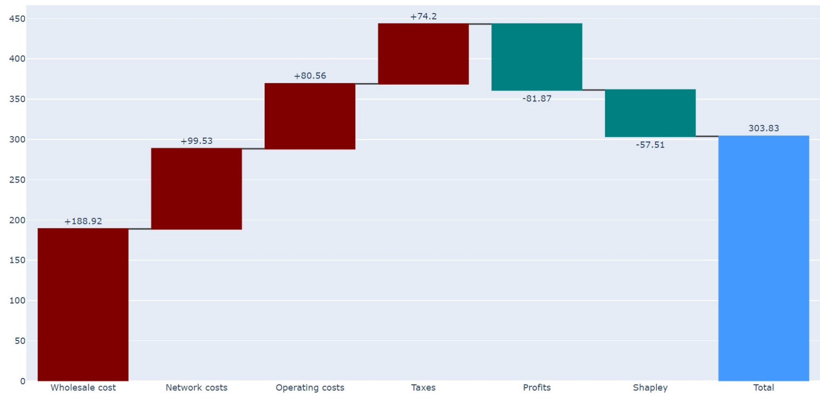
The extended electricity bills for every user and every case are then shown Figure 4.9. It is clear that every user has a profit in joining the REC in all the cases considered. That is because the Shapley value redistribution and the energy taken from the community are enough to balance the loss in the selling of energy with RID with granted minimum price. The highest savings within the community were shown



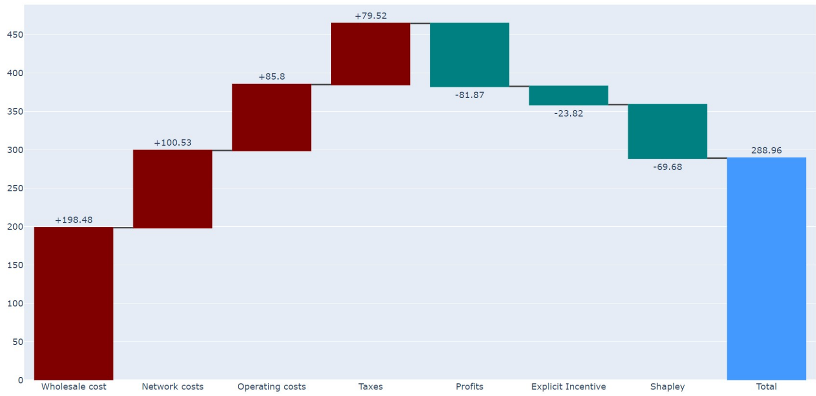
(a) Stand-alone user 5 with RID



(b) User 5 with community Case A



(c) User 5 with community Case B



(d) User 5 with community Case C

Figure 4.8. Extended energy bills (in €) for users with RID

among the users with an abundance of surplus energy (e.g. user 5) and passive users (e.g. user 6). That is a perfect driver for the formation of RECs as it can encourage active users to be part of them while helping passive users to save money in the electric bill.

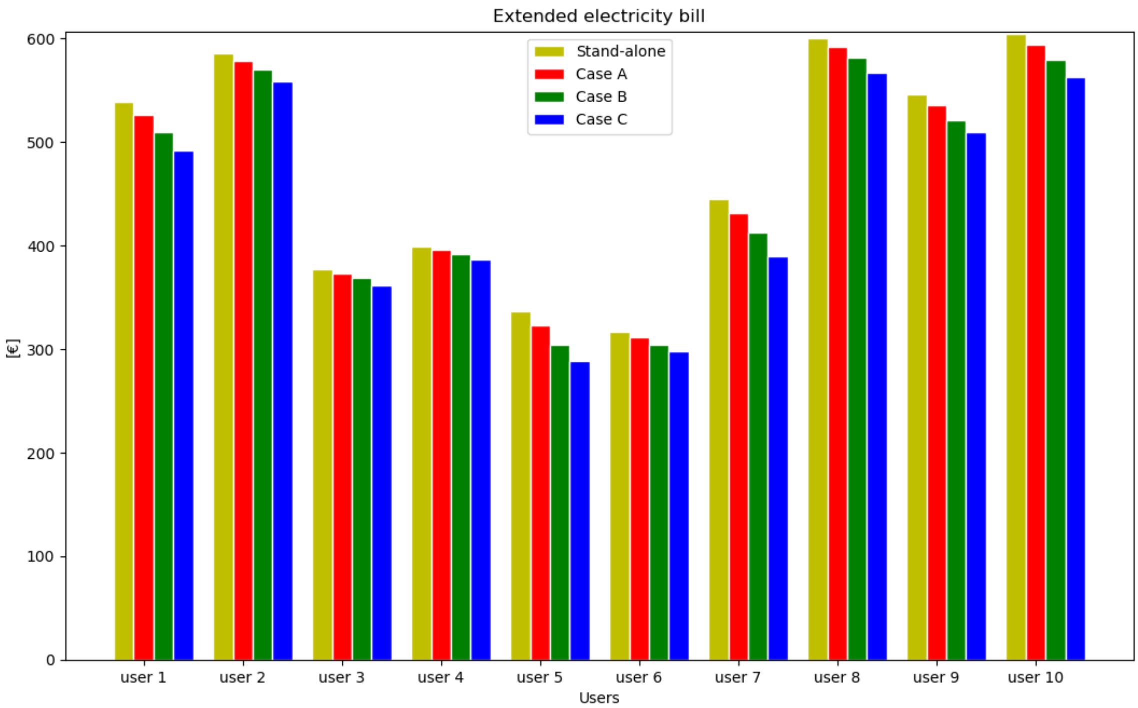


Figure 4.9. Comparison of electricity bills for stand-alone users with RID

4.2.2 Stand-alone users, SSP

Figure 4.10 and Table 4.9 summarise the PV capacity obtained with the MILP optimization for stand alone users valuing the surplus energy with SSP.

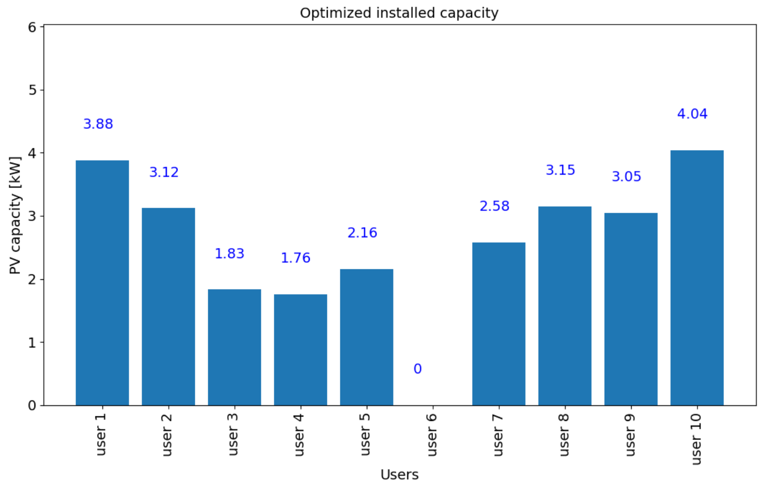


Figure 4.10. PV capacity for stand-alone users with SSP

	user 1	user 2	user 3	user 4	user 5	user 6	user 7	user 8	user 9	user 10
Optimized PV [kW]	3,88	3,12	1,83	1,76	2,16	0,00	2,58	3,15	3,05	4,04

Table 4.9. PV capacity for stand-alone users with SSP

Each user has almost doubled its installed capacity with respect to the case of surplus energy valued by RID. That is because SSP is a mechanism that allows to use the national electric grid as a storage, that is why the most electricity demanding users could afford to install many kW of capacity. Self-consumption did not grow in parallel to the produced energy. As Figure 4.11 shows, no user has reached 50% of self-consumption. Nonetheless, the surplus energy of each user is injected into the grid and highly valued through the yearly grant of SSP.

Table 4.10 summarises the annual extended energy bills for each user. It is important to highlight the marked difference between these value and the one obtained with the valorisation through RID obtained in the previous section. SSP allows active stand-alone users to receive a steady revenue that lowers the electricity costs of 60% on average. Let's consider the sum of all extended electricity bills to evaluate the profitability of forming a REC. The extended electric bill of all stand alone users is 2682,89 €. The first row of Table 4.10 shows the individual annual electric bill. When the community is formed with the assumptions of Case A, the total electric bill will amount 3555,77 €. This time the total electric bill in community is higher than the stand-alone case. It means that instead of a margin, the users have obtained a loss of 872,89 €. In Case B the electric bill is 3444,80 € and the loss of 761,91 €. Lastly, in Case C the total electric bill is 3363,71 € and a loss of 680,83 €. The calculation

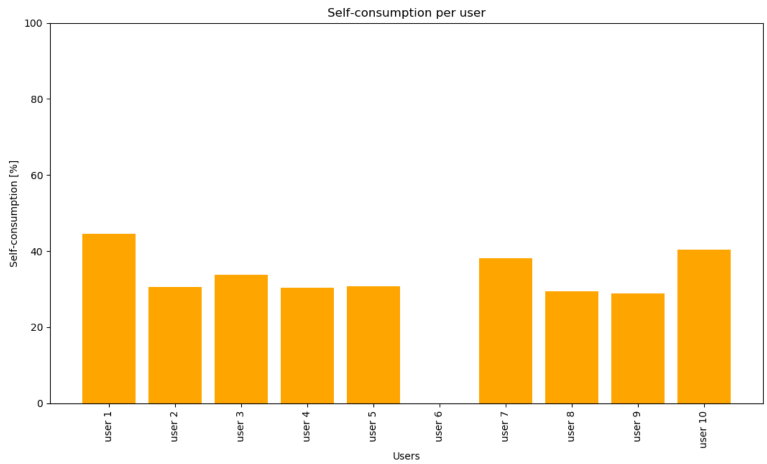


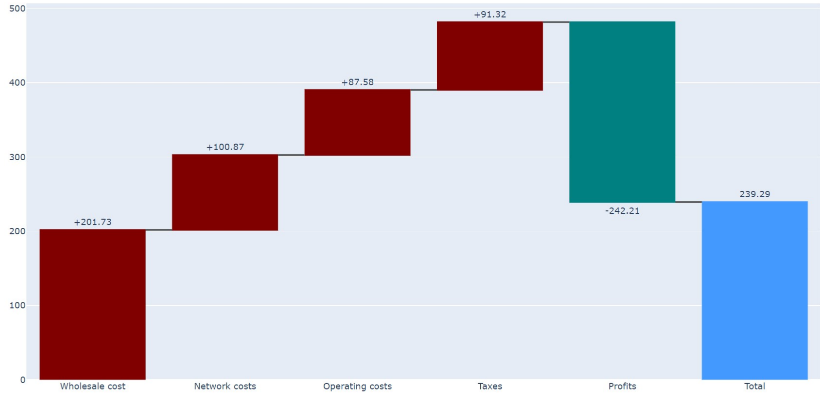
Figure 4.11. Share of self-consumption for stand-alone users with SSP

showed that the formation of the community does not allow to obtain a margin when compare to the benefit given by SSP. For this reason, it does not make sense to apply game theory for redistribution, as the users, driven by economic convenience, will chose the stand-alone configuration. Table 4.10 reports the perceptual loss for each user. Note that user 6 does not report a loss because it does not posses a PV plant, thus it can not benefit of SSP. Thus only user 6 sees savings in forming a community and in the Table are reported in parenthesis. For a more complete overview of the extended electric bill, please look Appendix B.

