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Techno-Economic Analysis of a Renewable Energy Community in a European Metropolis context:
the city of Milano

TESI DI LAUREA MAGISTRALE IN
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Giovanni Magenta, 10530561

Advisor:
Prof. Emanuele Giovanni Carlo Ogliari

Co-advisors:
Alessandro Bosisio

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Abstract: The aim of this thesis is to assess if a Renewable Energy Community could be profitable in a European Metropolis context. Energy communities have begun to penetrate European market but the most part of them, especially in Italian context, are located in rural area or in small municipalities. The beginning of the REC path took place thanks to European Directives RED II(2018/2001)[1] and IEM(2019/944)[2]. The latest transposition by Italian government is contained in *"DECRETO LEGISLATIVO 8 novembre 2021, n. 199* "[3]. The perfect case study, in order to analyse the impact of a REC in an urban environment, is represented by the condo of *"Villaggio dei Giornalisti"*. It is a condo located in the northern outskirt of Milan composed by twelve different buildings which inhabitants expressed the desire to know more about RECs . The first step of the thesis was to define the condo's loads. The data were not available by the condo's inhabitants so Synthetic Data Generation[4] has been adopted in order to create realistic loads. Once loads were defined the PV plant needed to be design. The assumption, on which the design was based, was to install the maximum possible power on the condo's roofs sheds excluding ones facing north. According to this assumption, the PV plant nominal power was 488.4KW. Later step was to define different cases in order to assess how different choice affect the techno economic analysis. The base case was to not install any PV panel the most complex case was to install PV panels, batteries and EV's charging stations and to establish a Renewable Energy Community in order to receive self-consumption incentives. The techno economic analysis time horizon was set to twenty years that are the years for which the incentives are granted. The last step was to compute the total return of the investment and the break even point for the various cases. The results had shown that in all the cases the investment was profitable. The size of the installed battery must be chosen carefully because after a certain value it became not economic profitable. The break even point varied from 8 years to 5 years. The analysis has been carried out both with the average electricity price computed on the period 2004-2020 and with the highest recorded electricity price of 2022. The REC, when the price of electricity raised, became more and more profitable by economic point of view.

Key-words: Renewable Energy Community, Collective self-consumption, Synthetic Data Generation, Energy storage implementation on PV plant, Electricity price effect on PV plant

Introduction

European context

Nowadays the European energy policy as stated in the European Green Deal [5] aims to reduce by 2030 the net greenhouse gasses emission by 55% respect to the level registered in 1955. One of the most critical areas where to pursue the energy transition are the urban ones. Despite various efforts in increasing the building efficiency their global emissions increased about 2% from 2017 to 2018. In this panorama a major role in the energy improvement of urban area could be carried by the Renewable Energy Community. In Italy on December 15, 2021, the Legislative Decree 199/2021 [3] came into force which finally transposes the two European directives RED II (2018/2001) [1] and IEM (2019/944) [2]. One of the aims of this directives is to increase the renewable energy share through the establishment of energy communities; actually there are various legal entities defined by these directives but all share a common aim: transform the energy consumer (the private families) into a prosumer, namely an active player in the energy market that is now able to self-produce energy, consume it and in case of over production even sell it to the grid. The additional energetic value of a community with respect to a single prosumer is the possibility of sharing the electricity between the members in order to obtain a higher overall self-consumption leading to a lower bill for all the participants and an easy management of the generated power. The role of the energy community is not only limited to the green improvement of the market energy mix, since the energy community architecture has a lot of other advantages both technical and social:

- It can improve the grid efficiency, matching geographically the position of the production and consumption of the electrical energy could help to decrease the transmission losses and increase the overall grid efficiency;
- It can help to generate social welfare by decreasing the electricity bill to all the participants of the energy community;
- It promotes collaborative social transformation by leading local communities to pursue common goals;
- It allows a higher self-consumption of the generated electric energy
- It can make the energy access easier in environment where before the access to the energy was not continuous or granted (e.g. rural application, remote mountain village...);
- It can help the electrification of the consumption (e.g. induction cooking, heat pump ...);
- It can enhance the inclusion of a less wealthy part of the population;
- It can promotes the combination of energy and mobility sectors (e.g. EV can work both as extra load and as battery in moment of overproduction or under-supply).

Looking to all the above listed terms, naturally an Energy Community is not merely a form of subsidy to increase the renewable energy share in the market, but it aims to deeply change the roots of our society making all the final consumers more aware of what electric energy is and giving also them a chance to do their part in reducing the greenhouse emission obtaining an economic reward for that.

In the following pages I will analyse a case study of a new Renewable Energy Community in the neighbourhood of *"Villagio dei Giornalisti"*,Milan, Italy. The main aim of this project is to clarify how a REC will work in an urban area like Milan. Until now the RECs have been mainly constituted in small villages, while adopting this new architecture in a city could be quite challenging because of the poor productivity of the PV plant that will feed the community. It is fundamental to carefully analyse the demand curve of the consumers in order to understand their needs. I will analyse different architecture because I want to define how convenient both economically and energetically,for a final consumer, is to change his mind and become a prosumer and a component of something bigger.

Now, before entering in the techno economic analysis of the case study it is important to understand which is the Italian scenario and how the European Directive has been adapted by the Italian Government .

Italian Law context

In Italy the legislative process started as it is possible to see in the timeline of figure 1 with the “Decreto Milleproroghe” entered into force at the end of February 2020. It introduced in the Italian legislation two new legal entities:

- **Renewable Energy Community**;
- **Renewable energy self-consumers acting collectively**.

Specifically, RECs are legal entities made up of groups of subjects (such as natural persons, local authorities, companies) located in the proximity of renewable energy production plants that meet on a voluntary basis to produce and consume clean electricity, according to the principles of self-consumption and energy self-sufficiency. The Renewable energy self-consumers in the other hand are final clients that decide to install a renewable energy plant for self-consumption and to sell the overproduction to the grid. It is defined as a group of self-consumers when more than one player decides to act together on the basis of a private contract. For the Renewable energy self-consumers acting collectively the selling of renewable energy must not be the mainly commercial or professional activities. In the *“Mille Proroghe”* there are also some important constrains about the REC constitution like the maximum size of the renewable power plants (200KW) and the physical position of the buildings (all must be connected to the same medium-low voltage cabin).

The following step was “Delibera ARERA 318/2020” in August 2020 that reported the disposition of the Authority regarding the collective self-consumption and sharing of electric energy in the ambit of REC.

Successively the “Decreto attuativo del Ministero dello Sviluppo Economico” in 15 September 2020 with the article 3 decided the feed-in tariffs, granted for 20 years, for the energy produced by renewable power plant in the previous configuration:

- 100 €/MWh if the plant belongs to a collective self-consumption configuration;
- 110 €/MWh if the plant belongs to a Renewable Energy Community.

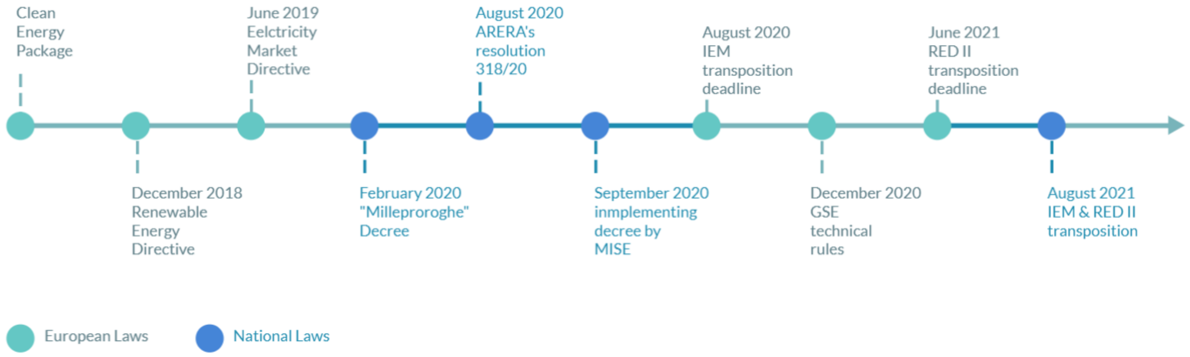


Figure 1: Timeline Energy Community legislation

The next step took place on the 15 December 2021 when the *“DECRETO LEGISLATIVO 8 novembre 2021, n. 199 “* [3] came into effect. With this decree Italy wanted on one hand to reduce the greenhouse gas emissions by 55% with respect to the ones of 1955 and in the other hand to reach a 30% renewable component in the total gross electric final consumption through incentives and simplifying the authorization mechanism.

In this decree the maximum size of the plant that can access the direct incentive mechanism is moved up to 1MW, the constrain regarding the location of all the members of a REC to be downstream respect the same medium-low voltage transformation cabin is removed and finally the implementation of an energy storage is promoted in order to smooth the typical dispatch-ability issue of the renewable sources. The condition of compatibility with the previous tax breaks defined for power storage and production systems are established.

Italian Development point

Thanks to the fast legislative process, in Italy, REC are becoming more and more relevant and interesting for the consumers communities. Their diffusion in the territory is becoming capillary day by day as it is possible to realize by taking a look at the RECs location map in figure 2. In the following paragraph five relevant examples, of already existing energy communities [6] are described, in order to highlight some important features.

1. **Magliano Alpi [7], renewable energy community from 2020**
   This project started thanks to Comune Magliano Alpi that provided two PV plant for a total PV power of 40KW that provide energy for both private and public buildings. In this experience is possible to note how a Public Administration can be a very strong driving force in the constitution of a REC. The PA can undertake all the major costs like the design and construction of the PV plant and then can decide to share the benefits coming from the formation of an Energy Community with all the private parts that want to become member of it.
2. **Pinerolo’s [8] condo energy community, Piemonte**

In Pinerolo, in the province of Turin, the first collective self-consumption condo was inaugurated. The condo was completely revamped with the construction of a PV plant and a solar thermal panel the first one for the electric energy production, the second one in order to provide hot water. In addition to this two production plants 13 energy storage system are installed in order to improve the self-consumption, this allows to cover 90% of the total energy needed by the private houses in the condo.

3. **GECO [9] project by ENEA in Emilia Romagna**
   GECO, Green Energy Community is a European project that aims at the foundation of a District Energy Community in Pilastro-Roveri, province of Bologna. It is an example of the maximum size that was reachable according to "Decreto Mille Proroghe". The PV installed power in this case is about 200KW to provide electrical power to 7500 private citizens and a commercial area of 20 hectares.

Figure 2: Map of Italian energy community

4. **KM0 agricultural Energy in Veneto [6]**
   This energy community was born in 2018 in Veneto and it is formed mainly by agricultural players. Nowadays it includes 1253 users between private citizens and industries. This REC allow a CO2 saving of 11140 tons/year
5. **Solisca in the Lodigiano [6]**
   Solisca is one of the latest established energy communities since it was set on the fourth of February in 2022. The project started in 2021 and now the plants are already operating. It is composed by two PV plants installed in the sport center and in the gym of a total Pnom of 45KW, the yearly production is about 50MWh. The Energy Community included: nine families, one parish and nine municipal utilities, all connected through smart meters in order to monitor all the data of the plant and to evaluate some important environmental sustainability parameters.

Motivation

After introducing the previous energy communities it is possible to note that all of them are located in rural areas or in small towns. This areas are characterized by huge open spaces and low population density and mostly of the time the REC in this areas comprehend both residential building and tertiary sector buildings. The REC architecture in this cases fits very well because it is easy to match the PV production curve and the load curve. Therefore it is interesting to analyze how the architecture of an energy community could work in a highly populated area like the one that it is found in the city of Milan. In this area the stakes are completely different because there are a lot of consumers in a small area and their traditional behavior is not well matched with a PV plant production curve. The PV plant produces mostly during the center hours of the days while our customers are at work and when the load is the highest, during the early morning and the evening, the PV production is the lowest. This typology of problem could be solved thanks to the installation of batteries that allows to store the energy while there is an overproduction and consume it when the PV plant is not able to fulfill the loads. This solution by the energetic point of view looks obvious, but what about the economic side? This thesis aims to analyze this question and understand how the economic side and the energetic one collide in an urban renewable energy community architecture.

1. Methodology

In this thesis a Monte-Carlo simulation[10] has been adopted. Before describing what a Monte-Carlo simulation is some terminology is introduced.

1.1. Terminology

Statistical distributions Statistical distributions or probability distributions describe the outcomes of varying a random variable, and the probability of occurrence of those outcomes. When the random variable takes only discrete values, the corresponding probability distributions are called discrete probability distributions. Examples of this kind are the binomial distribution, Poisson distribution, and hypergeometric distribution. On the other hand, when the random variable takes continuous values, the corresponding probability distributions are called continuous probability distributions. Examples of this kind are normal, exponential, and gamma distributions.
Random sampling In statistics, a finite subset of individuals from a population is called a sample. In random sampling, the samples are drawn at random from the population, which implies that each unit of population has an equal chance of being included in the sample.
Random number generator (RNG) A random number generator is a computational or physical device designed to generate a sequence of numbers that appear to be independent draws from a population, and that also pass a series of statistical tests. They are also called Pseudo-random number generators, since the random numbers generated through this method are not actual, but simulated.