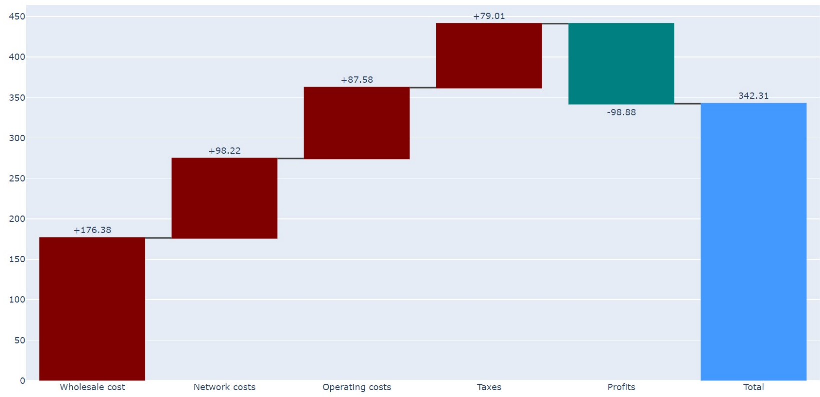
	user 1	user 2	user 3	user 4	user 5	user 6	user 7	user 8	user 9	user 10
Electricity bill stand-alone [€]	291,96	290,70	199,08	215,34	239,29	316,95	221,74	286,40	315,48	305,95
Case A										
Electricity bill in community [€]	393,73	395,53	265,09	305,54	342,32	283,70	302,02	384,20	462,02	421,62
Loss	34,86%	36,06%	33,16%	41,89%	43,06%	(-10,49%)	36,21%	34,15%	46,45%	37,81%
Case B										
Electricity bill in community [€]	381,92	386,58	260,31	301,86	327,15	266,49	284,61	372,70	454,31	408,86
Loss	30,82%	32,98%	30,76%	40,18%	36,72%	(-15,92%)	28,35%	30,13%	44,00%	33,64%
Case C										
Electricity bill in community [€]	374,96	384,41	258,74	304,23	313,15	236,89	265,48	366,12	458,39	401,33
Loss	28,43%	32,24%	29,97%	41,28%	30,87%	(-25,26%)	19,73%	27,84%	45,30%	31,18%

Table 4.10. Electricity bills and losses

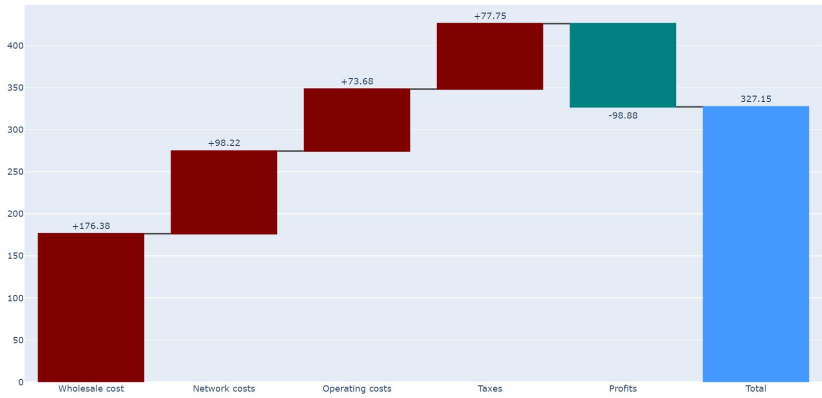
To better understand why SSP is so convenient, let's once again analyse the extended energy bills of user 5 for each case as in Figure 4.12. As shown by Subfigure 4.12a, SSP allows a yearly grant that almost halves the cost of the energy bill. This positive cash flow is not balanced by the incentives allowed to members of the community one this is formed. In particular, considering Case A and B in Subfigures 4.12b and 4.12c, the exemptions allowed in the energy bills and the partial revenue coming from selling the surplus energy at the zonal price, are not enough to balance the incomes from SSP. In a similar fashion in Case C, shown in 4.12d, the explicit incentive on shared energy summed to the profits from selling energy reveal to be unprofitable.



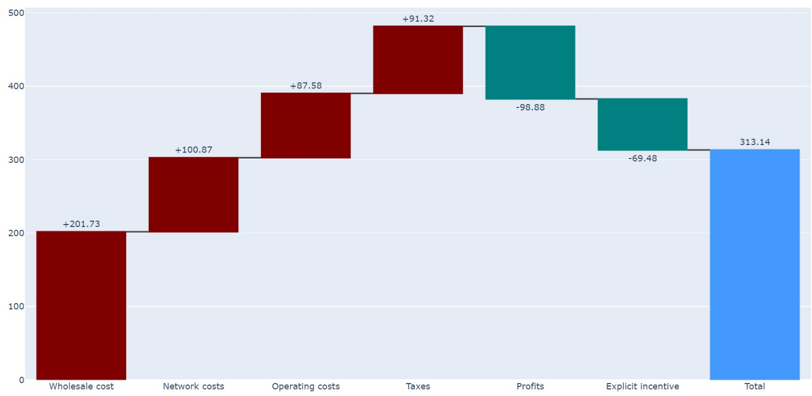
(a) Stand-alone user 5 with SSP



(b) User 5 with community Case A



(c) User 5 with community Case B



(d) User 5 with community Case C

Figure 4.12. Extended energy bills (in €) for users with SSP

We can conclude that if the users are already benefiting of SSP in stand-alone mode, the incentives given to shared energy considered in the scenarios will not be enough to encourage the formation of a community. One exception, that confirms instead the convenience of SSP, comes from the only passive user, user 6, that obtains some savings when it is a member of the community. This is due to the fact that, by not possessing a PV plant, it cannot sell energy to the grid and benefit SSP.

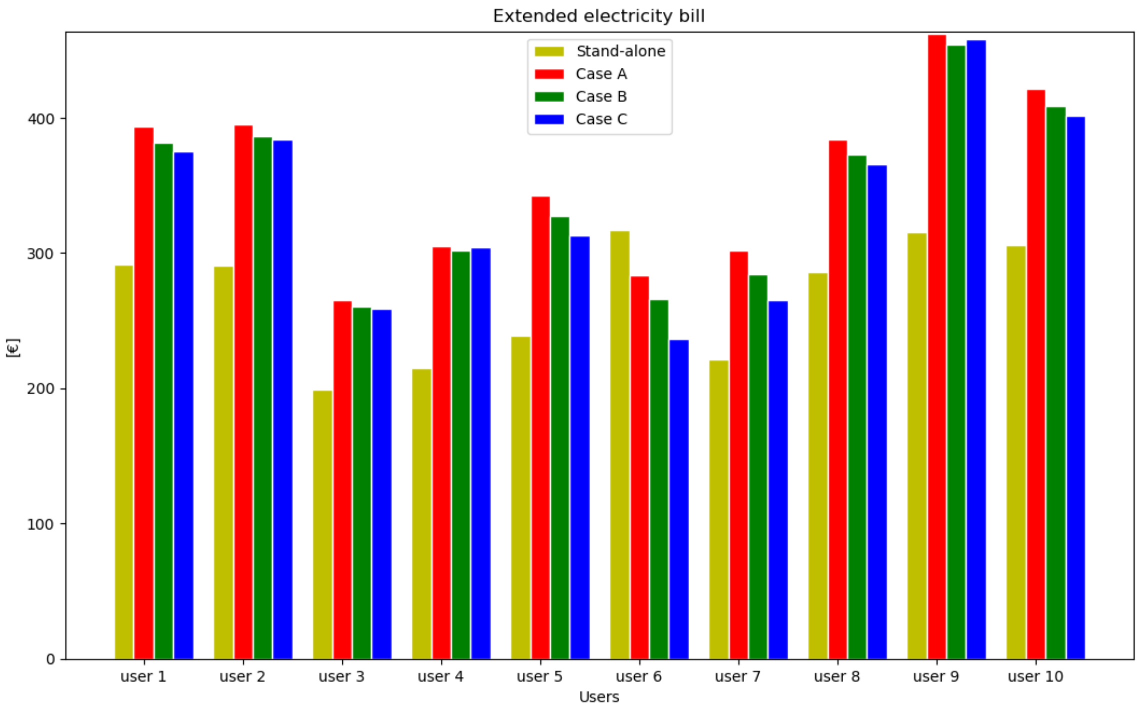


Figure 4.13. Comparison of electricity bills for stand-alone users with SSP

4.3 Results of the long-term analysis

The second part of the analysis will investigate which is the best business model for a user that has decided to invest in renewable energy. Once the CEP will be transposed into national law, the user will be able to choose whether invest in a stand-alone configuration or in a community, teaming up with other users. The section presents different optimizations for the single user benefiting if RID and SSP and for different community configurations: self-consumption priority, shared-energy priority and community with storage. Different values of the SESi (Case A, Case B and Case C) are taken into account.

4.3.1 Stand-alone users, RID

Let's consider now the results obtained in the previous section for stand-alone users, but seen from a holistic point of view. RID allows users to self-consume almost one-fourth of the overall energy needs, but still almost half of the energy generated is injected into the grid. Because of that, almost half of the annual demand is satisfied by electricity taken from the grid. The NPV reported in 4.11 is the sum of the NPVs of the stand-alone users.

	Total of stand-alone users, RID
Total PV installed [kW]	12,66
Load [kWh]	30903,62
Produced [kWh]	15391,36
Injected [kWh]	7846,97
Withdrawn [kWh]	23359,22
Self-Consumed [kWh]	7544,39
Shared [kWh]	0,00
NPV [€]	5531,85

Table 4.11. Main results for stand-alone users with RID

The energy fluxes of the stand-alone users are represented in Figure 4.15. Each user is identified with its own color, on the left the PV production and on the right the electricity consumption. The interactions with the grid are represented at the extremes of the image, the injections into the grid from the PV being on the extreme left and the withdrawing on the extreme right. Self-consumption fluxes are instead the central links. It can be seen that self-consumption is encouraged by this configuration as globally 51% of the generated energy energy is self-consumed, and the remaining 49% injected into the grid. Unfortunately, only 25% of the produced energy satisfies the demand, that has to rely on the energy withdrawn from the grid.

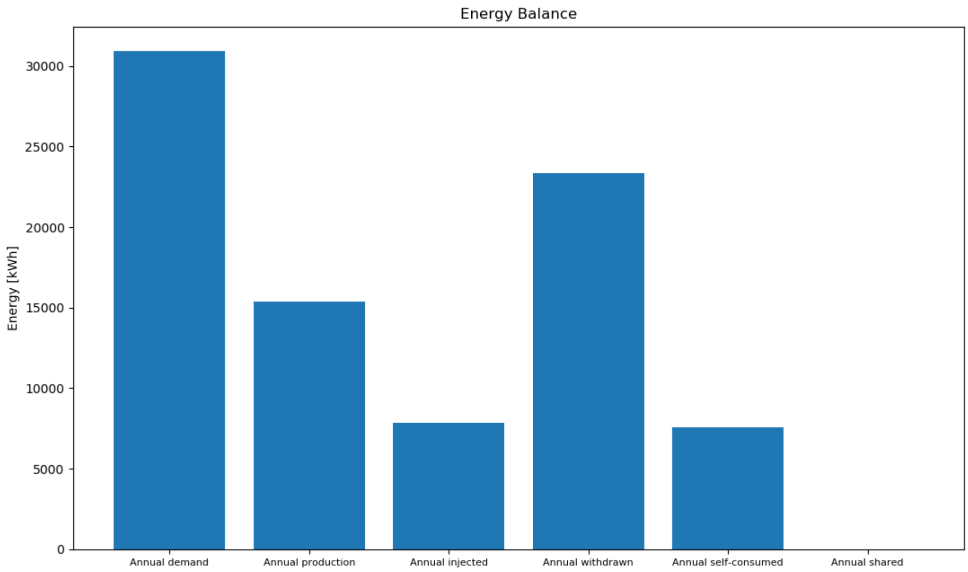


Figure 4.14. Annual energy values for stand-alone users with RID

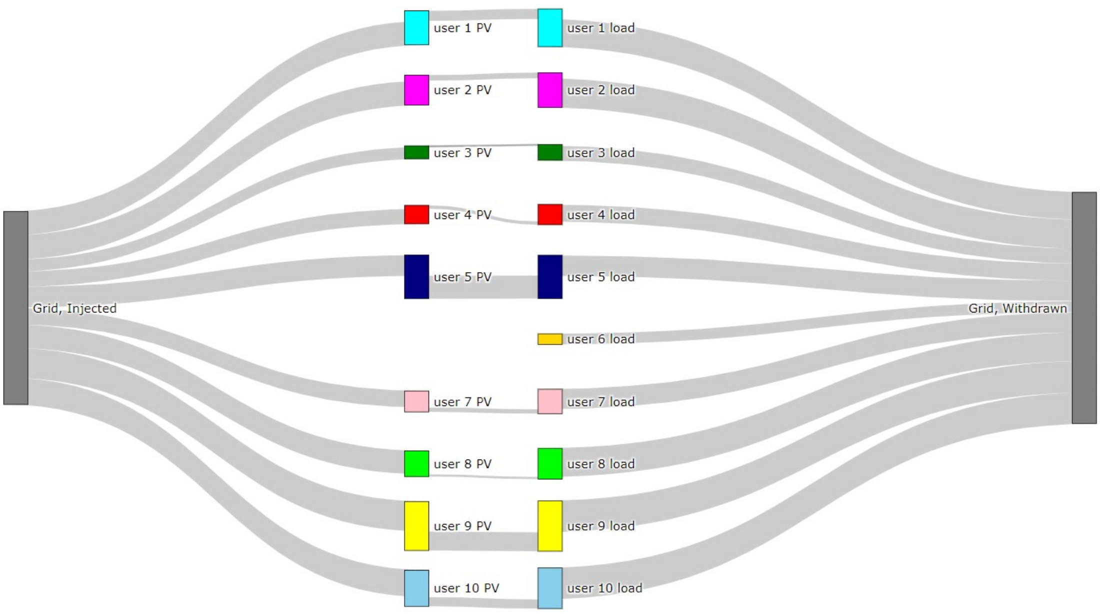


Figure 4.15. Energy fluxes of stand-alone users with RID

4.3.2 Stand-alone users, SSP

The overall results of the previous optimization for stand-alone users is presented in Table 4.12 and Figure 4.16. The great PV capacity installed by the users allows a self-generation that almost covers the overall demand of the stand-alone users. Due to this reason, self-consumption is encouraged as well as injections into the grid that will be highly valued at the end of each year.

	Total of stand-alone users, SSP
Total PV installed [kW]	25,57
Load [kWh]	30903,62
Produced [kWh]	29819,69
Injected [kWh]	19487,58
Withdrawn [kWh]	20571,50
Self-Consumed [kWh]	10332,11
Shared [kWh]	0,00
NPV [€]	16904,57

Table 4.12. Main results for stand-alone users with SSP

Once again the NPV reported in Table 4.12 is the sum of all the individual NPVs of the stand-alone users. The NPV is almost three times higher than in the previous case thanks to the high profit assured by SSP.

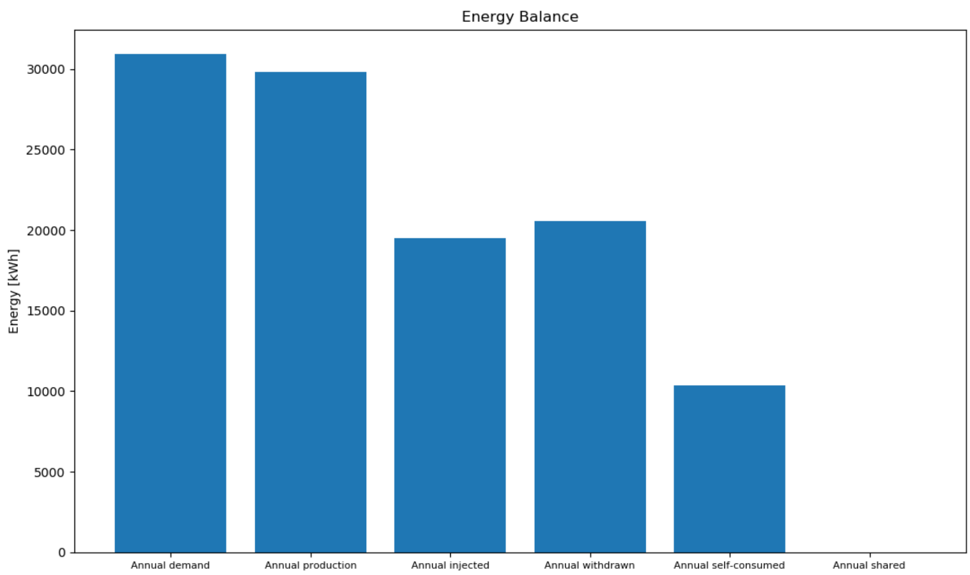


Figure 4.16. Annual energy values for stand-alone users with SSP

The energy fluxes reported in 4.16 confirm the fact that SSP is more a tool that encourages injections into the grid rather that self-consumption, that is anyhow increased with respect to the case with RID. The same trend is confirmed my the Sankey chart of Figure 4.17, that graphically shows that the electricity introduced into the grid increased to 65% of the produced energy, compared to the 49% of the case with RID. Due to the greater PV capacity installed the users are still able to self-consume and the withdrawn energy reduces to 66%.

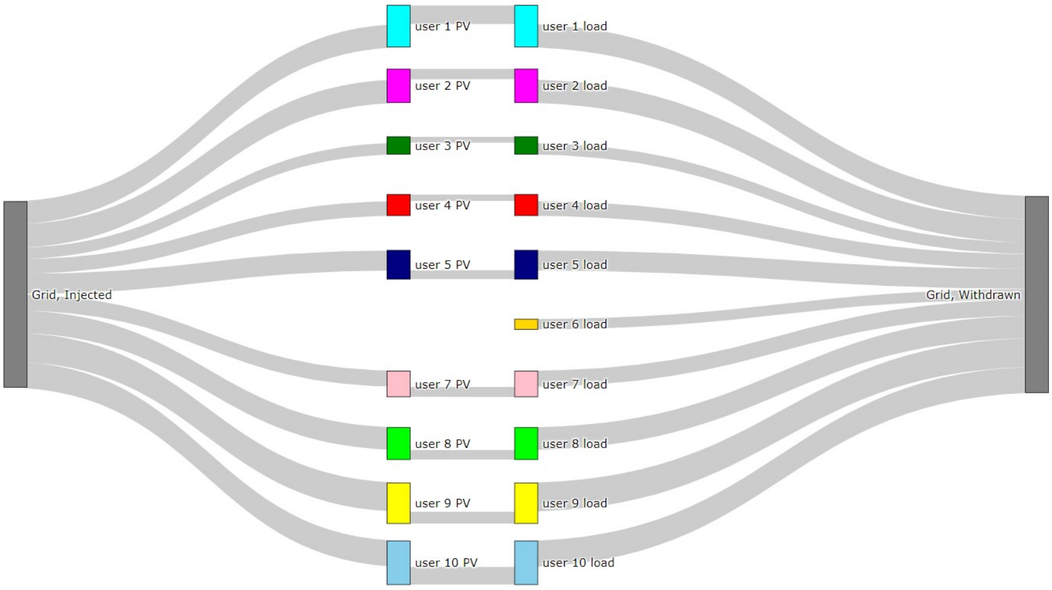


Figure 4.17. Energy fluxes of stand-alone users with SSP

4.3.3 Community with shared-consumption priority

The optimization of the community when shared-consumption priority is considered led to the PV capacity summarized in Table 4.13 and Figure 4.18, in which Case A is reported in red, Case B in green and Case C in blue.

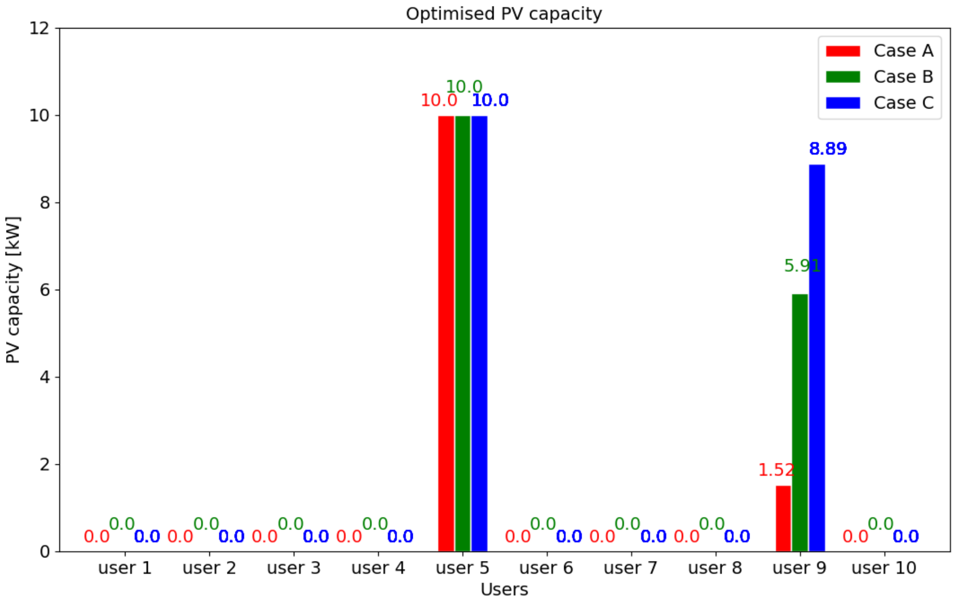


Figure 4.18. PV capacity for the community with shared-consumption priority

Optimized PV [kW]	user 1	user 2	user 3	user 4	user 5	user 6	user 7	user 8	user 9	user 10
Case A	0,00	0,00	0,00	0,00	10.00	0,00	0,00	0,00	1,52	0,00
Case B	0,00	0,00	0,00	0,00	10.00	0,00	0,00	0,00	5,91	0,00
Case C	0,00	0,00	0,00	0,00	10.00	0,00	0,00	0,00	8,89	0,00

Table 4.13. PV capacity for the community with shared-consumption priority

As the energy produced by the PV plant is owned by the whole community and not by the user on which roof the PV is installed, the capacity is concentrated on a few roofs, in particular the ones oriented to the South. A higher SESi allows to install more PV capacity, as the shared energy is more valued. As it can be seen from the annual energy values reported in Table 4.14, the energy community is still dependent from the grid as almost two-thirds of the annual electricity is withdrawn. In Case B and Case C, the higher capacity is used to sell more electricity to the grid, rather than for shared-consumption that remains roughly steady.

The NPVs reported in the last row of Table 4.14 are common profits for all the members. The difference in the three cases is mainly given by the profit coming from selling the energy at the zonal price rather that from savings from self-consumption.

	Case A	Case B	Case C
Total PV installed [kW]	11,52	15,91	18,89
Load [kWh]	30903,62	30903,62	30903,62
Produced [kWh]	16105,70	22237,93	26407,86
Injected [kWh]	5998,47	10822,88	14410,95
Withdrawn [kWh]	20796,39	19488,57	18906,71
Self-Consumed [kWh]	0,00	0,00	0,00
Shared [kWh]	10107,23	11415,05	11996,90
NPV [€]	5182,88	11968,88	19066,24

Table 4.14. Main results for the community with shared-consumption priority

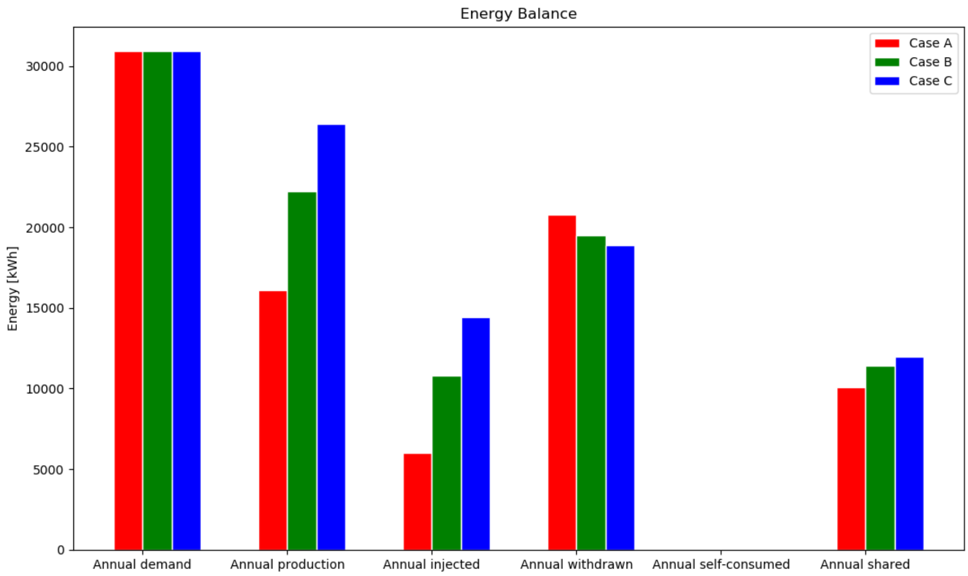
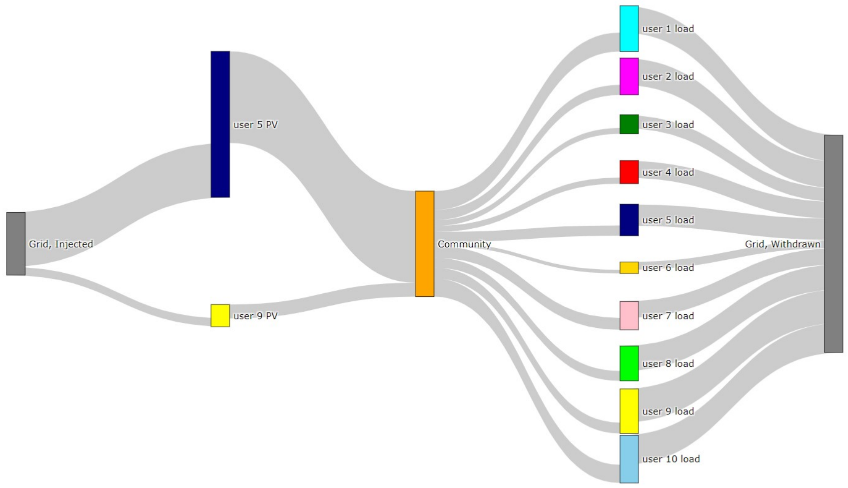
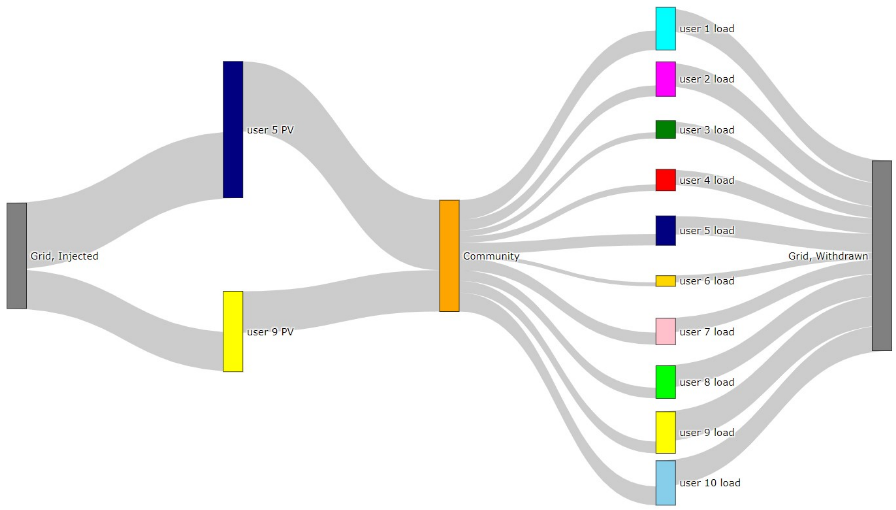


Figure 4.19. Annual energy values for the community with shared-consumption priority

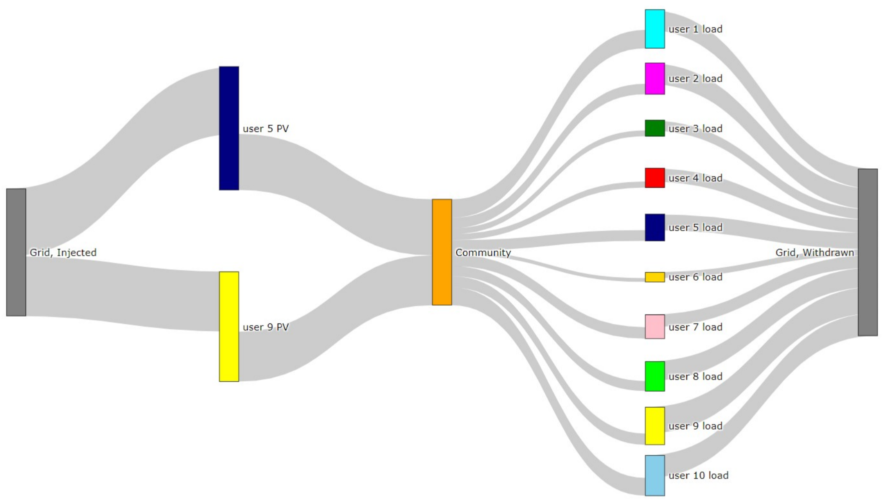
The energy fluxes are shown in the Sankey diagram of Figure 4.19, showing in each Case how the electricity produced by the two PV plants benefits the whole community. As a matter of fact, the energy needed by the community is taken from the generated energy and then redistributed among the members. The surplus energy is then sold to the grid. It is anyhow evident how the users have to rely on the electricity withdrawn from the grid. It is interesting to report how in Case A, shared energy amounts to 65% of the total generated energy, while in Case C the share plummets to 45%. This is due to an increase of 37% of the PV capacity and generated electricity.