1.2. Monte-Carlo

Monte Carlo simulation is a type of simulation that relies on repeated random sampling and statistical analysis to compute the results. This method of simulation is very closely related to random experiments, experiments for which the specific result is not known in advance. In Monte Carlo simulation, we identify a statistical distribution which we can use as the source for each of the input parameters. Then, we draw random samples from each distribution, which then represent the values of the input variables. For each set of input parameters, we get a set of output parameters. The value of each output parameter is one particular outcome scenario in the simulation run. The following steps are typically performed for the Monte Carlo simulation of a physical process.
Static Model Generation Every Monte Carlo simulation starts off with developing a deterministic model which closely resembles the real scenario. In this deterministic model, we use the most likely value (or the base case) of the input parameters. We apply mathematical relationships which use the values of the input variables, and transform them into the desired output.
Input Distribution Identification When we are satisfied with the deterministic model, we add the risk components to the model. As mentioned before, since the risks originate from the stochastic nature of the input variables, we try to identify the underlying distributions, if any, which govern the input variables.
Random Variable Generation After we have identified the underlying distributions for the input variables, we generate a set of random numbers (also called random variates or random samples) from these distributions. One

set of random numbers, consisting of one value for each of the input variables, will be used in the deterministic model, to provide one set of output values. We then repeat this process by generating more sets of random numbers, one for each input distribution, and collect different sets of possible output values. This part is the core of Monte Carlo simulation.

Analysis and Decision Making After we have collected a sample of output values in from the simulation, we perform statistical analysis on those values.

1.3. Identification of input distribution

In this section, it will be discussed the procedure for identifying the input distributions for the simulation model, often called distribution fitting. When there are existing historical data for a particular input parameter, we use numerical methods to fit the data to one theoretical discrete or continuous distribution. Fitting routines provide a way to identify the most suitable probability distribution for a given set of data. Each probability distribution can be uniquely identified by its parameter set, so, distribution fitting is essentially the same as finding the parameters of a distribution that would generate the given data in question. From this perspective, fitting routines are nothing but nonlinear optimization problems, where the variables are parameters of the distributions. There are a few standard procedures for fitting data to distributions the one adopted in this thesis is called **Method of Maximum Likelihood(ML)**. ML estimation (MLE) is a popular statistical method used to make inferences about parameters of the underlying probability distribution from a given data set. If we assume that the data drawn from a particular distribution are independent and identically distributed (iid), then this method can be used to find out the parameters of the distribution from which the data are most likely to arise. Let θ be the parameter vector for f , which can be either a probability mass function (for discrete distributions) or a probability density function (for continuous distributions). We will denote the pdf/pmf as f_θ . Let the sample drawn from the distribution be x_1, x_2,..., x_n. Then the likelihood of getting the sample from the distribution is given by the equation 1.

$$L(\theta) = f_\theta\left(x_1, x_2, \ldots, x_n \mid \theta\right) \tag{1}$$

This can be thought of as the joint probability density function of the data, given the parameters of the distribution. Given the independence of each of the datapoints, this can be expanded to the equation 2 .

$$L(\theta) = \prod_{i=1}^{n} f_\theta\left(x_i \mid \theta\right) \tag{2}$$

In MLE, we try to find the value of θ so that the value of L(θ) can be maximized. Since this is a product of probabilities, we conveniently consider the log of this function for maximization, hence the term 'loglikelihood'. So, the MLE method can be thought of as a nonlinear unconstrained optimization problem as given below in equation 3.

$$\max LL(\theta) = \sum_{i=1}^{n} \ln f_\theta\left(x_i \mid \theta\right), \quad \theta \in \Theta \tag{3}$$

Here, Θ represents the domain of each of the parameter of the distribution. After we have identified the underlying distributions for the input parameters of a simulation model, we generate random numbers from these distributions. The generated random numbers represent specific values of the variable. The most common method for generating random variates (RV's) from discrete and continuous distributions is now reported.

1.4. Inverse Transformation Method

The inverse transformation method provides the most direct route for generating a random sample from a distribution. In this method, we use the inverse of the probability density function (PDF) (for continuous distributions) or probability mass function (PMF) (for discrete distributions), and convert a random number between 0 and 1 to a random value for the input distribution. The process can be mathematically described as follows. Let X be a continuous random variate (which we want to generate) following a PDF function f . Let the cumulative probability distribution function (CDF) for the variate be denoted by F, which is continuous and strictly increasing in (0,1). Let F^{-1} denote the inverse of the function F, which is often called inverse CDF function. Then, the following two steps will generate a random number X from the PDF f .

- Generate U $\sim$ U(0,1).
- Return X = F^{-1} (U).

Note that, since $0 \leq \text{U} \leq 1$, F^{-1} (U) always exists. The schematic diagram 3 below depicts the process. We show the curve of a CDF of a certain lognormal distribution in the right hand side. In the left hand side, we show an uniform distribution. A randomly generated number U(0.1)number (say 0.65), corresponds to 160 at the lognormal CDF curve. So, this number is a random variate from the lognormal distribution. If we generate 100 such U(0,1)numbers and replicate the process using the same curve, we will obtain 100 random variates from this distribution.

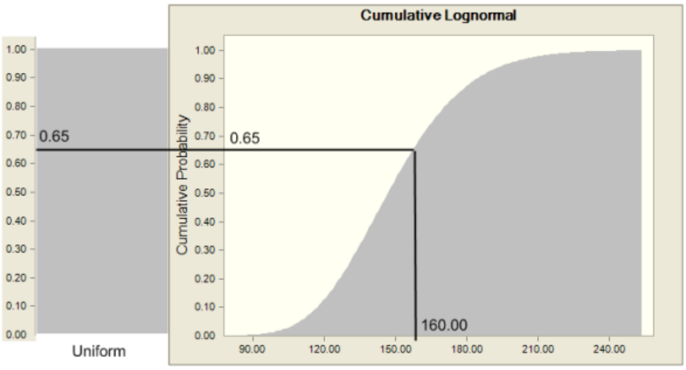


Figure 3: Generation of random variates.

1.5. Generating RV's from a DataSet: Bootstrapped Monte Carlo

Often it is not possible to obtain an underlying distribution for an input variable in a simulation model. This can be because of the complicated shape of the original distribution (like non-convex or multi-modal), scarcity of data (for example, destructive testing or costly data) and so on. In those cases, we might end up with nothing more than a few historical values for the input parameter. In those cases, bootstrapped Monte Carlo (MC) simulation (often called bootstrapping) can be used to generate random variates. In bootstrapping, we do not really generate random variates. Instead, we repeatedly sample the original dataset to choose one of the data points from the set (choose a number with replacement). For many datasets, this method provides good result for simulation purposes. . For bootstrapped MC simulation, one has to still use an uniform RNG, specifically an RNG to generate integer random numbers among the indices of an array, which is being used for storing the original dataset. Bootstrapped simulation can be a highly effective tool in the absence of a parametric distribution for a set of data. One has to be careful when performing the bootstrapped MC simulation, however. It does not provide general finite sample guarantees, and has a tendency to be overly optimistic. The apparent simplicity may conceal the fact that important assumptions are being made when undertaking the bootstrap analysis (for example, independence of samples) where these would be more formally stated in other approaches. Failure to account for the correlation in repeated observations often results in a confidence interval that is too narrow and results in a false statistical significance. Therefore, the intrinsic correlation in repeated observations must be taken into account to draw valid scientific inference.
In this thesis **Bootstrapped Monte Carlo** has been adopted because the outcomes have the same probability to happens. From an uniform RNG random number is drawn. With that number we enter in a database from which an outcome is drawn. Next the process is repeated with the constrain of repeating the draw if the outcome is identical to the previous one. This constraint has been chosen because in the real phenomena, that are now simulated, no same outcome happens consecutively. Finally the outputs are analyzed in order to verify that resemble the real phenomena. In figure 4 a generic Monte-Carlo simulation scheme is reported.

Figure 4: Monte-Carlo simulation scheme

In the **Bootstrapped Monte Carlo** adopted, the input data is a number that vary from 1 to 297 that are the indices of an array, which is being used for storing the original dataset. A load profile is drawn from the dataset as the one in figure 5.

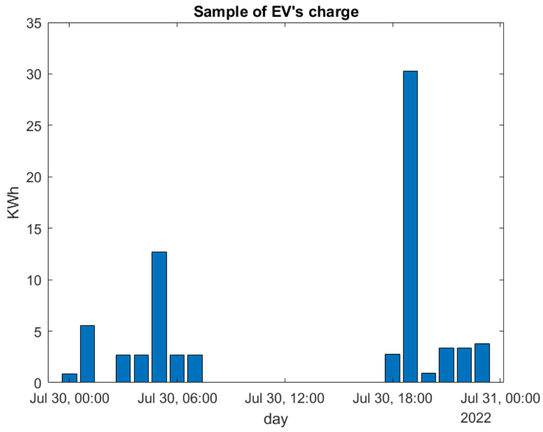


Figure 5: EV charging Sample

This procedure is performed 365 times in order to generate an artificial year. At each draw an analysis is performed to avoid successive repetitions because in the reality this does not happen. If it is highlighted a successive repetitions the draw is repeated.

2. Case Study

2.1. Introduction

A fitting case study in order to analyze the impact of a REC in an urban environment is represented by the condo of *"Villaggio dei Giornalisti"*. It is located in the Milan northern outskirts, an highly populated area. The space available to install PV plant is limited to the building's roof and all the buildings are residential. All the previous cited aspects are present. In the first meeting that I had with the condominium councilors a great desire to evaluate the feasibility of a REC emerged. The motivation was both economical, due to the recent increase of the energy bills, and environmental, because nowadays people are more concerned by their ecological footprint. In the next paragraph I will deal with the technical aspects of the site.

2.2. Site

The techno economic analysis is referred to the condo of *"Villaggio dei Giornalisti"* that is an aggregation of twelve buildings located in the north part of Milan. The view from above of the condo is reported in figure 6. Each building is inhabited by a number of families that can vary from 7 to 10.

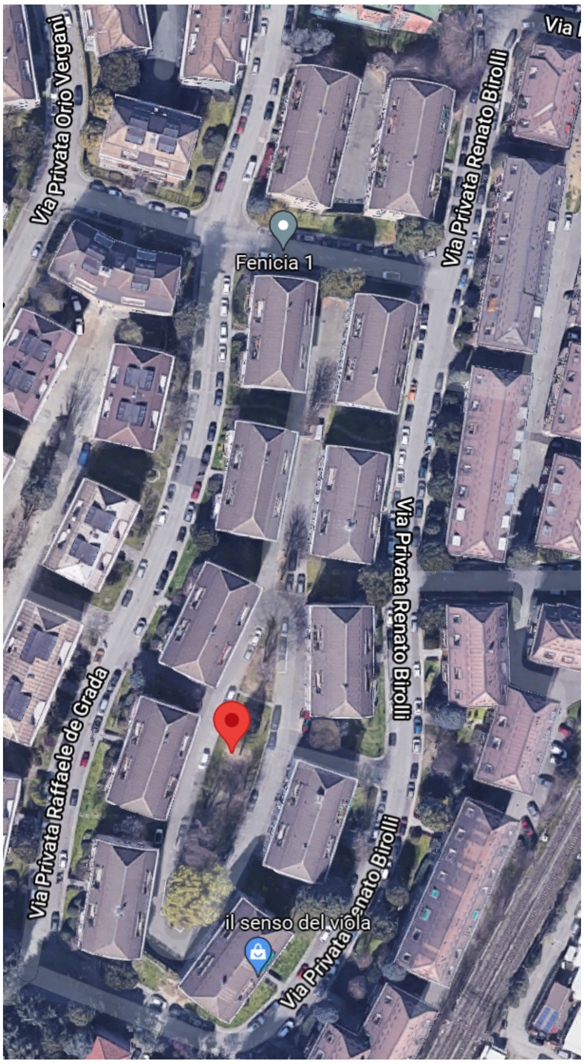


Figure 6: Map of the condominium

The available areas to install the PV plants are the two main flaps (one looking E and one looking W) and the tympanum of each roof. In total there are thirty six fields each one characterized by its own azimuth and tilt. The site geographical coordinates are 45°30'2.34"N 9°12'14.36"E. The area is a metropolitan one so it is highly populated. As previously stated the technical challenge in this site is quite relevant because the load curve and the production curve are expected to be not matching.

2.3. Cases Definition

In order to better investigate the problem it is useful to dis-aggregate it in four different configurations, in this way it will be easier to understand the impact that different hypothesis have on the final results. For this reasons the analysis will focus on the following aspects

- characterize the residential loads in an urban condos when the real data are missing;
- define the energy production by an urban PV plant accounting near shadowing;
- asses if installing a PV plant is economically profitable in a highly populated urban area, where the plant size is limited;
- compute the effects of a REC establishment both economically and energetically respect to a self-consumption configuration and respect to the benchmark case;
- analyze the effects of the batteries implementation and assess if their installation is justified by the future revenues;
- analyze if by adding EVs recharging station to the condo the REC became more or less profitable

In order to analyze the previous aspects the best procedure is define cases that highlight one aspects each. So the following four scenarios plus the benchmark one are defined:

- **C0:**this scenario takes care only of the load definition for the urban renewable energy community, it is the benchmark case;

- **C1:**the load and the PV production of each different building are analysed without considering a REC configuration;
- **C2:**the building are now able to virtually share energy accordingly to REC laws;
- **C3:**the addition of the batteries is analyzed depending on their size;
- **C4:**the EVs charging facility is added to the load curve;

The table number 1 summarizes all the previous cases characteristics.

Scenario	Load	PV	REC	Batteries	EVs
C0	X				
C1	X	X			
C2	X	X	X		
C3	X	X	X	X	
C4	X	X	X	X	X

Table 1: Scenarios summary

3. Load Curve

3.1. Problem

The definition of a load curve is very challenging in this type of area. It is needed to define an hourly load curve in order to simulate a typical year of the energy community. People are not very willing to share their private electric consumption and even if they accept to share their private consumption, often this is not very useful because the data are referred to monthly consumption. This happens for various reasons, the two biggest that emerged during the condominium meeting are: on the one hand old people usually are not familiar with technology and is not easy for them to find their own loads on web portals, in the other hand not being able to share them because their electricity meter is dated and does not permit to access the hourly loads. The solution to this problem may be provided by the synthetic data generation. In fact one of the main application is to generate artificial data when the real data are not available , as it is possible to read in the description of What Is Synthetic Data [4], a Guide published on Datagen website.

3.2. Synthetic Data

Synthetic data are artificial data generated with the purpose of preserving privacy, testing systems or creating training data for machine learning algorithms as it is stated on Datagen website [4]. The synthetic data can be generated in various way:

- Generating according to distribution;
- Fitting real data to a known distribution;
- Using Machine Learning techniques.

The synthetic data generation is very useful because can helps in different situations, for example: it can be used to create a data-set from limited samples, it can eliminate private data from a data-set, it can be used to create multiple data-sets from one native data-set (for training A.I.)... I decided to use it in order to create a data-sets of loads for twelve different condo starting from two different data-sets: one from a real consumption of a Milan family measured through smart-meter, the other one containing the consumption of a 100 square meters flat computed by an agglomeration of city electrical loads coming from a distributor. Also a data-set for EV's charge load is created starting from the data collected by Caltech [11] that is a Californian university that is collecting EV's charging data in order to develop an adaptive charging network. It is important to highlight that different phenomena and different data sets must be treated with different strategies in order to obtain synthetic data that are meaning-full.

3.3. Data-sets

The data-sets utilized in this thesis are three. The first one is refereed as **Real consumption of a Milan family**. It is composed by the hourly load registered in a real flat in Milan thanks to a smart monitoring device. The data are available for 69 days. The data have been processed in order to divide them in the ones referring to weekdays and ones referring to week-end days. This data were collected during spring so does not comprehend air conditioning and heating. The second one is referred as **Consumption of a 100 square meters flat**. This data come from an agglomeration of city electrical loads provided by a distributor. In this data it is not present a differentiation between weekdays and week-end ones because they are computed from an average between different years. Despite that in this data set are present data for all the year's months so it is possible to highlight the contribute of the air conditioning in summer's months. The last data set is referred as **EV's charge load**. This data set was created thanks to a tool present on Caltech[11] website. This data set is composed thanks to smart monitoring of EVs charging in the Caltech university facilities. The data have been first decoded from a json file that reported each charging session separately. Then the year profile has been computed by loading all the session in an artificial year. Then the year has been divided in 365 days. Finally only 297 days were kept,the ones where at least one recharging session took place. The days where no recharging took place were eliminated.

3.4. Synthetic Data Generation

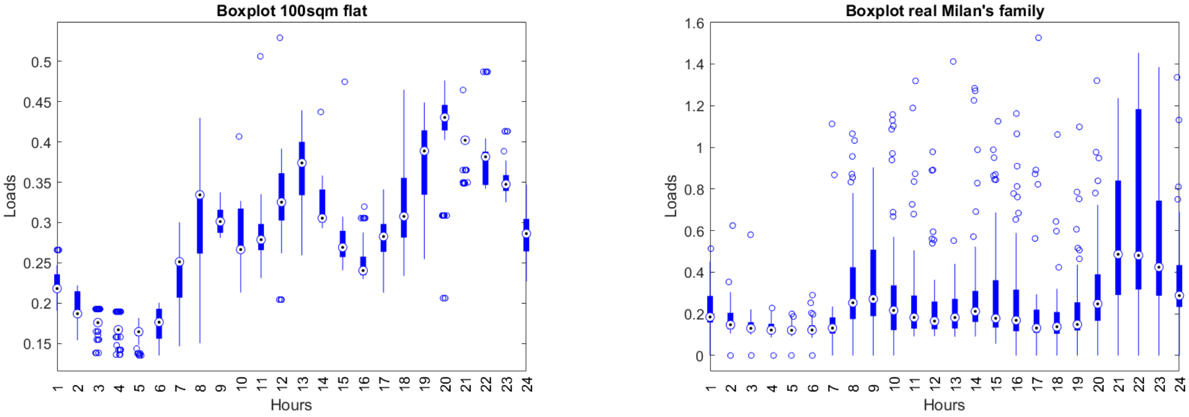
In order to generate the synthetic data data-set I decided to adopt two different strategies. The first one is based on mathematical distribution sampling [12] the second one is based on random extraction of load profile, both methods will be described in the following paragraphs.

3.5. Strategy one

The first strategy, adopted for the generation of the load data-sets referring to the condos, is based on the real data coming from the Milan's family and from the typical loads for an 100 square meters flat is:

1. for each starting data-set divide the data between ones referring to week days and ones to the week-end days
2. compute the mean hourly consumption for all the distribution
3. compute the hourly standard deviation for all the distribution
4. generate the two synthetic data-set defining for all the year's hour a load that is equal to the mean hourly value plus a noise which is defined in equation 4

The hour load is created by adding to the mean load value for each hour a noise. The noise component is computed by multiplying the standard deviation of each hour's distribution by a value drawn from a standard normal distribution thanks to Matlab Randn function [13]. It is possible to look at the computed distribution for each hour in figure 7. The boxplot diagrams reported below refer to the week day's loads. The same computations have been done for the week-end's days loads. For the 100sqm flat the computations have been also done for each month separately.



(a) Typical flat data Boxplot.

(b) Milan's family data Boxplot.

Figure 7: Data Boxplots

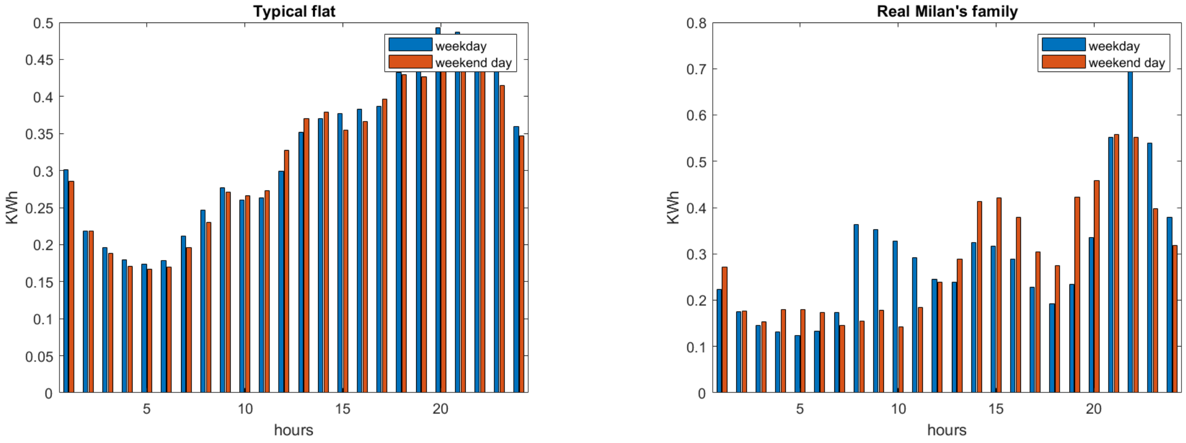
Below is possible to look at the Pseudo Code 1 of the Matlab code utilized in order to produce the synthetic data. This algorithm is the core of the one utilized to generate the data regarding the Milan's family. It is possible to note how the code (line 8) is able to differentiate the synthetic data generation between weekdays and week-end days. The code adopted in order to create the data for the 100 square meters flat is pretty similar except that it processes each month separately in order to keep the monthly patterns. It is also possible to note that the code in line 13 is performing a check on the generated data in order to assure that the values generated are always positive and if this does not happen the code repeats the generation of that particular hour's load implementing an attenuation to the noise. The hour load is generated with the input data defined for each day and each hour through equation number 4.

Algorithm 1 Milan's family synthetic data

```
 1: for $i = 1 : 8760$ do
 2:     attenuation initialized = 1
 3:     check initialized = 1
 4:     while $check == 1$ do
 5:         current-day is the day that is generated
 6:         h equal to the hour of current day that is generated ranging from 1 to 24
 7:         a is the weekly number of the day that is generated ranging from 1 to 7
 8:         if $2 <= a <= 6$ then
 9:             initialize the i hour load with mean, std and attenuation referring to week-day's hour h
10:         else
11:             initialize the i hour load with mean, std and attenuation referring to weekend-day's hour h
12:         end if
13:         if $loads >= 0$ then
14:             check equal 0
15:         else
16:             the attenuation is increased
17:         end if
18:     end while
19:     synthetic load(i)=hour load
20: end for
21: The final output is the vector synthetic load that represent all the hourly load of the synthetic
    year.
```

$$\boldsymbol{P_L = \mu_{L_i} + \sigma_{L_i} \cdot \epsilon \cdot randn(1)} \tag{4}$$

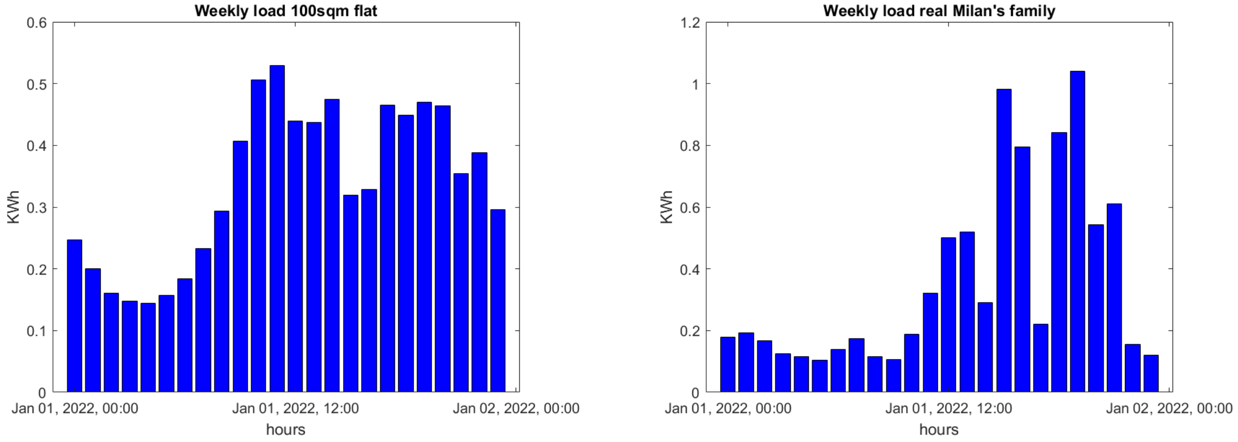
In the previous equation P_L represents the hourly load, μ_{L_i} represents the mean load at that hour, σ_{L_i} represents the standard deviation at that hour and randn(1) is adopted because on Matlab it draws a value from the standard normal distribution. $\boldsymbol{\epsilon}$ represents an attenuation factor and it is initialized equal to 1. In the following picture 8a and 8b it is possible to look at the mean data computed from the starting distribution. Comparing the mean data with the data present in figure 9 ,that reports two sample day extracted from the starting database, it is possible to note that the data present similar trends. It must be noted that different data set's origin leads to a different quality of the data. The data collected from a real family in Milan show a sensible difference between week days and week-end days, while the ones coming from the data-set generated for a 100 square meters flat don't show the same difference. This is not a problem for the analysis carried out in this thesis but it is important to note that it is impossible to create synthetic data that replicate week-end and weekly days starting from a data-set that doesn't have this distinction if, as in this case, it is not possible to make accurate assumptions to simulate the trend. When using synthetic data, it is important to define which trends of data are relevant case by case and check if the starting data-set has these same statistical characteristics.



(a) Typical flat mean load.

(b) Milan's family mean load.

Figure 8: Mean load.