(a) Case A



(b) Case B



(c) Case C

Figure 4.20. Energy fluxes of the community with shared-consumption priority

4.3.4 Community with self-consumption priority

The results of the PV capacity optimization are presented in Figure 4.21 and Table 4.15. The internal rules of this community prioritise the self-consumption of the produced electricity and only after the sharing of the surplus to the other members of the community. Please note that when valuing the self-consumed electricity and the shared electricity the same amount, the so-called Case B, the optimization becomes the same of a community with shared consumption priority. When considering Case C instead, the optimization becomes very similar, but not equal to the case with community with shared-consumption priority.

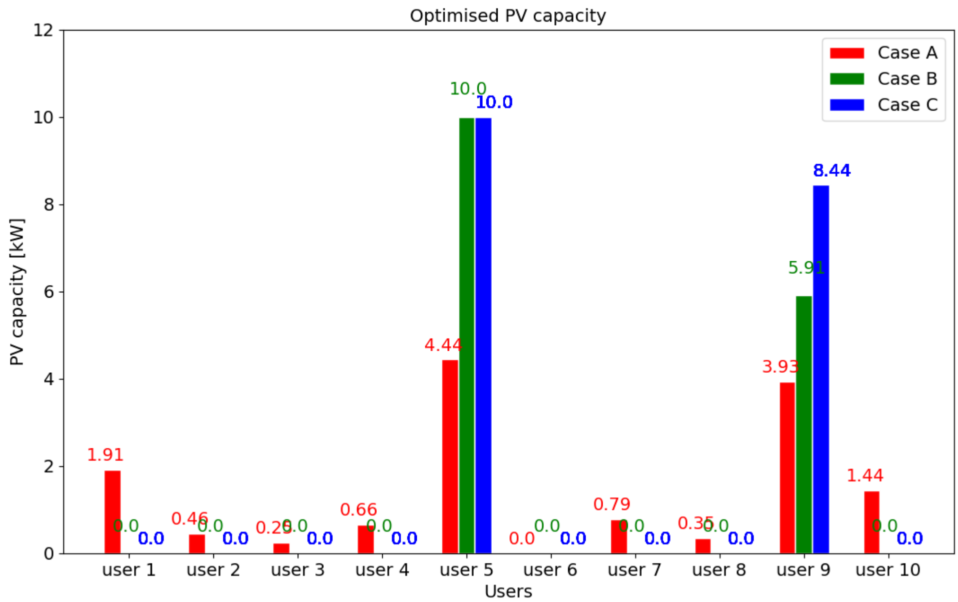


Figure 4.21. PV capacity for the community with self-consumption priority

Optimized PV [kW]	user 1	user 2	user 3	user 4	user 5	user 6	user 7	user 8	user 9	user 10
Case A	1,91	0,46	0,25	0,66	4,44	0,00	0,79	0,35	3,93	1,44
Case B	0,00	0,00	0,00	0,00	10.00	0,00	0,00	0,00	5,91	0,00
Case C	0,00	0,00	0,00	0,00	10.00	0,00	0,00	0,00	8,44	0,00

Table 4.15. PV capacity for the community with self-consumption priority

Considering Case A, when self-consumed energy is valued more than shared energy, each user has the opportunity to self-consume the energy produced on their roof, that is why almost every user can afford to install its own PV. When SESi assumes higher values than the SCSi, it becomes more convenient to share energy rather than self-consume it, then the PV capacity centers around two better oriented roofs that assure more electricity production. Anyhow, internal consumption is still limited by the impossibility of meeting production and demand, thus only one-third of the generated electricity is internally consumed, while the rest is injected into the grid, still assuring some revenues. Comparing the NPVs in the last row of Table 4.16, the value improves due a combination of an increase of the electricity sold and of the energy self-consumed, while the withdrawing stays stable.

	Case A	Case B	Case C
Total PV installed [kW]	10,30	15,91	18,44
Load [kWh]	30903,62	30903,62	30903,62
Produced [kWh]	18279,15	22237,93	25784,21
Injected [kWh]	7426,19	10822,88	13863,33
Withdrawn [kWh]	20050,66	19488,57	18982,74
Self-Consumed [kWh]	7089,58	0,00	2992,33
Shared [kWh]	3763,38	11415,05	8928,54
NPV [€]	8147,79	11968,88	17250,27

Table 4.16. Main results for the community with self-consumption priority

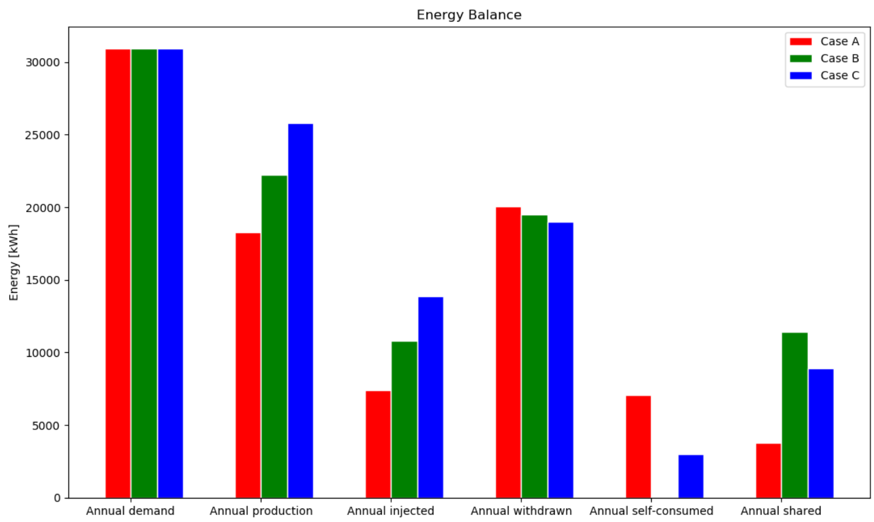
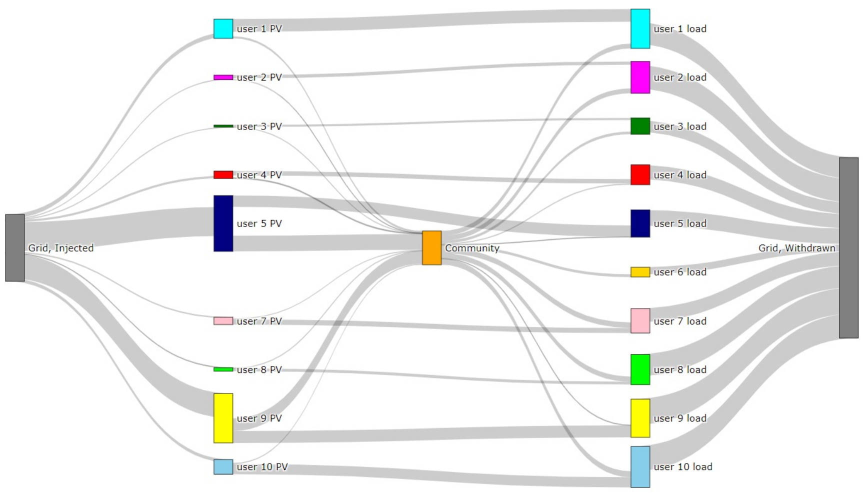
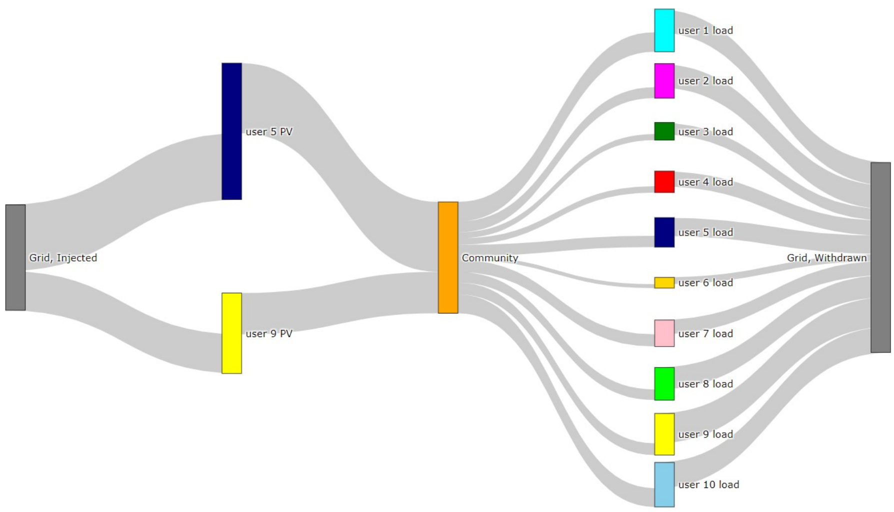


Figure 4.22. Annual energy values for the community with self-consumption priority

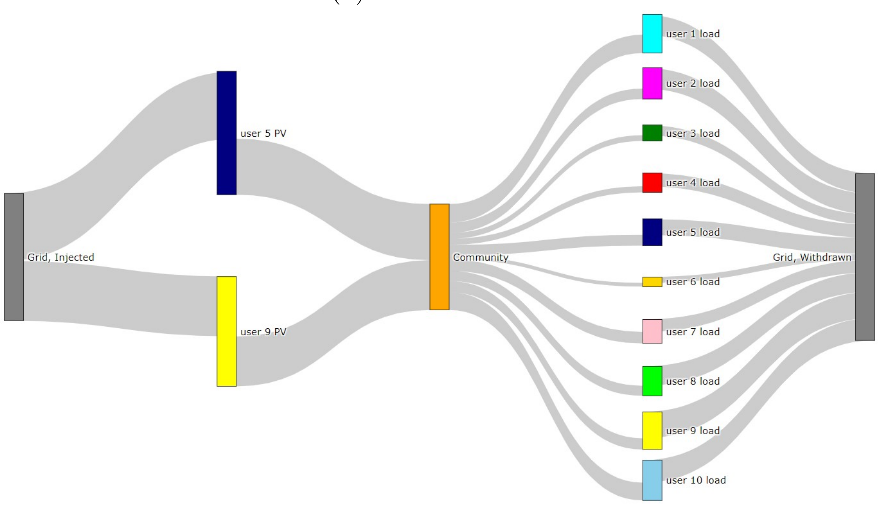
Figure 4.23 shows the annual energy fluxes for the community in each Case. For Case A almost every user can enjoy some self-consumption, while the rest is mainly given to the community for a further share. In particular, 23% of generated energy is self-consumed, while only 12% is shared. The rest is injected into the grid. It is interesting to see how the biggest producers, users 5 and 9, still inject the majority of the generated energy into the grid.



(a) Case A



(b) Case B



(c) Case C

Figure 4.23. Energy fluxes of the community with self-consumption priority

4.3.5 Community with BESS

This case explores the possibility to install a shared lithium-ion battery in the community, that allows to store the surplus energy for a delayed use. The community rule is the shared-energy priority as the battery is owned by the whole community, it is also reasonable to assume that also the PV plants are community owned.

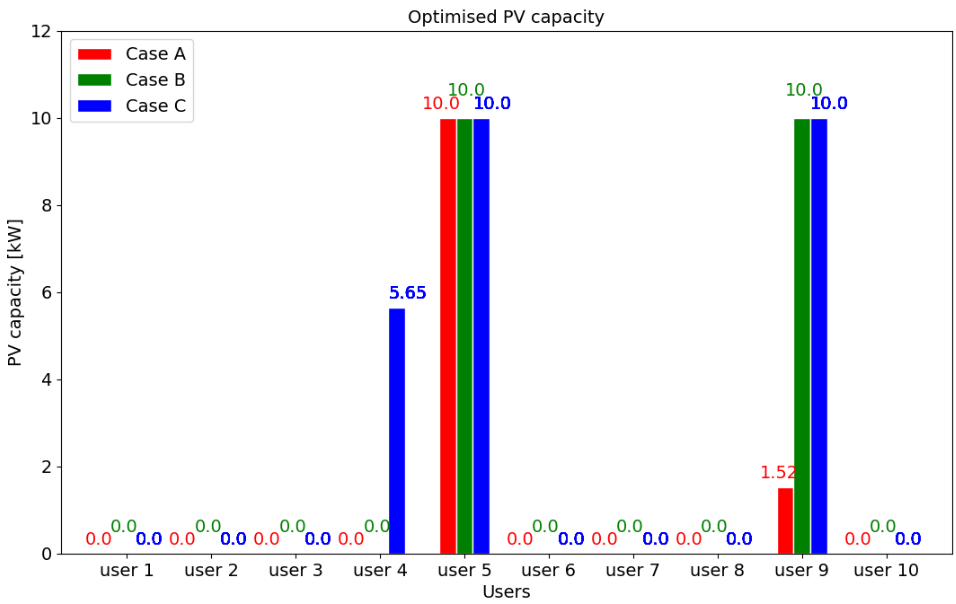


Figure 4.24. PV capacity for the community with BESS

Optimized PV [kW]	user 1	user 2	user 3	user 4	user 5	user 6	user 7	user 8	user 9	user 10
Case A	0,00	0,00	0,00	0,00	10.00	0,00	0,00	0,00	1,52	0,00
Case B	0,00	0,00	0,00	0,00	10.00	0,00	0,00	0,00	10,00	0,00
Case C	0,00	0,00	0,00	5,65	10.00	0,00	0,00	0,00	10,00	0,00

Table 4.17. PV capacity for the community with BESS

	Case A	Case B	Case C
Optimized BESS [kWh]	0,00	58.66	76,65

Table 4.18. BESS capacity for the community with BESS

When a lower value of the shared energy is considered as in Case A, it does not become convenient to install a storage system, and the optimization becomes equal to an optimization for a community with shared-consumption priority. On the other hand, a highly valued shared energy as in Case B leads to the installation of a battery with a capacity of 58,66 kWh. The battery allows to install more PV capacity by exploiting the two roofs that are oriented to the South. Furthermore, when considering Case C, the battery capacity reaches 76,65 kWh, allowing to saturate the roofs of users 5 and 9 with PV and installing more power on roof 4.

The PV capacity installed in Case B allows to share almost 85% of the produced energy and consequently to reduce the energy withdrawn into the grid. As a consequence of the battery, also the energy injected has a reduction. Furthermore in Case C, the increased electricity generation improves the energy sharing of a few hundreds kWh, thus decreasing the withdrawn energy, but its main effect is in a surge of the electricity sold. From Case A to Case C, the NPV has steadily grown, despite the increase of the magnitude of the initial investment. That is because the battery allows to install more PV and improve the shared-consumption within the community, by reducing the dependence from the electric grid while selling more electricity.

	Case A	Case B	Case C
Total PV installed [kW]	11,52	20,00	25,65
BESS capacity instaled [kWh]	0,00	58,66	76,65
Load [kWh]	30903,62	30903,62	30903,62
Produced [kWh]	16105,7	27958,10	35031,20
Injected [kWh]	5998,47	3960,86	7776,88
Withdrawn [kWh]	20796,39	8885,23	6340,47
Self-Consumed [kWh]	0,00	0,00	0,00
Shared [kWh]	10107,23	23051,01	24563,14
NPV [€]	5182,88	16389,05	30445,79

Table 4.19. Main results for the community with BESS

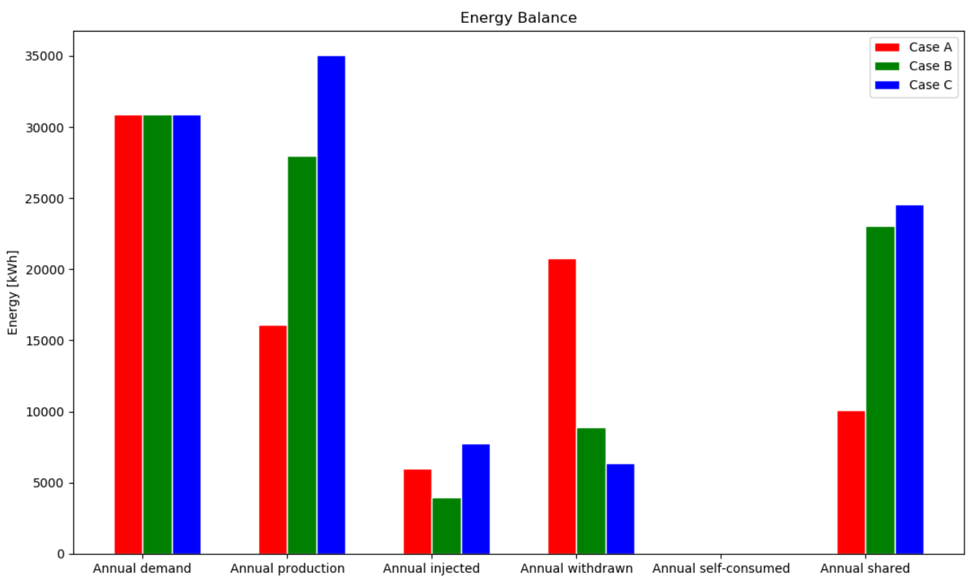
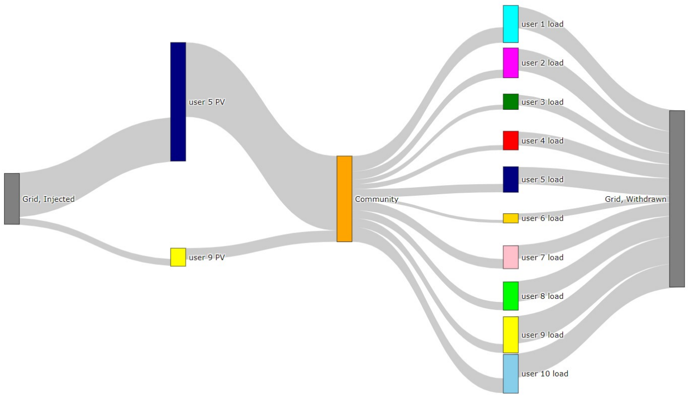
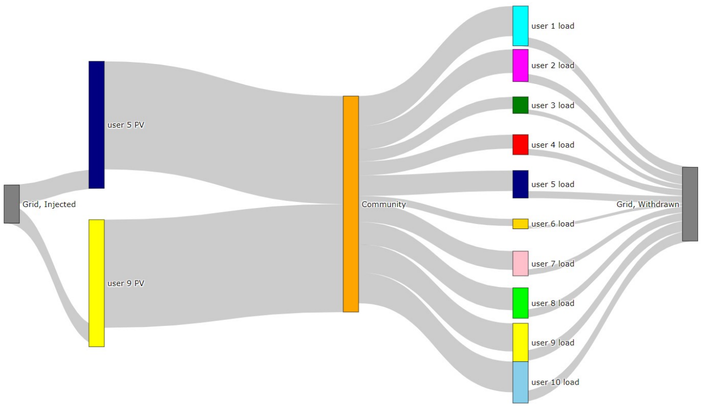


Figure 4.25. Annual energy values for the community with BESS

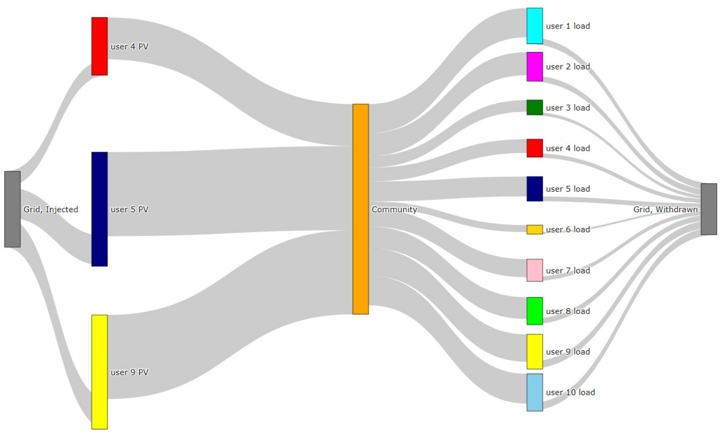
The energy fluxes are reported in the Sankey diagram of Figure 4.26. Case A is equal to the configuration with shared energy. The charts of Case B and C shows the great amount of energy that can be stored within the community and the limited energy injected into the grid. The battery in the community allows to decouple the generation from PV and the demand of the members. Most of this demand is then satisfied by the electricity coming from the community that is equally sorted among the members. In particular, in Case A only 33% of the demand is satisfied by internal production, while in Case B is the 75% and in Case C the 79%.



(a) Case A



(b) Case B



(c) Case C

Figure 4.26. Energy fluxes of the community with BESS

4.3.6 Comparison

It is now useful to summarise all the results found so far and draw a comparison among the business models. The results are grouped by case, Table 4.20 summarises the findings of stand-alone users and Case A, Table 4.21 for Case B and Table 4.22 for Case C.

	RID	SSP	Shared	Self	BESS
Total PV installed [kW]	12,66	25,57	11,52	10,30	11,52
BESS capacity installed [kWh]	0,00	0,00	0,00	0,00	0,00
Load [kWh]	30903,62	30903,62	30903,62	30903,62	30903,62
Produced [kWh]	15391,36	29819,69	16105,7	18279,15	16105,7
Injected [kWh]	7846,97	19487,58	5998,47	7426,19	5998,47
Withdrawn [kWh]	23359,22	20571,50	20796,39	20050,66	20796,39
Self-Consumed [kWh]	7544,39	10332,11	0,00	7089,58	0,00
Shared [kWh]	0,00	0,00	10107,23	3763,38	10107,23
NPV [€]	5531,85	16904,57	5182,88	8147,79	5182,88

Table 4.20. Comparison of the optimization results for Case A

When considering a value of shared energy of SESi = 0,108 €kWh, the formation of the REC is not economically convenient when compared to stand-alone users with SSP as it can be seen by the last row of Table 4.20, reporting the NPVs. As already mentioned, SSP favours electricity injection rather than self-consumption. This can be seen by the fact that, even if the stand-alone SSP configuration has the highest capacity installed, the internally consumed energy (i.e. self and shared consumption) is higher in the community configuration with self-consumption priority, 10332,11 kWh for SSP against 10852,96 kWh for the community, even tough here the installed PV capacity is more than halved. It has to be noticed that the implicit incentive of Case A is not enough to justify the use of a battery in the community.

	RID	SSP	Shared	Self	BESS
Total PV installed [kW]	12,66	25,57	15,91	15,91	20,00
BESS capacity installed [kWh]	0,00	0,00	0,00	0,00	58,66
Load [kWh]	30903,62	30903,62	30903,62	30903,62	30903,62
Produced [kWh]	15391,36	29819,69	22237,93	22237,93	27958,10
Injected [kWh]	7846,97	19487,58	10822,88	10822,88	3960,86
Withdrawn [kWh]	23359,22	20571,50	19488,57	19488,57	8885,23
Self-Consumed [kWh]	7544,39	10332,11	0,00	0,00	0,00
Shared [kWh]	0,00	0,00	11415,05	11415,05	23051,01
NPV [€]	5531,85	16904,57	11968,88	11968,88	16389,05

Table 4.21. Comparison of the optimization results for Case B

When the electricity shared within the community is valued the same as self-consumed electricity, the community configurations start to become competitive with respect to the stand-alone case with SSP, even if the NPV of the latter case remains undisputed as shown in Table 4.21. With respect to Case A, the internally consumed electricity is higher in all the community configurations compared to the SSP stand-alone case, with a surge of the community with BESS that allows a storage of electricity. Moreover, the community with BESS configuration allows a more efficient electricity generation with less installed capacity. That is because the centralization of energy production allowed to exploit the best oriented roof, while in stand-alone configuration an higher PV capacity was spread among the users.

	RID	SSP	Shared	Self	BESS
Total PV installed [kW]	12,66	25,57	18,44	18,89	25,65
BESS capacity installed [kWh]	0,00	0,00	0,00	0,00	76,65
Load [kWh]	30903,62	30903,62	30903,62	30903,62	30903,62
Produced [kWh]	15391,36	29819,69	25784,21	26407,86	35031,20
Injected [kWh]	7846,97	19487,58	13863,33	14410,95	7776,88
Withdrawn [kWh]	23359,22	20571,50	18982,74	8906,71	6340,47
Self-Consumed [kWh]	7544,39	10332,11	2992,33	0,00	0,00
Shared [kWh]	0,00	0,00	8928,54	11996,90	24563,14
NPV [€]	5531,85	16904,57	17250,27	19066,24	30445,79

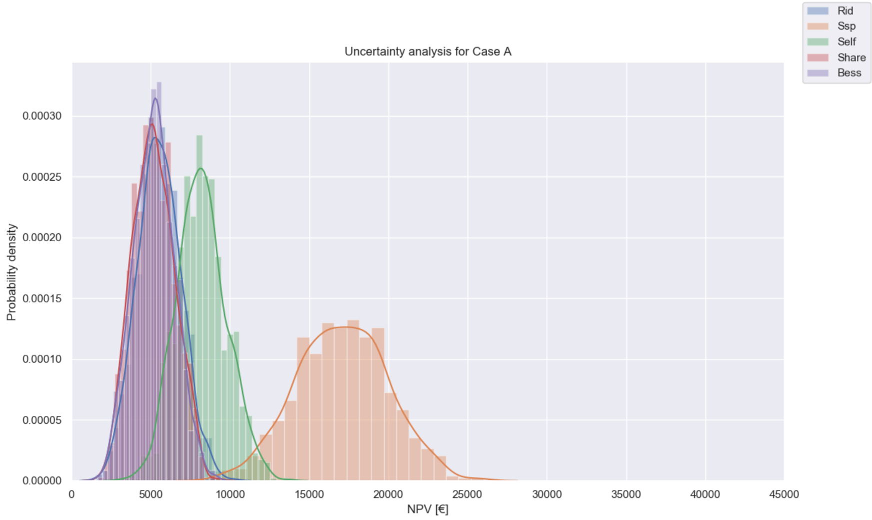
Table 4.22. Comparison of the optimization results for Case C

The high explicit incentive on shared energy allowed in Case C, makes eventually two out of three community configurations more profitable that the stand-alone configuration with SSP. As it can be seen by Table 4.22, the NPVs of community with BESS and community with shared consumption priority overtake the NPVs of the stand-alone configuration. As in the previous case, the battery allows the community a more efficient electricity production an increased consumption of internally generated electricity.