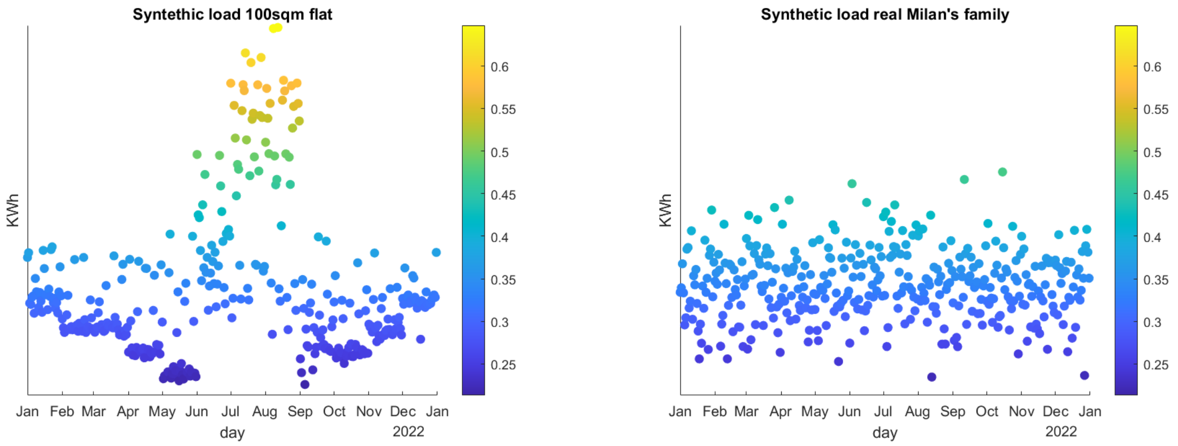


(a) Example of weekly load 100sqm flat.

(b) Example of weekly load real Milan's family.

Figure 9: Example of weekly real loads.

The data for the traditional flat were available all year long and this made possible to keep a monthly difference in the synthetic data by differentiating the previous process for all the months. This was not possible for the data from a real Milan's family because only some months were available, so I needed to extend the data-set, this was not a problem for the synthetic year generation. The synthetic year, generated according to this assumption, will not show different monthly trends. It is important to decide whether or not this is relevant based on the function of the synthetic data. In this thesis more or less half of the families loads have been assigned from the synthetic data coming from the Milan's family database and the other from the synthetic data coming from the typical flat. This leads, even if half of data do not show monthly trends, to a final synthetic year that shows them. In figure 10 is possible to look and compare the two different synthetic data-sets generated. In the figure 10a it is possible to highlight that during the summer the loads are higher, this is related to air conditioning, this trend is not visible, as previously anticipated, in the synthetic year created from the data coming from a real Milan's family.



(a) Syntethic load 100sqm flat.

(b) Synthetic load real Milan's family.

Figure 10: Synthetic year.

3.6. Strategy two

The second strategy, adopted in order to generate synthetic EV's load is different because it is meaningless to assume a noise on the EV's charge. A charging session is distinguished by a constant loads for some hour and it does not show a similar pattern between different days as it has been possible to note on the EV's charge load database. A different strategy must be defined:

1. the starting data-set from Caltech is processed and the data are divided in daily charging session
2. artificial year is created extracting for each day a random profile from the database accordingly to a Monte-Carlo[10] approach.

In figure 11 the average charging session computed from the Caltech database is reported. By comparing figure 11 with examples of a real charging session in figure 12 ,it is possible to confirm , as anticipated, that a mean value between different sessions is not an accurate model of a real charging session.

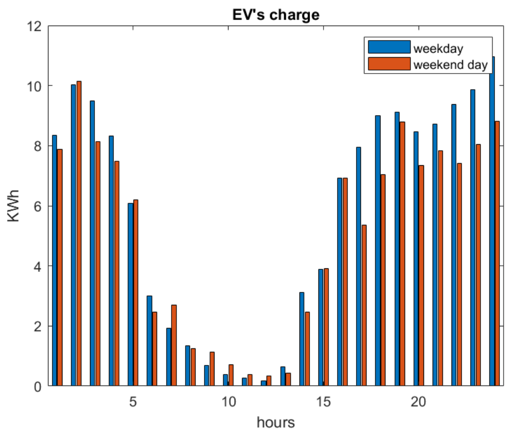
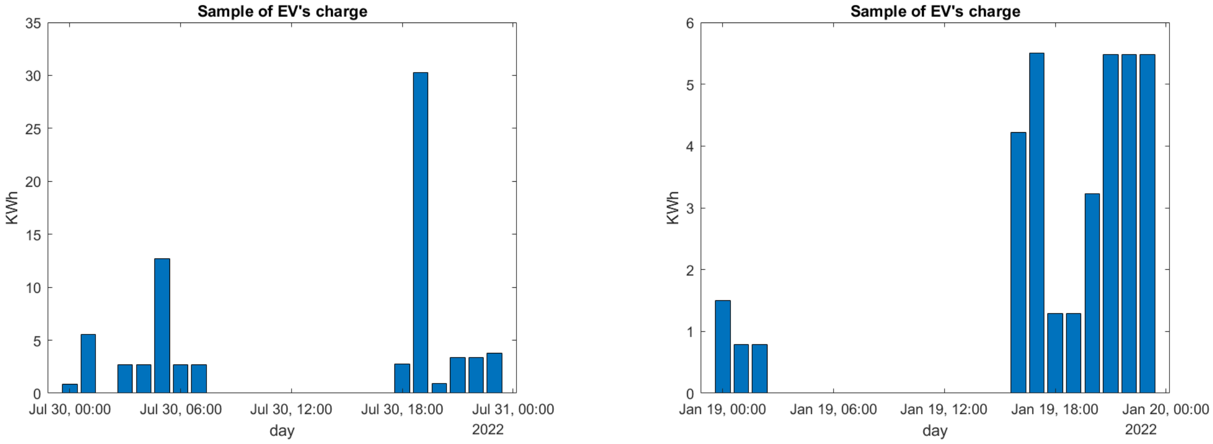


Figure 11: EV's mean charge



(a) Sample Ev 1.

(b) Sample Ev 2.

Figure 12: Sample of real EV's.

3.7. REC's components definition

As previously stated the REC of *"Villaggio dei Giornalisti"* is composed by twelve condos. It was impossible for privacy reasons to have familiar composition's data of all the twelve condos, despite that it was possible to define that in each building there are a total number of families that can vary between seven and ten. Each building was so randomly initialized with a number of families that can vary from 7 to 10. I decided to assign at each family randomly the synthetic load curve computed or from the real Milan's family or the one computed from the typical flat's data. This leads to assume that more or less half of the families has conditioning air and this is consistent with the real situation.

4. PV Plant

4.1. PV fields

The first step regarding the PV generation was to define the location of the REC, its coordinate are: 45°30'2.34"N 9°12'14.36"E. Once the site coordinate are defined it is necessary to define all the areas available to install PV panels; in the site the available areas are the two main flaps (one looking east and one looking west) and the tympanum of each roof for a total of thirty six fields. The buildings are numerated from B1 to B12 starting from the north east corner and moving clockwise and in each one there are the WEST, the SOUTH, and the EAST field. In the table the azimuth of each field is reported. In the following table all the azimuths of the fields are reported.

	B1	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B9**	**B10**	**B11**	**B12**
West	103	96	101	115	108	100	126	108	90	99	100	100
South	13	6	11	25	18	10	36	18	0	9	10	10
East	-77	-84	-79	-65	-72	-80	-54	-72	-90	-81	-80	-80
N panels	130	112	112	112	112	112	112	112	112	112	112	130
Pnom	48.1	39.2	39.2	39.2	39.2	39.2	39.2	39.2	39.2	39.2	39.2	48.1

Table 2: Field's azimuth & Pnom

4.2. PV production

The production of the PV field's was computed exploiting two different software. The first one was PVsyst [14] in order to compute the near shadowing losses, the second one was the web tool of PVGIS.
The first step in PVsyst was to model all the twelve buildings and their roofs in order to understand and to control how many PV panels is possible to install as is possible to see in figure 13. The chosen PV panel is long 1.776 meters and wide 1.052 meters [15]. It is mono-crystalline with a Pnom of 370W. The total install-able PV power is 488.4KW divided in 96.2 KW installed onto the two northern buildings that are little bit bigger and the other 392.2KW installed in the ten remaining buildings.

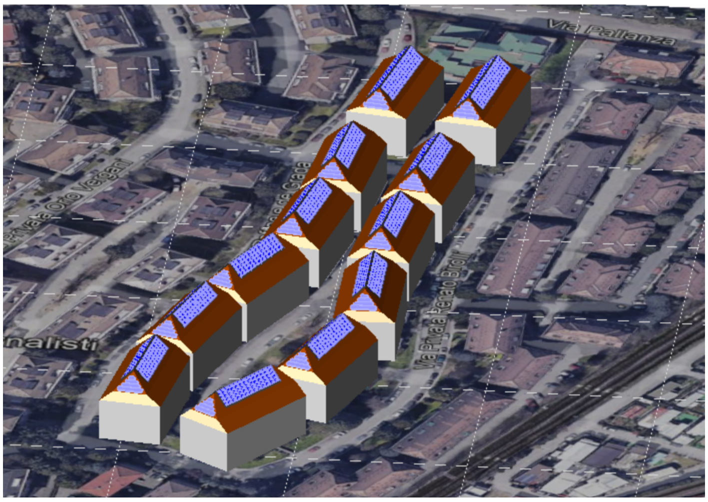
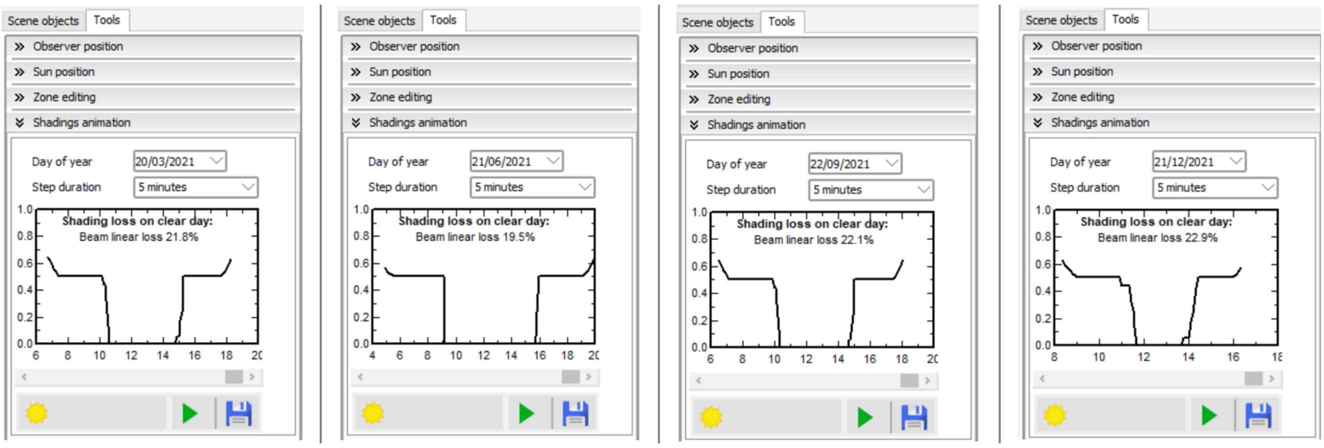


Figure 13: 3D model

The second step was to perform the shadowing simulation at the summer and winter solstice and at the equinoxes, in this way is possible to evaluate the four different linear beam losses due to the reciprocate buildings shadowing and finally compute an overall near shadowing loss coefficient that is defined as the mean between the previous four. The near shadowing losses coefficient is equal to 21.57%.



Day of year 20/03/2021
Step duration 5 minutes
Shading loss on clear day:
Beam linear loss 21.8%

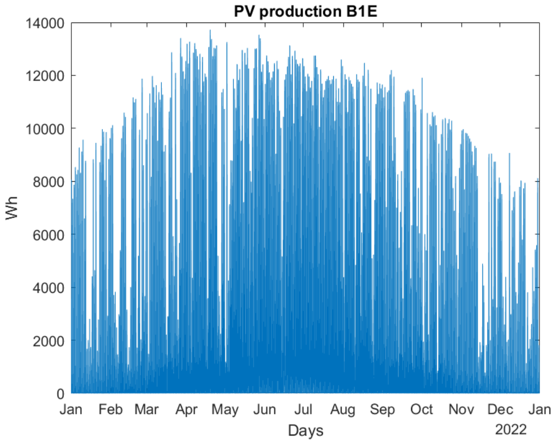
Day of year 21/06/2021
Step duration 5 minutes
Shading loss on clear day:
Beam linear loss 19.5%

Day of year 22/09/2021
Step duration 5 minutes
Shading loss on clear day:
Beam linear loss 22.1%

Day of year 21/12/2021
Step duration 5 minutes
Shading loss on clear day:
Beam linear loss 22.9%

Figure 14: Near Shadowing

PVGIS is the acronym of Photovoltaic Geographical Information System; it is a European Community's website where the tool [16] is available. The tool, having as input: the location, the azimuth of the field, the slope, and the PV panel technology allows to evaluate a typical meteorological year and to compute the PV production. The chosen PV panel technology is mono-crystalline and the tilt is 45° for both roof's flaps and tympanum. In the following figures are reported as example the PV production curve of the building 1 referring to the two different roof's sides (looking east and west)and to the tympanum(looking south).



(a) PV production B1E.

(b) PV production B1W.

Figure 15: PV production B1E & B1W

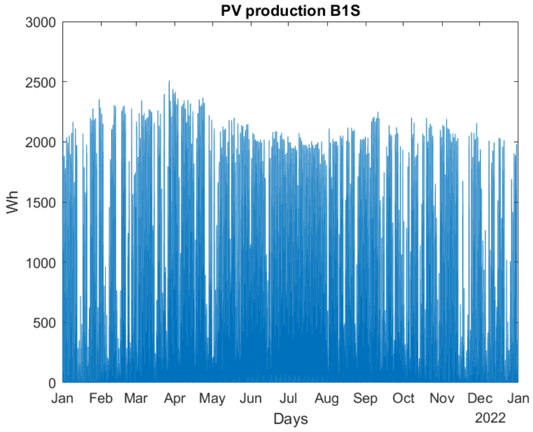


Figure 16: PV production B1S

The PV production will decrease during the years, in order to account this effect first of all is needed to define the expected yearly degradation. The degradation rate for mono crystalline PV cell could be find in the article "Compendium of photovoltaic degradation rates" [17] and it is equal to 1% year. For sake of simplicity in this thesis the PV production of the plant is assumed equal at the one computed at year 10 for all the lifetime. This assumption is conservative from the economical point of view because a lower production is assumed in the first ten years where the actualized cash flow are higher respect to the one of the last ten years.
Once all the PV plant's productions are computed is possible to sum all of them in order to obtain a production curve referred to all the REC. In figure 17 is reported a sample week of the REC's PV production and REC's load. The values are normalized by dividing them by the maximum PV plant hourly production that is 215.0713KWh.

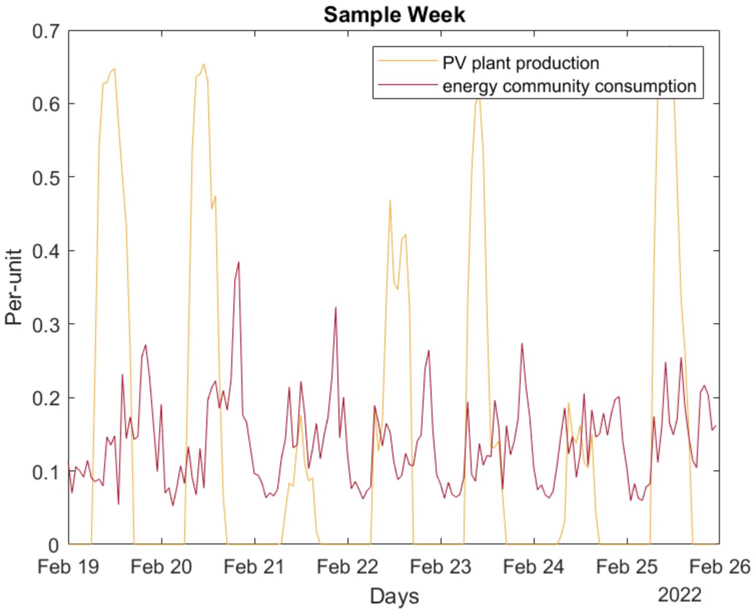


Figure 17: PV production REC

5. Cases simulation

Finally after the calculation of the load curve and the PV production curve it is possible to simulate all the cases defined in table 1.

5.1. Case 0 - No investment only loads

The case 0 is the starting one. It includes only the REC loads. In order to simulate this case only the REC loads defined through the synthetic data generation are needed. The simulation is performed through the algorithm in figure 18. All the steps are now described:

1. Definition of an hourly energy net value that is the total load for each hour of the year, it could be computed both for all the separate buildings or unifying all of them;
2. Memorize the purchased energy for each hour of the year;
3. Check if all the year's hours are processed or if some are still missing;
4. End the algorithm producing the vector 'purchased energy' that memorizes all the loads. It represents the amount of electric energy that the REC must buy from the grid in order to full-fill its demands.

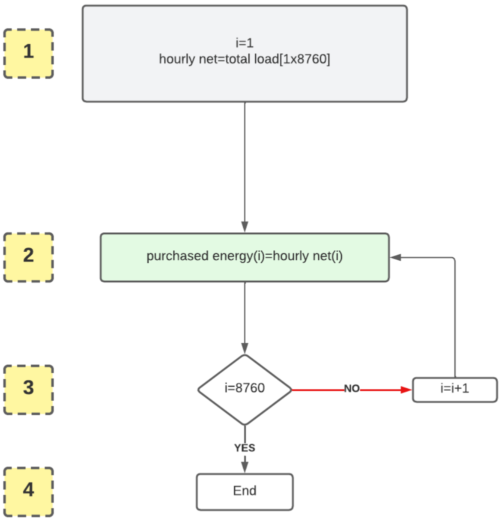


Figure 18: Case 0 only loads

This case is pretty basic but it is the starting point of the REC analysis because it is needed in order to perform a comparison between the architecture without PV panels and without REC configuration respect to all the following architecture upgrades. Below it is possible to look at the plant layout in figure 19. The black diamonds represents the electric meter. In this layout it is possible to see that each building does not interact with the others.

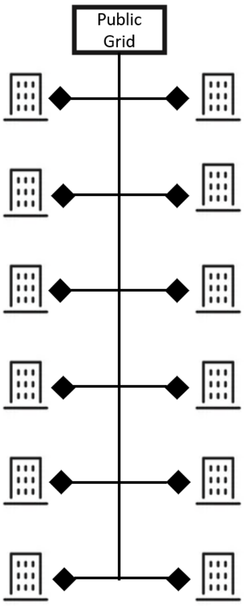


Figure 19: layout 0

5.2. Case 1 - PV installation

Case 1 includes the buildings loads and the PV generation. In order to simulate this case I need the REC loads defined through the synthetic data generation and the simulated PV generation data coming from PVGIS. In this simulation all the data are computed for each building separately because none on site exchange is permitted according to the regulations that rule the private PV plant installation. The energy can be consumed only in the user's building where it is produced and it is not possible to share it with the other buildings. All the overproduction is sell to the grid. The simulation is performed through the algorithm in figure 20. It is performed for all the twelve building separately but for the sake of conciseness only one is reported. All the steps are now described:

1. Definition of an hourly energy net value for building one, that is the total load for each hour of the year, minus the PV production referring to the same building;
2. calculate if the hourly energy net value at the hour i is higher or lower then 0;
3. If hourly energy net value is lower than zero memorize the overproduction that is the amount of energy produced and not consumed for each hour of the year, this energy is sold to the grid;
4. If hourly energy net value is higher than zero (or equal) memorize the amount of energy that must be purchased from the grid to meet the building consumption;
5. Control if all the year's hours are processed or if some are still missing;
6. End the algorithm exporting the hourly overproduction and the purchased energy.

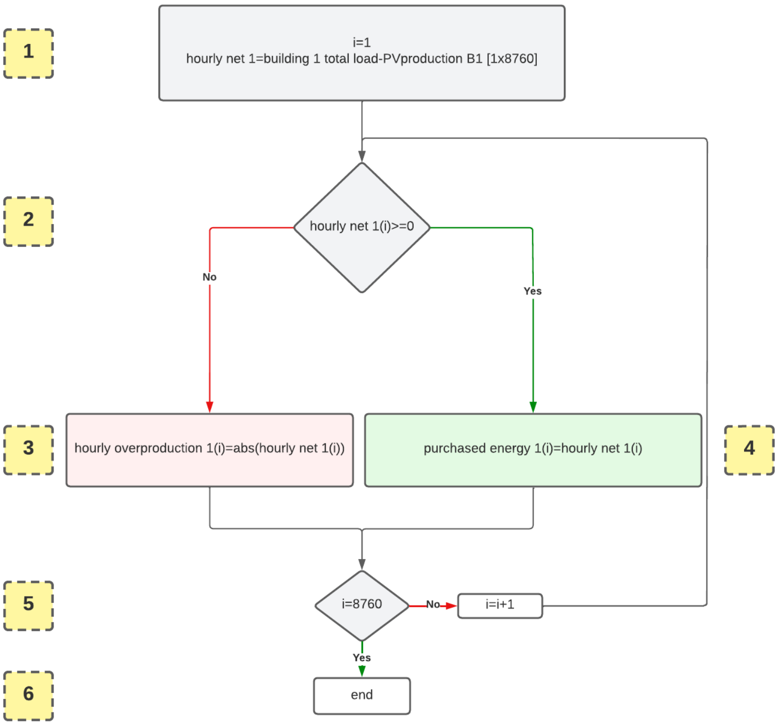


Figure 20: Case 1 Load & PV for Building1

The amount of energy that is self-consumed is not memorized from the algorithm; it is computed subtracting the overproduction to the total PV production. The choice of not memorize the self-consumption at each hour is made because the incentive is constant and does not depend on when self-consumption happen. The self-consumption in this configuration is incentivized according to the collective self-consumption configuration. The incentive is 100 €/MWh [3]. Below it is possible to see the layout of the plant in figure 21. It is possible to highlight that now each building has its own PV plant. The electric meters now are twelve. They are downstream respect to the Building because they have to record the net energy flow from each Building to the grid. Each PV plants have its own meter that record the PV production.

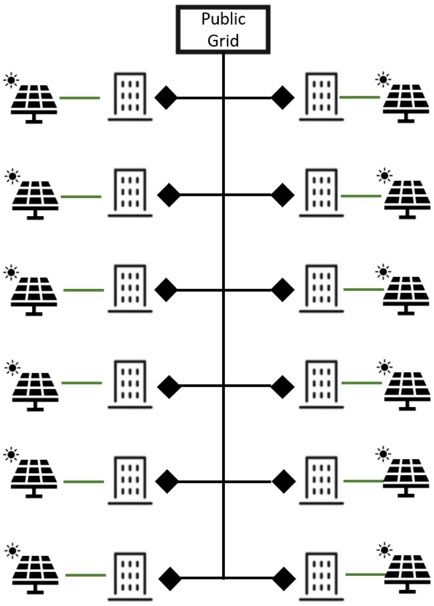


Figure 21: layout 1

5.3. Case 2 - REC configuration

Case 2 includes the REC loads and the PV generation. In order to simulate this case I need the REC loads defined through the synthetic data generation and the PV generation data coming from PVGIS. In this simulation the loads and the PV generation from all building are collected in only one vector; this happens because in a REC configuration the on site energy sharing is allowed and incentivized. It is important to note that it is not needed to build a new grid in order to perform the on site energy exchange in fact each plants belonging to an energy community is directly connected to the public grid and the energy sharing works according to the virtual power plant system [18]. For example this means that if at the 10 o'clock of the first of June the PV plant of the building 1 is producing an extra power respect to the one needed by the building 1 and the building 2 at that same moment is requiring more energy respect to the one that its power plant is producing the plant 1 will export its overproduction to the grid and the building 2 will take the energy directly from the public grid. This process in a virtual power plant logic is accounted as if the energy from the PV plant 1 was directly going to the building 2 even if, in reality, there is no guarantee that the real energy exported by PV plant 1 to the grid is the one actually imported to building 2 by the public grid. In order to analyze this case it is necessary to compute: hourly overproduction, purchased energy and self-consumption. This is performed by the algorithm in figure 22. All the steps are now described.

1. in step one is defined an hourly energy net value for all the building that is the total load for each hour of the year minus the PV production referring to all the REC;
2. in the second step it is controlled if the hourly energy net value at the hour i is higher or lower then 0;
3. If hourly energy net value is lower than zero the algorithm memorizes the overproduction that is the amount of energy produced and not consumed for each hour of the year, this energy is the one that is sold to the grid and the algorithm also memorizes as self-consumption the total load at that hour because it is full filled by the PV generation ;
4. If hourly energy net value is higher than zero (or equal) the algorithm memorizes the amount of energy that must be purchased from the grid to meet the building consumption and memorize the self-consumption as the difference between the total load at that hour and the amount of energy that is purchased from the public grid ;
5. The algorithm controls if all the year's hours are processed or if some are still missing;
6. End the algorithm exporting the hourly overproduction, self-consumption and the purchased energy.