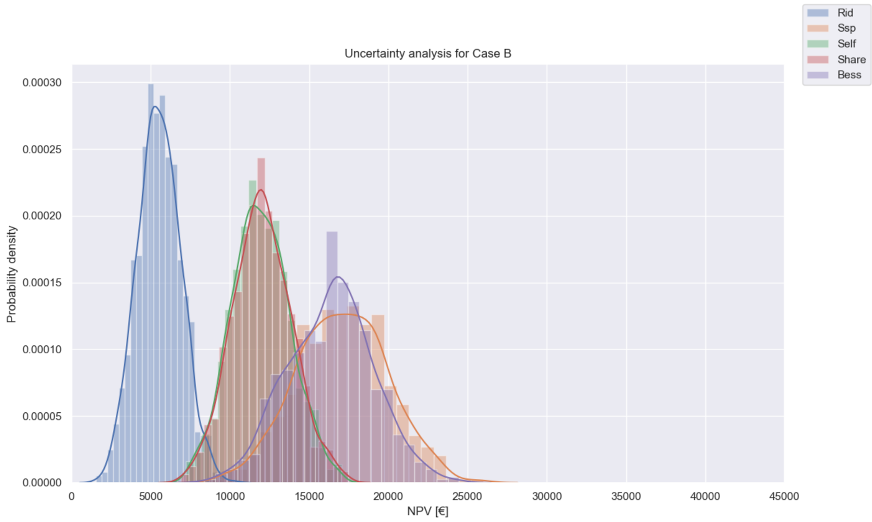
4.4 Results of the uncertainty analysis

In order to validate the approach and the results found in the case study, an Uncertainty Analysis (UA) is performed. The goal of the UA is to create a probability distribution of the output of the model, i.e. of the NPV, starting from the uncertainty of the input variables. The input parameters examined are the capex and opex of PV and BESS, the discount rate and BESS' efficiency. Their probability distribution is created from data found in literature. A Monte Carlo sampling method is used to select random values of input variables for every run of the model, consequently the outputs of the runs are used to build a histogram representing the uncertainty of the NPV. The results of the UA are reported in Figure 4.27, where the probability density functions of the NPVs are compared for each case. The extended outputs of the Monte Carlo process are instead shown in Appendix C.

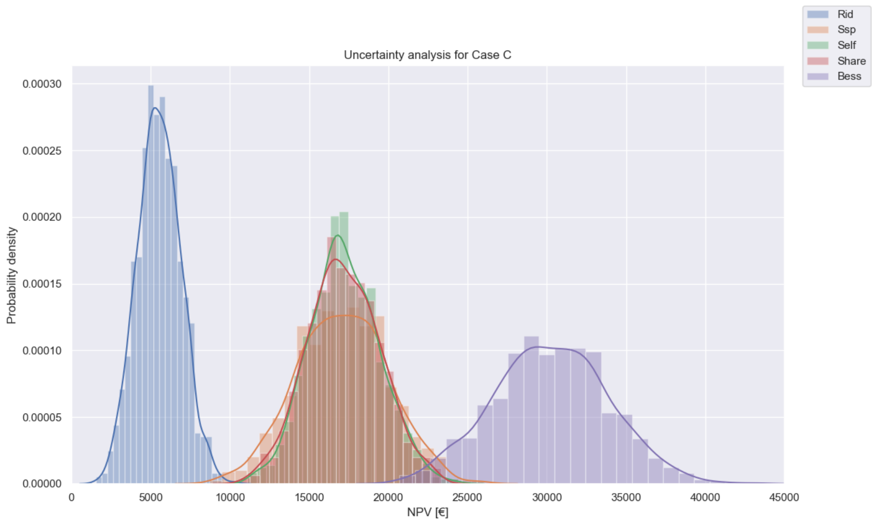
The UA for Case A shown in Subfigure 4.27c confirms the convenience of the stand-alone configuration with SSP (orange bell). Even though the standard deviation of this case is greater that the other configuration, great part of the bell is not overlapped



(a) Case A



(b) Case B



(c) Case C

Figure 4.27. Results of the uncertainty analysis

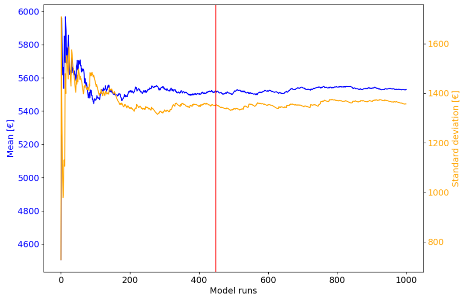
by the others. On the contrary, the uncertainty analysis for Case B, in Subfigure 4.27b, reveals that there is almost a complete overlapping between the stand-alone SSP configuration (in orange) and the community configuration with BESS (in purple), meaning that depending on the input data of each case, one configuration might result more convenient than the other. Lastly, Case C in Subfigure 4.27c confirms the absolute convenience of the community configuration with BESS (in purple). Let's assume to describe the outputs with Gauss distributions, the mean and the standard deviation of the NPV in each case are reported in Table 4.23.

Case		Mean [€]	Standard deviation [€]	Iterations to convergence
Stand-alone	SSP	17077.49	2867.52	150
	RID	5529,60	1356.43	448
Community share	A	5173.66	1294.69	317
	B	12037.82	1851.17	221
	C	17077.49	2867.52	248
Community self	A	8204.68	1560.78	181
	B	11934.22	1824.74	84
	C	17228.71	2194.27	38
Community BESS	A	5203.78	1263.65	296
	B	16349.85	2676.68	374
	C	30250.91	3605.03	188

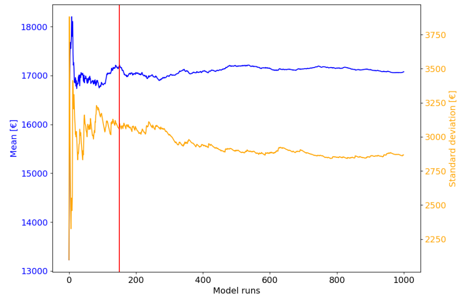
Table 4.23. Uncertainty of output data

Taking everything into consideration, the uncertainty analysis has confirmed the findings for Case A and C and the convenience of, respectively, the stand-alone SSP configuration and the community configuration with BESS. On the other hand, the uncertainty created by the input data has shown the similarity for those two configurations for Case B.

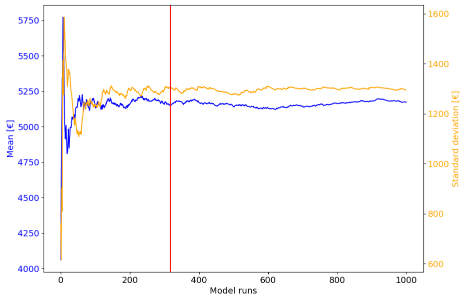
In order to detail and clarify the approach, in Figures 4.28 and 4.29 are detailed the trends of the mean (in blue) and of the standard deviation (in orange). The two outputs are reported on a same graph with different scales, over the number of the model runs. The red vertical line represents the number of iterations for which the convergence criterion is satisfied. The number of iterations for which the criterion is respected is also reported in the rightmost column of Table 4.23. However, 1000 iterations were performed as a conservative assumption to check the model's convergence.



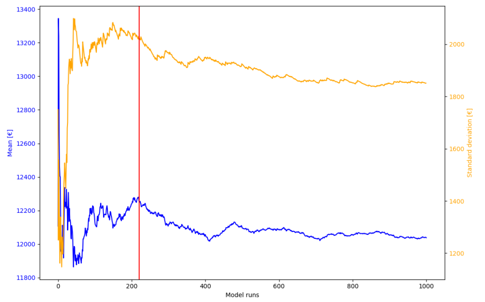
(a) RID



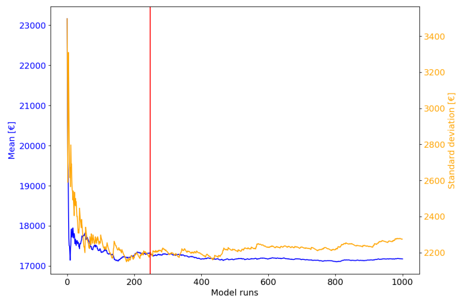
(b) SSP



(c) Community share, A

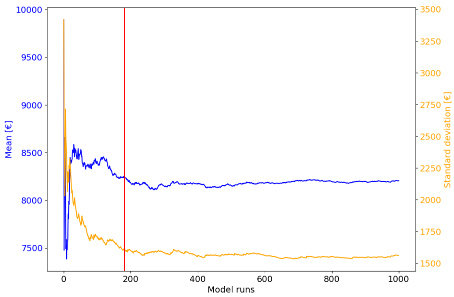


(d) Community share, B

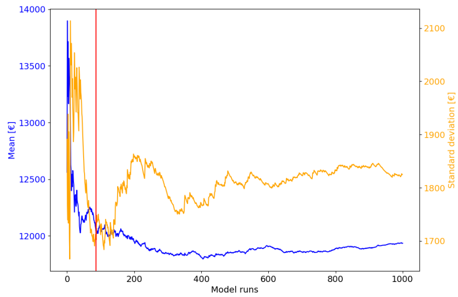


(e) Community share, C

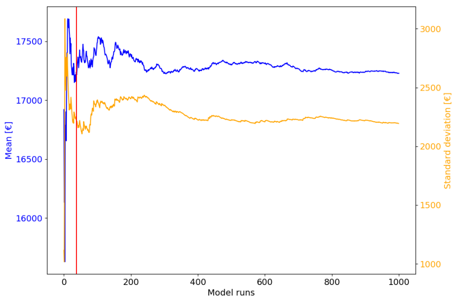
Figure 4.28. Convergence of the NPV means (blue) and standard deviations (orange) in the uncertainty analysis



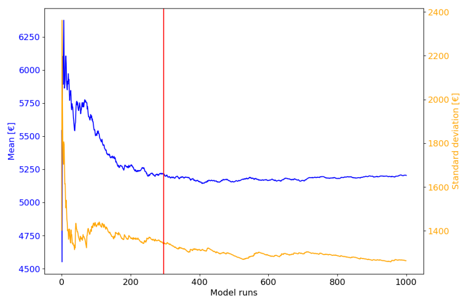
(a) Community self, A



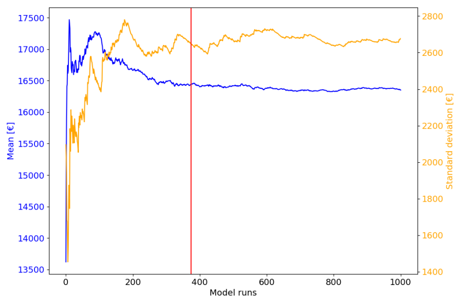
(b) Community self, B



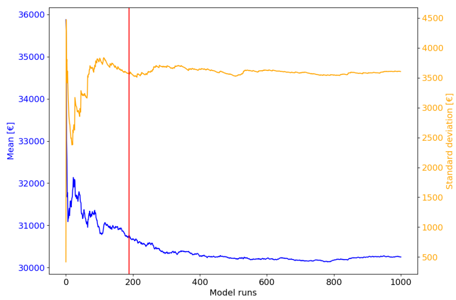
(c) Community self, C



(d) Community BESS, A



(e) Community BESS, B



(f) Community BESS, C

Figure 4.29. Convergence of the NPV means (blue) and standard deviations (orange) in the uncertainty analysis

Conclusions and future work

The main goal of this thesis was to develop a tool to simulate the energy flows and evaluate the economic feasibility of Renewable Energy Communities contextualized to the Italian framework. The thesis research comprises more layers of analyses that led to the final modelling of Energy Communities.

The first layer of the research is regulatory and legislative. Energy Communities will be new players in the energy field of European Member States, so the study started with a review of the European norms that led to the legal recognition of Energy Communities with the Clean Energy Package. The author performed an analysis on a majority of European Countries to show the level of maturity of community energy projects and self-consumption systems that will influence the process of transposition of the European Directives. A more detailed analysis for Italy revealed an intricate regulatory classification of self-consumption systems and energy cooperatives with a plurality of support schemes. The Italian transposition process of the Clean Energy Package, that started with the *Strategia Energetica Nazionale* and reached a milestone with the promulgation of the first law that recognises Energy Communities, is still not clear on the determination of the incentives that will encourage their development. It is opinion of the Italian energy Authority that support schemes for Energy Communities will in a first moment emulate the implicit incentives already given to self-consumption systems, meaning that the shared energy within the community will be exempted of at least the variable part of the wholesale cost of electricity and network costs in the electricity bill. The exemption of the operating costs is still under discussion as it would be counterproductive to the cost reflectiveness of the support scheme. The Authority believes that an explicit incentive given as a feed-in tariff on shared electricity would be the best solution in terms of transparency and control.