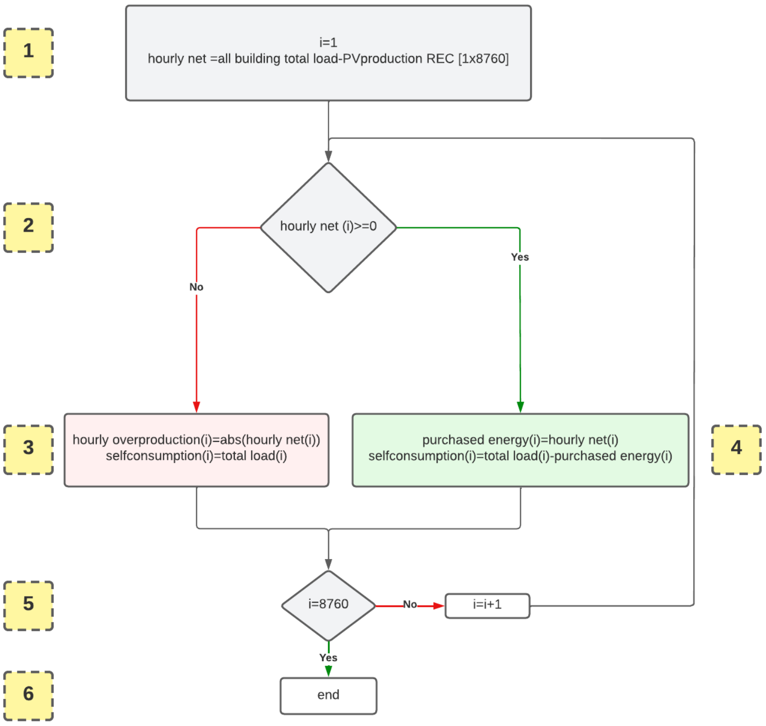


Figure 22: Case 2 REC no batteries

The amount of energy that is self-consumed, as previously anticipated, in this case is computed and memorized. The incentive granted for the self-consumption follows the REC regulations and is equal to 110 €/MWh

Below it is possible to see the layout of the plant in figure 23. It is possible to highlight that now the electric meter is downstream respect to all the buildings. It is located in that position in this layout only to render the idea that in a REC the energy flows are accounted at all the community and not at the single building.

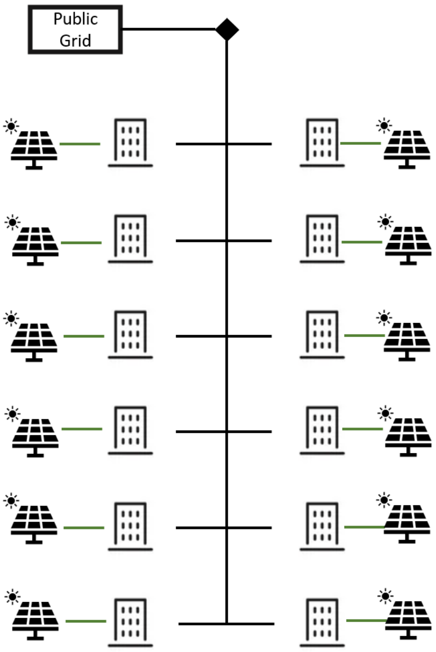


Figure 23: layout 2

5.4. Case 3 - REC with batteries

Case 3 includes the REC loads the PV generation and the batteries installation. This case is almost identical to the case 2, it is only added to the layout an energy storage system. The addition of the energy storage system is carried out in order to increase the REC's self-consumption and in this way exploit in a better way the energy produced by the PV plants. In the simulation has been implemented a new variable called battery level. This variable is adopted in order to store all the information regarding the battery path. The simulations have been carried out for various battery sizes in order to understand how the size can improve the self-consumption. The battery size range varied from 0 (same results as case 2) to 4000KWh, the algorithm is the same for all the simulations, only one input and some constraints change from one to another. For the sake of conciseness only one is reported in figure 24, but the variations that must be made in order to perform the different simulations are highlighted in here below. The steps of the algorithm are now described.

1. Definition of an hourly net for all the building that is the total load for each hour of the year minus the PV production referring to all the REC, definition of the battery start value that is the starting state of charge assumed for the simulation (0.5) definition of a battery net that is the available battery size (lower value longer lifetime) and finally battery level(0) initialized as battery start;
2. Upgrade of battery level(i) as battery level(i-1) minus hourly net;
3. Decide if battery level is higher or equal to 0;
4. Memorize in self-consumption the total load at that hour;
5. The purchased energy is equal to the abs of the battery level, the self-consumption is equal to the total load at that hour minus the purchased energy the battery level is updated to 0 and the battery level is stored in the battery path vector;
6. Decide if the battery level is higher than the net battery size;
7. Battery level remains the same and it value is stored in battery path;
8. Overproduction is memorized as the difference between the battery level and the net battery size, battery level is redefined as the battery size because a state of charge higher than the net battery size is not allowable;
9. Verification if all the year's hours are processed or if some is still missing;
10. Ends the algorithm exporting self-consumption overproduction purchased energy and battery path;

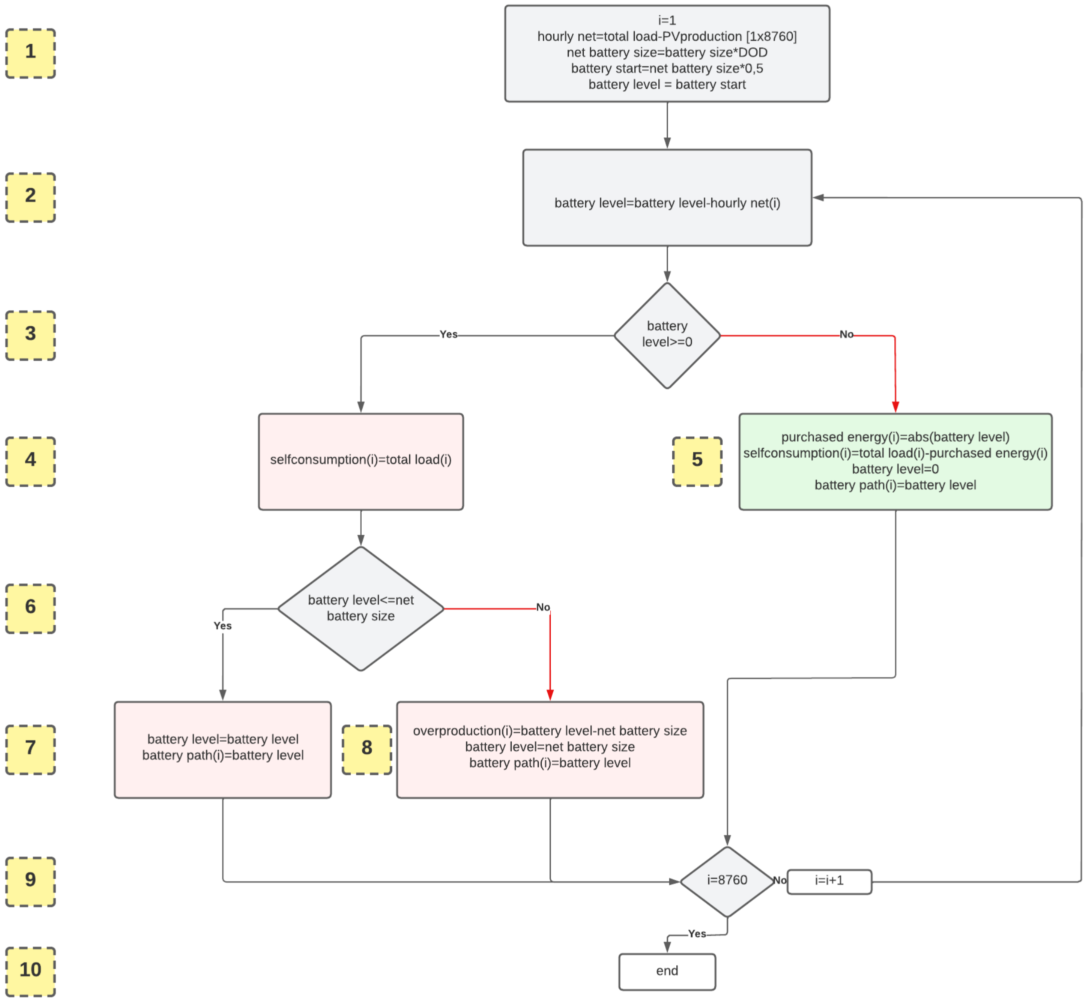


Figure 24: Case 3 REC and Batteries

What changes between the different algorithms linked to the different battery size is simply the starting value of battery size that affects the starting battery level.
Below it is possible to see the layout of the plant in figure 25. It is possible to highlight that now before the electric meter a new component is present. It is the battery. It is upstream to the electric meter because it is a community's choice how to manage the battery. In the thesis the battery logic is to try always to full-fill the building's electric demand.

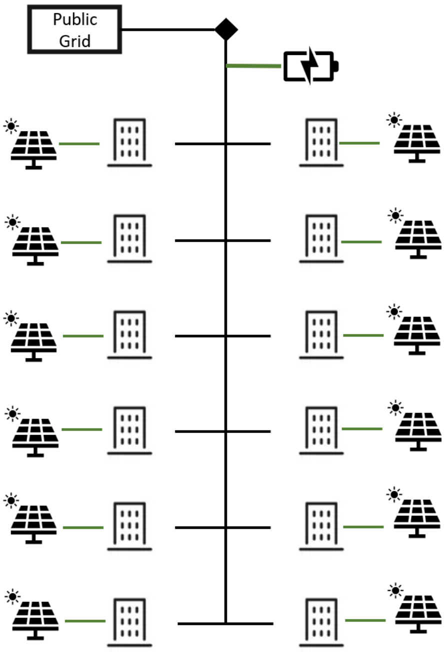


Figure 25: layout 3

5.5. Case 4 - REC with EVs

The fourth case is a simple variation of case 3 where instead of having only the REC loads also the charging session of the Evs, computed as shown in paragraph 3.6, is added to the total load.
Below it is possible to see the layout of the plant in figure 26. It is possible to highlight that now before at each building a EV-charging station is present. This represents that each building has one plug for charging an EV. This layout is the most complex one and account all the most important aspects that a REC in an urban context could face.

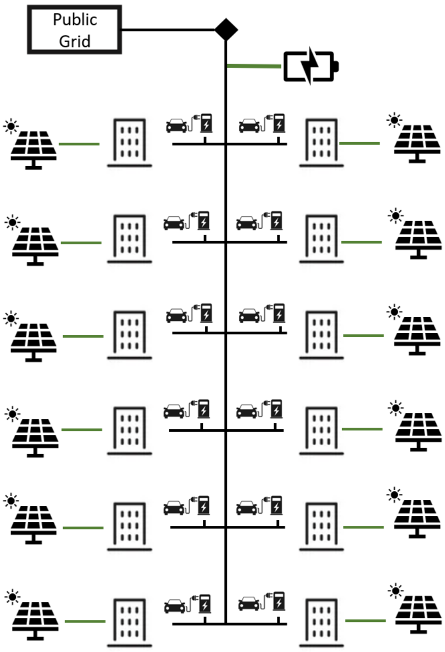


Figure 26: layout 4

6. Techno Economic Analysis

6.1. Economic aspects definition

In this section the results coming from the previous simulations will be discussed and will be utilized in order to perform an economic analysis. Before entering in the different cases it is necessary to introduce some assumptions, some data and some decisions that have been taken in order to perform the analysis. Most of the economic values come from the article Renewable Power Generation Costs in 2020 [19] published by IRENA. The other costs, directly computed from component's public offer, are specified.

- The battery cost, for a lithium based battery, is defined equal to 1069 [€/KWh];
- The PV inverter cost is defined equal to 65 [€/KW];
- The PV panel cost is defined equal to 220 [€/panel] from price to the public [15];
- The charging column price for Evs is 3000 [€/column] coming from the ARERA's report: "Mercato e caratteristiche dei dispositivi di ricarica per veicoli elettrici"[20];
- non modules cost 115 $[€/KW_{Pnom}]$;
- installation cost 145 $[€/KW_{Pnom}]$;
- engineering cost 180 $[€/KW_{Pnom}]$;

Once the costs regarding the PV plant are defined, also the costs regarding the purchased electricity and the self-consumption incentive must be defined. The first one is equal to 0.173 [€/KWh] this data is coming from statistics page of ARERA site [21], it is an average computed on the period 2004-2020. The price is referred to the sum of:

- expenditure on energy 9.07 [c€/KWh];
- costs for the transport and management of the meter 3.08 [c€/KWh];
- expense for system charges 2.76 [c€/KWh];
- taxes 2.39 [c€/KWh].

It is possible to look at the energy price trend in figure 27.