The second layer of the research is within the socio-technical field. The social analysis revealed the benefits that the recognition of Energy Communities will have on European Citizens in the matter of acceptance of renewable energy projects and involvement of the local population in the clean energy transition wanted by the European Commission. Past community energy projects confirm the role of Energy Communities as means to tackle serious issues such as energy poverty or creation of local jobs. For the technical analysis, the author performed a taxonomic analysis of Game Theory applied to community energy projects. The research revealed that non-cooperative games are used to describe competitive markets within microgrids, called P2P markets, in which users trade energy to maximise their individual profits. On the other hand, cooperative games are more adequate to describe community markets, in which members shared their energy and maximise a common profit.

Taking everything into consideration, the thesis work then introduces a methodology to analyse the economic feasibility of Renewable Energy Communities. The tool consists of a model able to describe the energy flows of stand-alone users and the sharing strategies within a community and compute the annual electricity bill for its members and a MILP optimization able to compute the optimal PV capacity for users inside or outside a community. The tool is validated with a case study built as a collection of ten households in Italy with domestic contracts within the protected regime. Considering the Italian discussion about support schemes on energy communities three cases are taken into account depending on the value assigned to the Shared Energy Saving index (SESi): a case (A) in which an implicit incentive is given on shared energy lower than the current incentive for self-consumed energy; a case (B) in which the implicit incentive given on shared energy equals the one given on self-consumed energy, a case (C) in which an explicit incentive is given on shared energy higher than the current incentive for self-consumed energy. An uncertainty analysis is then performed to critically confront the results. The analysis is performed through a Monte Carlo sampling method that, starting from the probability distributions of the inputs, selects random values in the latter for each run of the model and creates a probability distribution for the model outputs.

The tool is first used to determine the short-term profitability of the formation of an Energy Community for users already owning a PV plant and benefiting of individual incentives, such as *Ritiro dedicato* (RID) or *Scambio sul posto* (SSP). The annual electricity bill for the stand-alone users and the for users in the community is compared. The analysis revealed that the formation of an Energy Community is justified only if the users are originally selling their surplus energy with RID. In this scenario the savings induced by the energy sharing are enough to renounce the RID support scheme. That resulted to be true for all the values of SESi considered. On the other hand, SSP revealed to be too profitable for the active stand-alone users to form an EC. Even with the a high valorisation of shared energy, the annual grant received by stand-alone users with SSP is higher than the savings obtained in community.

The tool is then used to evaluate the profitability of investing in renewable energy as stand-alone users or in a community. The comparison is made with NPVs computed over the lifetime of PV panels. Considering the implicit incentive of Case A, the users will choose to invest in PV panels as stand-alone users benefiting of SSP. In Case B, a community with a shared BESS becomes competitive to the stand-alone configuration. In Case C, the high explicit incentive will make Renewable Energy Communities attractive in all its configurations, with a net profitability for the case of community with BESS. The uncertainty analysis took into account mainly the variability of the prices of the technologies, nevertheless their uncertainty propagated in the model did not change the final outcome of the research and confirmed the results.

The thesis demonstrated that the economic viability of Renewable Energy Communities in Italy will be highly influenced by the value of incentives granted to shared energy. A low incentive will not make communities profitable for its users, because the support schemes for individual self-consumption are still very advantageous. The role of the energy Authority is extremely complex, as even a cost reflective incentive on shared energy that quantifies the technical benefits that EC will bring to the electric system would not be enough to make EC economically profitable in the Italian panorama. Therefore, it will be necessary to quantify also the social role that EC will play among citizens.

The natural prosecution of this thesis will be the application of the tool to a real case study that will overcome the limitations given by a build-up case. Furthermore the community should be open also to other categories of users such as local authorities or small business that have their peak load during the central hour of the day. From the implementation point of view, the model can be further expanded by introducing also cooperative game theory in the allocation of the costs when considering shared assets in the community. While Shapley value could still be used as a redistribution logic, the computational burden would be considerable. The model can be expanded by taking into account a more detailed model for the battery and other charging logics. The uncertainty analysis might be expanded by taking also into account the variability of the electricity production from PV and the price of electricity.

Appendix A

Computational time of the models

The algorithms presented in the models are all implemented from scratch and coded in Python. The MILP optimisation is written and formalised with the Python-based modelling language Pyomo, using Gurobi as a solver. The analyses with the data of the case study of Chapter 4 are performed on a modern PC i7 5 GHz 16 GB and their indicative computational times, that vary on the specific simulation, are reported in the following Table A.1. The results in the Table shows that the proposed methodology is feasible from the point of view of computational time. However, when the model will be applied to an Energy Community comprising numerous users, the optimisation might require a not marginal computational cost. On the other hand, the uncertainty analysis in the current configuration revealed an important computational burden. Nonetheless in a real application, the input parameters entered in the uncertainty analysis will be characterised by a limited uncertainty, or at least by a smaller uncertainty than the one considered in the case study, which was taken from data in literature. Thus, it is reasonable to assume a steep reduction of the computational time of this last step.

Configuration	Case	Optimization	Energy Flows	Uncertainty Analysis
Stand-alone	SSP	20 min	30 sec	5 h
	RID	20 min	30 sec	5 h
Community share	A	1 h	30 sec	5 h
	B	1 h	30 sec	5 h
	C	1 h	30 sec	5 h
Community self	A	9 h	30 sec	5 h
	B	9 h	30 sec	5 h
	C	9 h	30 sec	5 h
Community BESS	A	5 h	1 min	19 h
	B	5 h	1 min	19 h
	C	5 h	1 min	19 h

Table A.1. Computational time of the models

Appendix B

Extended electricity bills

The following Appendix reports the extended electricity bills computed in the short-term analysis of the case study of Chapter 4. The extended bills take into account the conventional electricity bills plus profits coming from selling the surplus electricity to the grid, possible explicit incentives and redistributions internal to the community.

	Wholesale cost of electricity [€]	Network costs [€]	Operating costs [€]	Excises and VAT [€]	Profits [€]	Total [€]
user 1	255,60	106,51	117,12	112,59	-52,61	539,21
user 2	265,80	107,58	122,71	119,88	-30,06	585,91
user 3	155,95	96,08	62,48	68,22	-5,39	377,33
user 4	172,40	97,80	71,50	75,13	-17,37	399,46
user 5	198,48	100,53	85,80	77,21	-125,01	337,01
user 6	125,04	92,85	45,53	53,53	0,00	316,95
user 7	196,77	100,35	84,86	86,55	-23,24	445,28
user 8	262,94	107,28	121,14	120,31	-11,61	600,06
user 9	284,61	109,55	133,03	121,86	-102,87	546,17
user 10	283,92	109,47	132,65	127,01	-48,03	605,02

Table B.1. Extended energy bill for stand-alone users, RID

	Wholesale cost of electricity [€]	Network costs [€]	Operating costs [€]	Excises and VAT [€]	Profits [€]	Shapley Redistribution[€]	Total [€]
user 1	230,59	103,89	117,12	111,48	-33,70	-2,44	526,95
user 2	244,02	105,30	122,71	119,25	-22,73	10,41	578,96
user 3	142,01	94,62	62,48	67,86	-4,25	10,73	373,45
user 4	164,75	97,00	71,50	74,82	-12,18	0,22	396,11
user 5	188,92	99,53	85,80	75,96	-81,87	-45,10	323,24
user 6	106,39	90,90	45,53	53,03	0,00	15,64	311,50
user 7	160,98	96,61	84,86	85,26	-12,97	16,38	431,12
user 8	234,12	104,26	121,14	119,57	-8,62	21,43	591,91
user 9	276,63	108,71	133,03	120,93	-69,45	-33,91	535,94
user 10	256,10	106,56	132,65	126,06	-33,37	6,63	594,62

Table B.2. Community Case A from users with RID

	Wholesale cost of electricity [€]	Network costs [€]	Operating costs [€]	Excises and VAT [€]	Profits [€]	Shapley Redistribution[€]	Total [€]
user 1	230,59	103,89	103,41	109,93	-33,70	-4,18	509,94
user 2	244,02	105,30	110,77	118,47	-22,73	14,61	570,44
user 3	142,01	94,62	54,83	67,43	-4,25	14,03	368,68
user 4	164,75	97,00	67,30	74,41	-12,18	0,27	391,54
user 5	188,92	99,53	80,56	74,20	-81,87	-57,51	303,83
user 6	106,39	90,90	35,30	52,42	0,00	19,75	304,77
user 7	160,98	96,61	65,23	83,55	-12,97	18,90	412,30
user 8	234,12	104,26	105,34	118,67	-8,62	28,25	582,03
user 9	276,63	108,71	128,65	119,61	-69,45	-42,73	521,43
user 10	256,10	106,56	117,39	124,74	-33,37	8,60	580,02

Table B.3. Community Case B from users with RID

	Wholesale cost of electricity [€]	Network costs [€]	Operating costs [€]	Excises and VAT [€]	Profits [€]	Explicit Incentive [€]	Shapley Redistribution [€]	Total [€]
user 1	255,60	106,51	117,12	114,59	-33,70	-62,29	-5,89	491,93
user 2	265,80	107,58	122,71	120,81	-22,73	-54,28	18,73	558,62
user 3	155,95	96,08	62,48	68,74	-4,25	-34,72	17,27	361,55
user 4	172,40	97,80	71,50	75,66	-12,18	-19,08	0,32	386,42
user 5	198,48	100,53	85,80	79,52	-81,87	-23,82	-69,68	288,97
user 6	125,04	92,85	45,53	54,27	0,00	-46,47	27,11	298,32
user 7	196,77	100,35	84,86	88,70	-12,97	-89,1	7 21,37	389,92
user 8	262,94	107,28	121,14	121,38	-8,62	-71,80	34,94	567,26
user 9	284,61	109,55	133,03	123,59	-69,45	-19,88	-51,38	510,07
user 10	283,92	109,47	132,65	128,74	-33,37	-69,31	10,54	562,63

Table B.4. Community Case C from users with RID

	Wholesale cost of electricity [€]	Network costs [€]	Operating costs [€]	Excises and VAT[€]	Profits [€]	Total [€]
user 1	227,02	103,52	101,45	103,77	-243,80	291,96
user 2	229,15	103,74	102,62	104,83	-249,63	290,70
user 3	133,62	93,75	50,23	57,76	-136,28	199,08
user 4	158,65	96,37	63,96	70,09	-173,72	215,34
user 5	201,73	100,87	87,58	91,32	-242,21	239,29
user 6	125,04	92,85	45,53	53,53	0,00	316,95
user 7	169,94	97,55	70,15	75,65	-191,55	221,74
user 8	221,82	102,98	98,60	101,22	-238,21	286,40
user 9	272,70	108,30	126,49	126,28	-318,29	315,48
user 10	249,23	105,84	113,63	114,72	-277,48	305,95

Table B.5. Extended energy bill for stand-alone users, SSP

	Wholesale cost of electricity [€]	Network costs [€]	Operating costs [€]	Excises and VAT[€]	Profits [€]	Total [€]
user 1	207,51	101,48	101,45	90,63	-107,34	393,73
user 2	214,20	102,18	102,62	91,49	-114,95	395,53
user 3	125,75	92,92	50,23	51,23	-55,04	265,09
user 4	152,82	95,76	63,96	61,87	-68,87	305,54
user 5	176,38	98,22	87,58	79,01	-98,88	342,32
user 6	95,83	89,79	45,53	52,55	0,00	283,70
user 7	141,43	94,56	70,15	65,56	-69,68	302,02
user 8	202,83	100,99	98,60	88,21	-106,42	384,20
user 9	260,26	107,00	126,49	109,57	-141,30	462,02
user 10	227,89	103,61	113,63	100,10	-123,61	421,62

Table B.6. Community Case A from users with SSP

	Wholesale cost of electricity [€]	Network costs [€]	Operating costs [€]	Excises and VAT[€]	Profits [€]	Total [€]
user 1	207,51	101,48	90,75	89,52	-107,34	381,92
user 2	214,20	102,18	94,42	90,74	-114,95	386,58
user 3	125,75	92,92	45,92	50,76	-55,04	260,31
user 4	152,82	95,76	60,76	61,39	-68,87	301,86
user 5	176,38	98,22	73,68	77,75	-98,88	327,15
user 6	95,83	89,79	29,51	51,36	0,00	266,49
user 7	141,43	94,56	54,52	63,78	-69,68	284,61
user 8	202,83	100,99	88,18	87,13	-106,42	372,70
user 9	260,26	107,00	119,68	108,67	-141,30	454,31
user 10	227,89	103,61	101,93	99,04	-123,61	408,86

Table B.7. Community Case B from users with SSP

	Wholesale cost of electricity [€]	Network costs [€]	Operating costs [€]	Excises and VAT [€]	Profits [€]	Explicit Incentive [€]	Total [€]
user 1	227,02	103,52	101,45	103,77	-107,34	-53,45	374,96
user 2	229,15	103,74	102,62	104,83	-114,95	-40,97	384,41
user 3	133,62	93,75	50,23	57,76	-55,04	-21,58	258,74
user 4	158,65	96,37	63,96	70,09	-68,87	-15,96	304,23
user 5	201,73	100,87	87,58	91,32	-98,88	-69,48	313,15
user 6	125,04	92,85	45,53	53,53	0,00	-80,06	236,89
user 7	169,94	97,55	70,15	75,65	-69,68	-78,12	265,48
user 8	221,82	102,98	98,60	101,22	-106,42	-52,07	366,12
user 9	272,70	108,30	126,49	126,28	-141,30	-34,08	458,39
user 10	249,23	105,84	113,63	114,72	-123,61	-58,49	401,33

Table B.8. Community Case C from users with SSP

Appendix C

Uncertainty analysis results

This Appendix reports the results of the uncertainty analysis (UA) performed for every users' configuration and for every incentive case. The graphs report on the y axis the value of the model's output, i.e. the NPV, while on the x axis the number of the run of the model. The values of the NPV for each run are then plotted on a histogram to show the probability distribution of the output. Table C.1, already presented in Chapter 4, reports the mean values and the standard deviations of the outputs.

Case		Mean [€]	Standard deviation [€]
Stand-alone	SSP	17077.49	2867.52
	RID	5529,60	1356.43
Community share	A	5173.66	1294.69
	B	12037.82	1851.17
	C	17077.49	2867.52
Community self	A	8204.68	1560.78
	B	11934.22	1824.74
	C	17228.71	2194.27
Community BESS	A	5203.78	1263.65
	B	16349.85	2676.68
	C	30250.91	3605.03

Table C.1. Uncertainty of output data

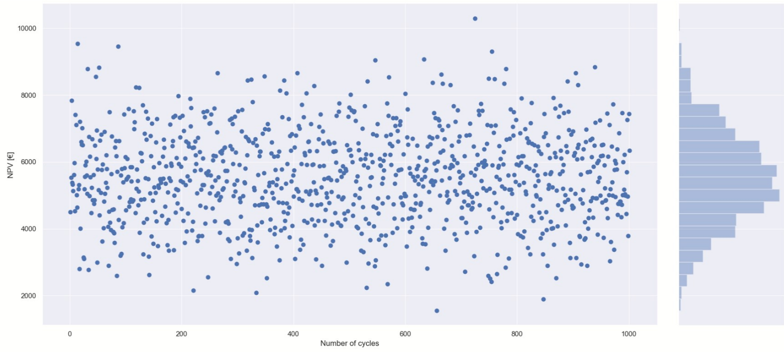


Figure C.1. UA for stand-alone users with RID. NPV on the vertical axis and model runs on horizontal axis.

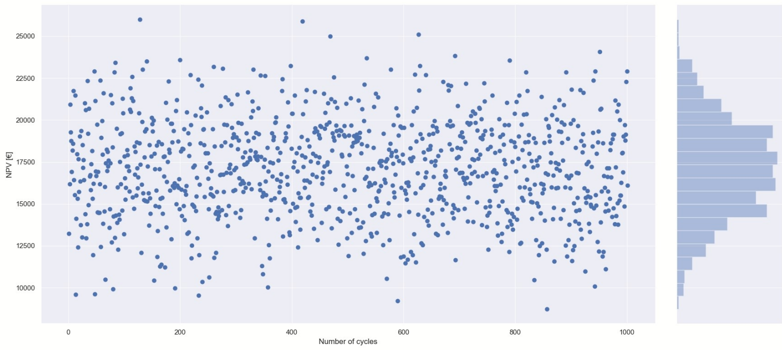


Figure C.2. UA for stand-alone users with SSP. NPV on the vertical axis and model runs on horizontal axis.

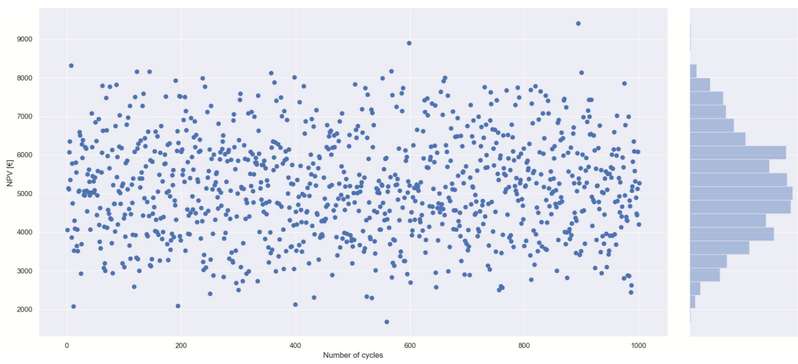


Figure C.3. UA for community with shared-consumption priority, Case A. NPV on the vertical axis and model runs on horizontal axis.

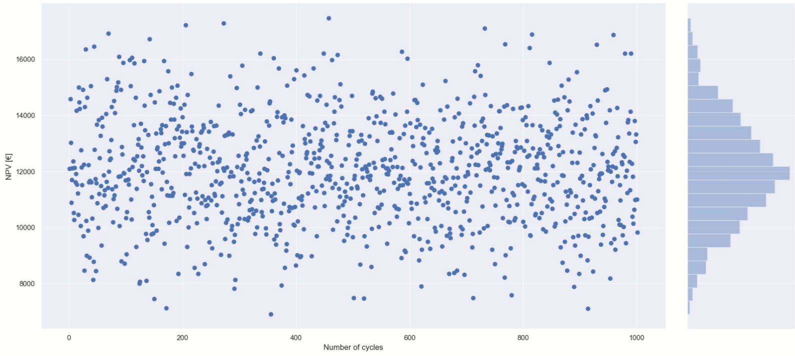


Figure C.4. UA for community with shared-consumption priority, Case B. NPV on the vertical axis and model runs on horizontal axis.

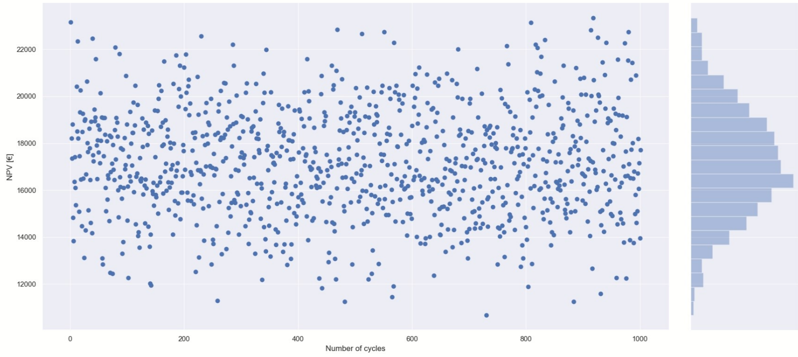


Figure C.5. UA for community with shared-consumption priority, Case C. NPV on the vertical axis and model runs on horizontal axis.

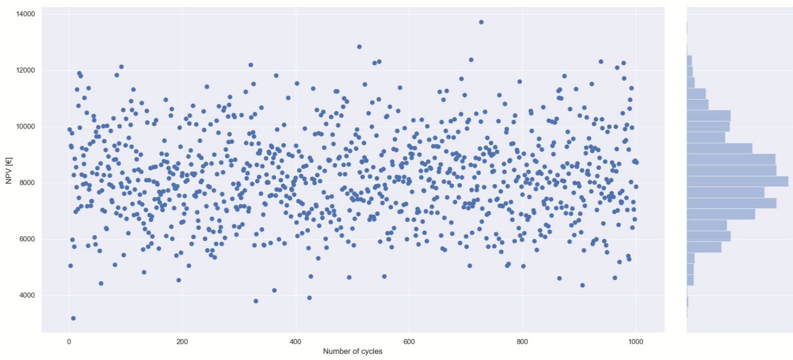


Figure C.6. UA for community with self-consumption priority, Case A. NPV on the vertical axis and model runs on horizontal axis.

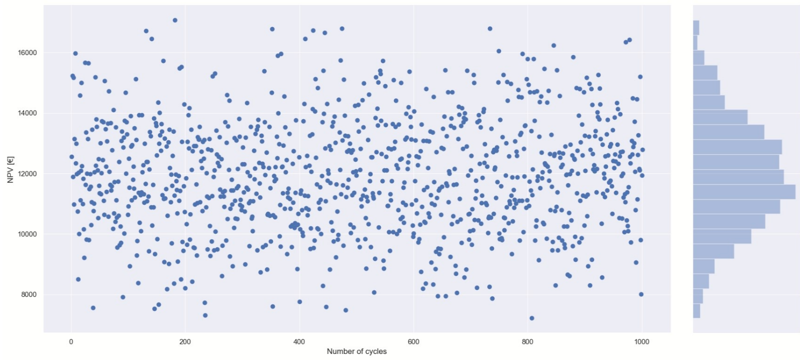


Figure C.7. UA for community with self-consumption priority, Case B. NPV on the vertical axis and model runs on horizontal axis.

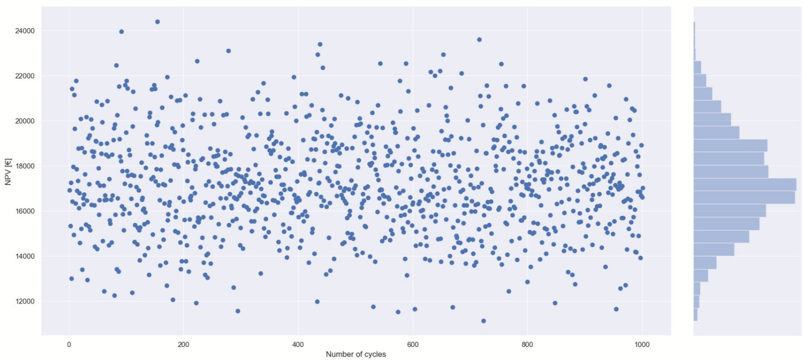


Figure C.8. UA for community with self-consumption priority, Case C. NPV on the vertical axis and model runs on horizontal axis.

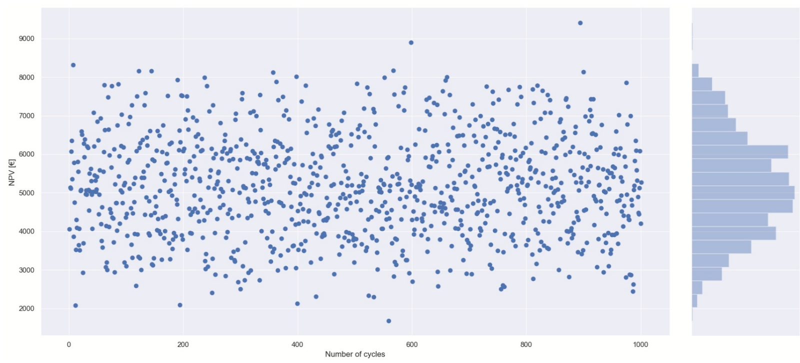


Figure C.9. UA for community with BESS, Case A. NPV on the vertical axis and model runs on horizontal axis.

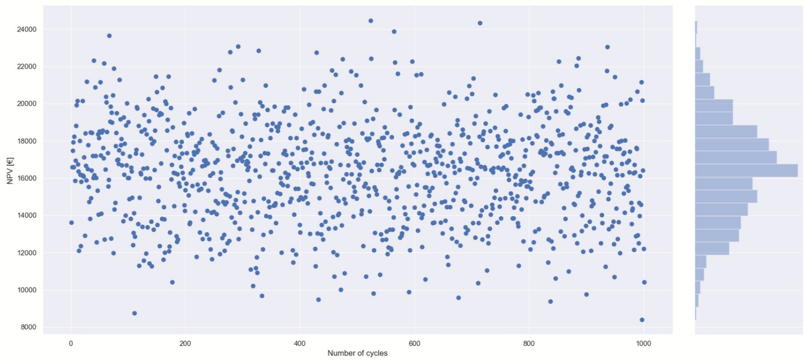


Figure C.10. UA for community with BESS, Case B. NPV on the vertical axis and model runs on horizontal axis.

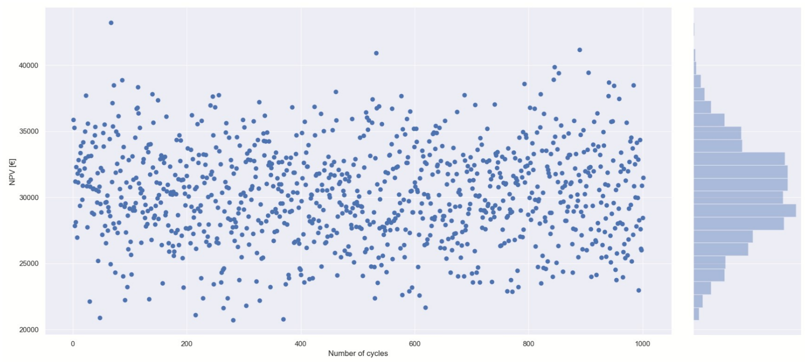


Figure C.11. UA for community with BESS, Case C. NPV on the vertical axis and model runs on horizontal axis.

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Acronyms

ARERA Autorità di Regolazione per Energia Reti e Ambiente

BESS Battery Energy Storage Systems

CEP Clean Energy Package

CEC Citizens Energy Community

DSO Distribution System Operator

EC Energy Community

EU European Union

GSE Gestore dei Servizi Energetici

MILP Mixed Integer Linear Programming

NPV Net Present Value

PV Photovoltaic

REC Renewable Energy Community

RES Renewable Energy Sources

RID Ritiro dedicato

SCSi Self-consumption Saving index

SDC Sistemi di Distribuzione Chiusi

SME Small Medium Enterprises

SOC State of Charge

SSP Scambio sul Posto

SSPC Sistemi Semplici di Produzione e Consumo

TSO Transmission System Operator

UA Uncertainty Analysis

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