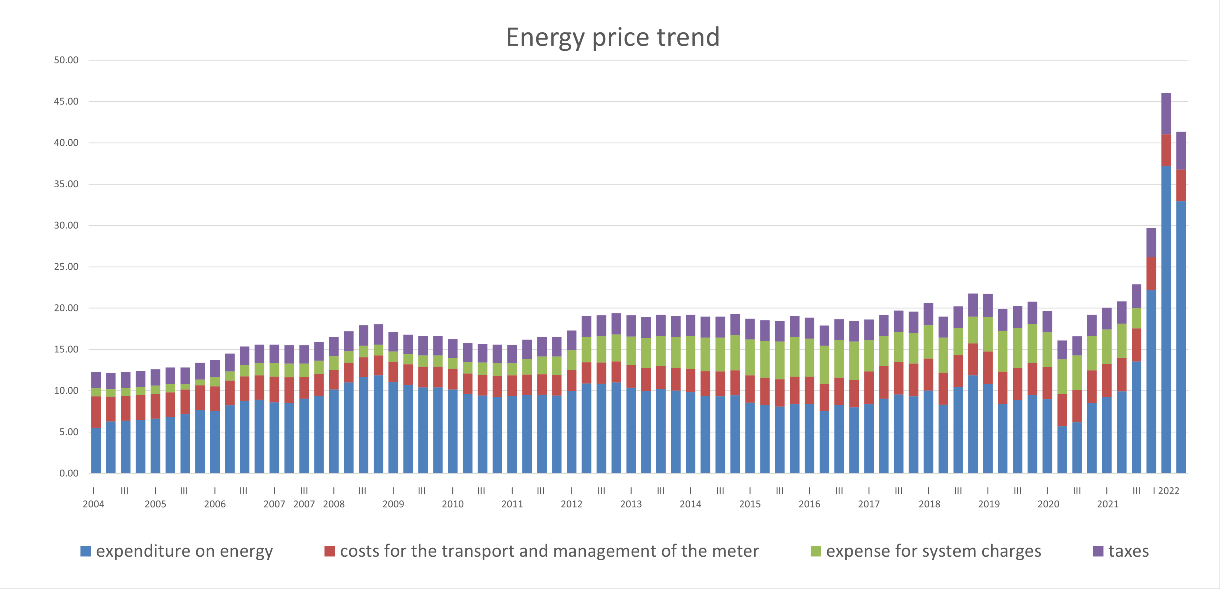


Figure 27: Energy price trend

The second one is defined in the Italian's legislative decree n.199 [3] and it is equal to 110[€/MWh] for a REC configuration and 100 [€/MWh] for a collective self-consumption configuration. The last four core parameters that must be defined in order to perform an economic analysis are the cost of capital, the typology of tax deduction that the project can access, the incentives referred to the self-consumption and finally the price at which the overproduced energy could be sold to the grid . The definition of a cost of capital is quite difficult and subjective because in this typology of project the investor could belong to different categories. The CoC for a private family respect to the one for a company is quite different. It has been decided,looking at the article dynamic analysis of financing conditions for renewable energy technologies [22], to assume as CoC 2.5%. That, as is also possible to see from figure 28a, is the cost of capital computed for renewable solar PV power plant in 2017.

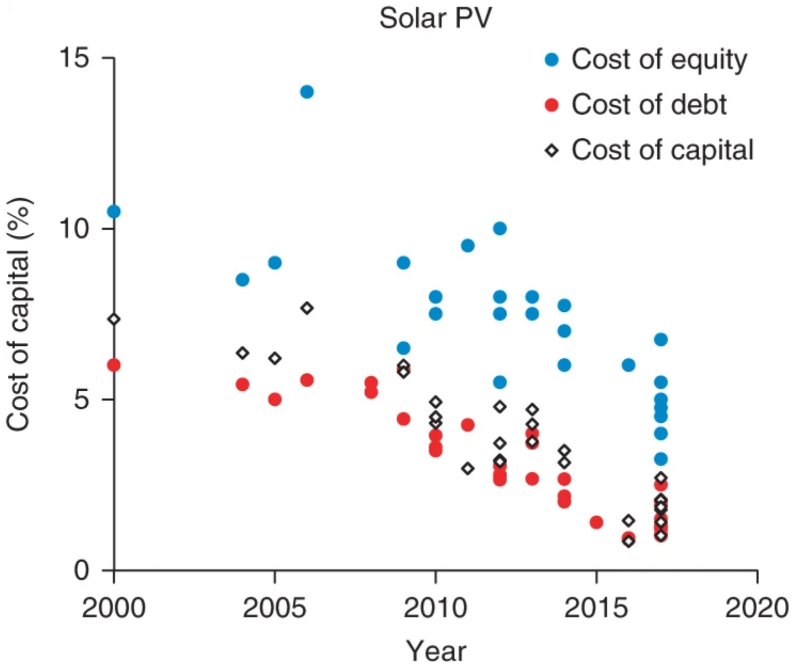


Figure 28: Cost of Capital

About the tax deduction, the decree limits the access to the 110% deduction to a maximum PV installed power of 20KW as it possible to read in the resolution of the tax office [23]. In the same article it is also stated that the part of the plant that exceed 20KW and is lower than 200KW can access the 50% tax deduction. This is not up-to-date because when that resolution was published the maximum size of the plant belonging to an REC was 200KW. Today the maximum size is 1 MW as is possible to read in DECRETO LEGISLATIVO 8 novembre 2021 [3] and this means that the maximum PV installed power in order to access the incentives is likely to be 1MW.

The incentives for the self-consumption are defined, 100 [€/MWh] for a collective self-consumption configuration, 110 [€/MWh] for a Renewable Energy Community configuration as is possible to read from the decree [3]. Also a refund of 9 [€/MWh] is defined by ARERA to account the reduction of the cost sustained to balance the grid.

The selling price of the renewable energy fed to the grid is quite hard to define because it varies according to the PUN (single national price). The average reward based on the PUN computed on the last twenty years is 60 [€/MWh] as it is possible to read on an article published on Enel X website [24].

Finally before entering in the detail of each cases it is useful to recall the meaning of Capex and Opex.

- CapEx refers to a Capital expenditure,it is incurred when a business acquires assets that could be beneficial beyond the current tax year. For instance, it might buy brand new equipment or buildings;
- OpEx refers to an Operational expenditure, it consists of those expenses that a business incurs to run smoothly every single day. They are the costs that a business incurs while in the process of turning its inventory into an end product.

6.2. Techno Economic Analysis Case 0 - No investment only loads

The case 0 is the starting point of the economic analysis in fact it is the benchmark case. In order to analyze this case has been necessary to characterize the residential loads in an urban condos when the real data was missing. It represents the choice of not investing in the PV or in the REC. This case is necessary because it defines the ordinary costs that the members of the Super condos must sustain in order to satisfy their electricity need. In this case the total purchased energy for a typical year, computed from the case 0 simulation, is multiplied by the electrical energy cost as it is possible to see in formula 5.

$$\boldsymbol{TotalElectricityCost} = \boldsymbol{TotalPurchasedEnergyB1} \cdot \boldsymbol{ElectricityPrice} \tag{5}$$

The total cost in year one, assuming the previous cited electricity cost of 0.173 [€/KWh] , is equal to 4020 €. It is also useful to compute the mean total cost for each family in order to verify if the synthetic loads calculation leads to a realistic electricity expenditure and also in order to have an idea of the single consumption of a family.

The formula adopted in order to compute the mean electricity expenditure is the number 6.

$$MeanElectricityCostB1 = \frac{TotalElectricityCostB1}{B1'sNumberOfFamilies} \tag{6}$$

Recalling that 8 families live in building 1 the mean family expenditure is equal to 502.58 €. I want to compute the total cost in a time horizon equal to 20 years that is the time for which the incentives are granted, it is also computed in order to make a comparison with the next cases. This computations are also done for a different electricity price equal to 46.03[c €/KWh] that was the highest price recorded in Italian electricity market during 2021 as it is possible to see in figure 27. This results in a total cost in year one equal to 10698 € and a mean family expenditure of 1337 €. This, as will be shown in the following paragraphs, affects a lot the investor's choice. This increase in the energy price was caused by external unpredictable and unusual phenomena, despite that this studio it is useful because highlights how much a variation in the electricity price can affects the break even point and the optimization of the battery size. In this case no investment is needed so the Capex is equal to 0. The table 3 summarizes all the results computed for traditional electricity price for the different buildings.

	B1	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B9**	**B10**	**B11**	**B12**
Total Cost	4.02	3.52	4.52	4.52	4.01	4.00	4.00	3.52	4.01	4.00	5.04	4.01
Mean Cost	502	503	502	502	501	500	500	503	501	500	504	501

Table 3: Total Cost in [K €] & Mean Cost in [€]

6.3. Techno Economic Analysis Case 1 - PV installation

In case 1 the first active choice of the investors is analyzed. We started from the consumption and the PV production of each single building because the on site exchange is not allowed in this configuration.
The starting point of the analysis is to define the cash flow that takes place each year.

- purchase of electricity;
- self-consumption incentives;
- earnings from overproduction selling.

The following formulas are used in order to evaluate this costs (the incomes are considered as a negative cost).

$$Electricity_{Cost} = \sum_{i=1}^{i=8760} PurchasedElectricity_i \cdot ElectricityPrice \tag{7a}$$

$$Incentive = -\sum_{i=1}^{i=8760} SelfConsumption_i \cdot 100 \tag{7b}$$

$$Earnings = -\sum_{i=1}^{i=8760} Overproduction_i \cdot GreenEnergySellingPrice \tag{7c}$$

$$YearlyCashFlow = Electricity_{Cost} + Incentive + Earnings \tag{7d}$$

I computed the total cost of the purchased electricity and the total incentive recognized for the collective self-consumption. The following data are the one belonging to the building 1. In order to compute the cost of electricity of building one I multiplied the total purchased energy of building 1 by the electricity price adopting formula number 7a. In order to compute the self-consumption's incentive I multiplied the total self-consumed energy of building 1 by the incentive (100 [€/MWh]) as it is shown in formula number 7b. The total earnings are computed through the formula number 7c.
The total electricity cost is 2264 €, the total incentive is 1015 € and the total earnings is 1708 € so in the year one the total cost is -459 € respect to case 0 where it was 4020 €. The $\Delta_{cashflow}$ is 4479 €. It is defined in formula 8. Looking at the formula it is possible to highlight that if the Δ is positive it means that it represents a saving if it is negative it represents an higher cost respect case zero.

$$\Delta_{cashflow} = \sum_{n=1}^{n_{max}} TotalCostCaseZero_n - \sum_{n=1}^{n_{max}} TotalCostCaseI_n \tag{8}$$

	B1	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B9**	**B10**	**B11**	**B12**
EL cost	2.26	2.00	2.62	2.63	2.30	2.29	2.31	2.00	2.30	2.29	2.98	2.25
Incentives	1.02	0.88	1.10	1.09	1.01	0.99	0.98	0.88	0.99	0.99	1.20	1.02
Earnings	1.71	1.71	1.22	1.21	1.28	1.29	1.25	1.34	1.29	1.29	1.16	1.71
Yearly Net	-460	-594	301	327	11	20	78	-224	15	20	618	-470
Δ	4.48	4.12	4.22	4.19	4	3.98	3.92	3.75	4	3.98	4.43	4.48

Table 4: El cost, Incentives, Earnings, Δ in [K€] & Yearly Net in [€]

In this case the Capex is not equal to 0 because it is necessary to buy the plant equipment and install them. The Opex, for a plant of this size, can be assumed equal to 1.2% of the Capex [25]. For the sake of simplicity in the following computation they are considered equal to 0. This assumption is justified by two main reasons: the PV modules and the inverters have been chosen with a warranty of 20 years, the battery depth of discharge has been chosen equal to 60% in order to grant 10000 cycles according to figure 29. This figure comes from the article [26] that aims at asses the battery expected lifetime. That article proposes a semiempirical battery capacity degradation model intended for offline battery life assessments. The model combines theoretical analyses with experimental observations, and provides a model that is accurate not only within the operating region covered by the experimental data, but is also applicable to other operating conditions as battery energy storage. In battery degradation, it is possible to identify a converging trend in the capacity loss when the BES energy capacity increases. This is because cycles have smaller DoD and the cycle aging becomes slower. In very large BES, the cycle aging approaches zero, leaving only the calendar aging so it is possible to obtain a very large number of cycles limiting the DoD. The average yearly number of battery cycle computed for the plant is 401 that multiplied by the plant lifetime lead to a total number of expected cycles equal to 8023. The number of yearly cycles has been computed by summing the delta between each values of the battery path and then dividing the total by the battery size multiplied by 2 as shown in equation 9. The multiplication by 2 is done because a cycle is made by the charging and discharging of the battery, in the equation it is considered an absolute value for the delta so the cycle's delta is the double of the battery available capacity. For example taking a battery that has a capacity of 20KWh a full cycle of that battery has a delta of 40KWh.

$$B_{yearlycycles} = \sum_{i=1}^{8759} \frac{|BatteryPath_i - BatteryPath_{i+1}|}{B_{size} \cdot DoD \cdot 2} \tag{9}$$

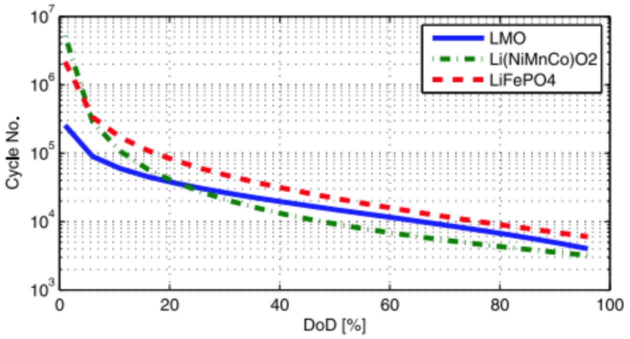


Figure 29: Depth Of Discharge

In order to define the Capex is necessary to sum the following items:

- the cost of the PV panels;
- the cost of the inverters;
- the cost of non panel material (cables, fuses, supports, screws...);
- the installation cost;
- the engineering cost;

The panels cost is computed trough the formula number 10.

$$\boldsymbol{TotalPanelCost = SinglePanelCost \cdot N_{panels}} \tag{10}$$

As it is possible to see from table 2 the total number of panels belonging to building 1 is 130 that multiplied by the panel's price lead to a panel's total cost equal to 28600 €.
The costs that depend on the Plant size are computed with the formula number 11.

$$\boldsymbol{TotalCost_n = SpecificCost_n \cdot P_{nom}} \tag{11}$$

The cost of the inverter is equal to its nominal power multiplied by its power unit price. Assuming that for a 48.1 KW plant I choose an inverter of 50KW its final price is 3250 €. With the same procedure, the cost of non panel material is equal to 5531 €, the installation cost is equal to 6974 € and the engineering cost is equal to 8658 €. Once all the costs are defined it is possible to compute the project's Capex trough the equation number 12.

$$\boldsymbol{Capex = \sum_{n=1}^{n_{max}} TotalCost_n} \tag{12}$$

The Capex for the building 1 is equal to 53014 €. This is the total investment needed to build the plant. As said before the Opex for a PV plant is assumed equal to 0. In the table number 5 the Capex components for the various buildings are reported.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12
Panels	28.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6	28.6
Inverter	3.25	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	3.25
Non modules	5.53	4.77	4.77	4.77	4.77	4.77	4.77	4.77	4.77	4.77	4.77	5.53
Installation	6.97	6.01	6.01	6.01	6.01	6.01	6.01	6.01	6.01	6.01	6.01	6.97
Engineering	8.66	7.46	7.46	7.46	7.46	7.46	7.46	7.46	7.46	7.46	7.46	8.66
Total	53.0	45.5	45.5	45.5	45.5	45.5	45.5	45.5	45.5	45.5	45.5	53.0

Table 5: Capex and Capex components express in K€

Once defined the costs and the yearly Δ, it is almost possible to perform a calculation of the break even point and the net present value of the project. The net present value is the difference between the present value of cash inflows and the present value of cash outflows over a period of time. In our case it is assumed equal to 20 years, that is the duration of the collective self-consumption incentives granted by laws. The value of a cash flow at year$_i$ is computed through formula 13. The Ecobonus represents the cost of the investment multiplied by 50 % and divided by 10. This value in reality are discounted for ten year from the taxes but it is also possible to consider it as an earning to be split in the first ten operating years.

$$\boldsymbol{CashFlowYear_i = \Delta_i + Ecobonus} \tag{13}$$

The present value of the cash flow is computed through the formula number 14 where r is the actualization factor. It is assumed equal to the cost of capital previous defined.

$$\boldsymbol{NetCashFlow = \frac{CashFlowYear_i}{(1+r)^i}} \tag{14}$$

In picture number 30 it is reported the sum of the net cash flow for all the years. It is possible to see that the break even time is equal to 8 years. It means that in 8 years the investors will get back their investment cost and the following cash flows will represent a pure earning. It is also possible to highlight that the slope of the curve shows a variation at year 10 because after 10 running year the Yearly Cash flow will change because the Ecobonus earning will end. Another interesting aspect that is possible to see from the image is that the Investment cost of B1 is higher, in fact at year 0 the net cash flow is lower respect to B2 but at the end of the lifetime the total net present value computed by summing all the actualized cash flow is higher. This happens because even if the investment is higher also the benefits coming both from the PV plant and the correlated incentives are higher.

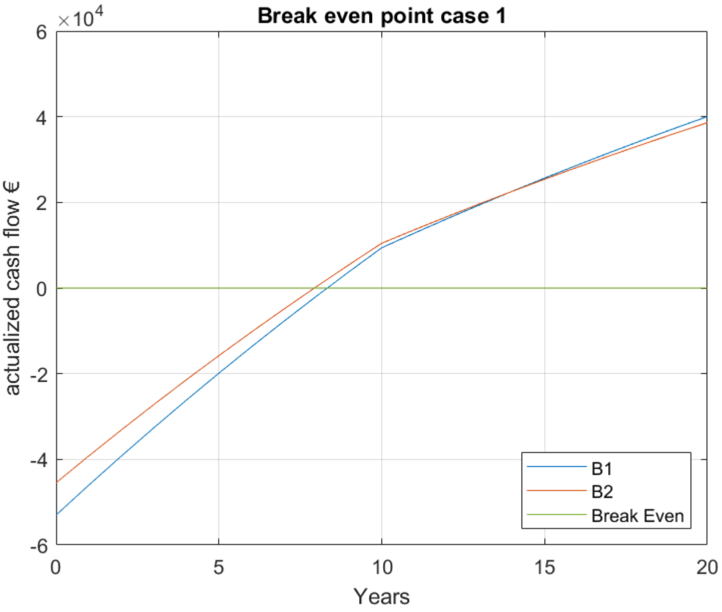


Figure 30: Break even case 1

6.4. Techno Economic Analysis Case 2 - REC configuration

In case 2 finally the renewable energy community is created.
Thanks to case 2 is possible to highlights the effects of a REC establishment both economically and energetically respect to a self-consumption configuration and respect to the benchmark case.
The main advantage respect to the previous case is the ability to share the PV production not only in the building where the plant is installed but in all the buildings belonging to the energy community. This allows to increase the self-consumption and it is also a benefit for the public grid because the on site consumption increases. From the grid perspective consuming the energy where it is produced is the best case because it allows to break down the transmission losses. The analysis is identical to the one performed for the case 1 except that now all the items are referred to all the community. This is true for PV production, buildings consumption investment cost etc. The other main difference respect to case 1 is that now the incentive is equal to 119 [€/MWh].
The total electricity cost computed through formula number 5 is equal to 28134 €. The total incentives is equal to 14483 € and the total earning coming from the overproduction energy selling is 16061 €. This lead to a Yearly cash flow equal to -2411 €. By summing the year net of all buildings from case 1 it is obtained a total equal to -351 €. The yearly cash flow is lower in case 2 and this means that the revenue are higher respect to the previous case. The total $\Delta_{cashflow}$ is equal to 51600 €. The total Capex is equal to the summation of the Capex of the previous case and it is equal to 560764 €. Same as for costs and Capex, an identycal procedure is applied to the computation of the yearly actualized cash flow. In figure 31 the summation of the yearly actualized cash flow is reported. It is possible to highlight the same trend spotted in figure 30 referring to case 1, because the ecobonus mechanism works the same. The only difference is that the Δ is different because the incentive is higher. The net present value computed on 20 years lifetime in case 2 is equal to 489040 € while the summation of the net present value of case 1 is equal to 456920 €. That means that a REC architecture is actually beneficial for the investors in fact its net present value for the same identical plants and loads is more ore less 30000 € higher.

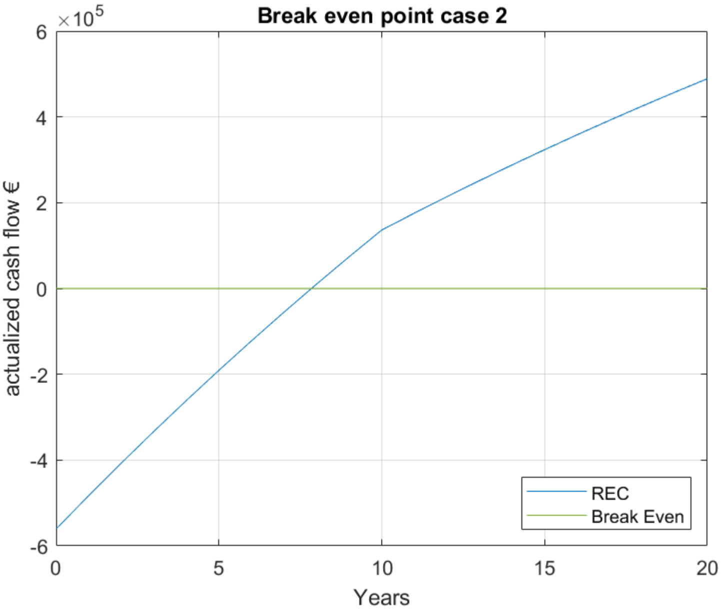


Figure 31: Break even case 2

In practice we expect that the beneficial effect obtained by moving from case 1 to case 2 should be even higher. In this simulation at each family a load curve coming from two synthetic one generated is assigned. In a real case the typology of habits is much more diversified and so the possibility to aggregate different load curve is expected to create an even higher production consumption matching.

6.5. Techno Economic Analysis Case 3 - REC with batteries

In the third case the effect of adding the battery to the REC is evaluated. Thanks to this case is possible to analyze the effects of the batteries implementation and assess if their installation is justified by the future revenues First of all it must be said that the battery implementation could lead to different improvement in the REC.

- It grants the possibility of store on site the energy over-production and consume it later in order to obtain a better matching between production and consumption;
- It allows the REC to have an autonomy energy range that may feed the REC during public grid blackouts;
- It makes possible to install fast and super-fast Evs charging station in DC.

Some improvements are quite difficult to be accounted in economical terms like the ability to feed the electricity needs during a blackout, on the other hand others are quite easy to be accounted because directly lead to an economic benefit. For example a better matching between production and consumption lead to higher incentives for self-consumption. The first evaluation that has to be done is the Capex expenditure linked to the purchase of the battery. As sad in subsection 6.1 the battery cost is equal to 1069 [€/KWh]. Reminding that the simulation has been done for battery size ranging from 0 to 4000KWh and using formula number 15 the price vary from 0 € to 4276000 €.

$$\boldsymbol{TotalCostBattery = SpecificCost \cdot Battery_{size}} \tag{15}$$

In order to chose the battery size that maximize the revenues the following procedure is adopted:

1. definition of a battery reward that is the extra self-consumption granted by the battery multiplied by the incentives plus the energy price minus the selling price of the overproduction;
2. definition of a lifetime battery reward that is equal to the battery reward multiplied by the plant lifetime;
3. definition of the battery cost for each battery size;
4. definition of an ecobonus regarding the battery purchase, it is equal to 50% of its price and will be returned in the first ten operating years;
5. definition of two Actualizing factors, one for the battery reward and one for the ecobonus through formula number 16;
6. computing the actualized lifetime reward and ecobonus multiplying them by their respective actualizing factor;
7. define a battery effect equal to the difference between the actualized reward and the battery cost minus the actualized ecobonus, formula 17.

$$ActualizingFactor = \sum_{i=1}^{timehorizon} \frac{1}{(1+r)^i} \tag{16}$$

$$BatteryEffect = ActualizedReward - (BatteryCost - ActualizedEcobonus) \tag{17}$$

The results of this computation are shown in graph 32. As it is possible to see from the graph increasing the battery size up to 500KWh leads to a positive effects on overall economic balance. Increasing more the battery size is disadvantageous from economic perspective but it still permit to have an higher independence from the public grid in case of blackouts.

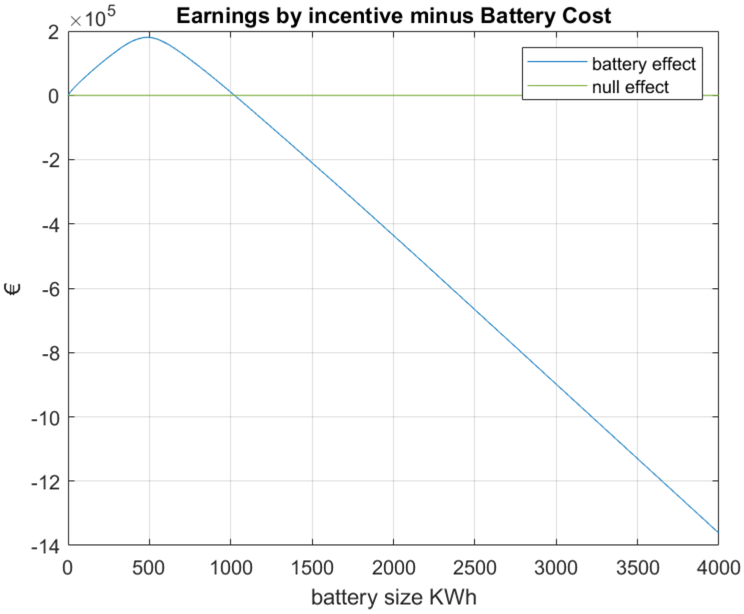


Figure 32: Battery effect

The break even calculation in this case is differs from the previous one by accounting the higher investment cost and also the higher yearly self-consumption rewards. The results are reported in graph number 33. Comparing the case 3 represented by the blue line with the case 2 that in the graph is represented by the red line it is possible to highlight that without batteries the initial investment is lower but, if I look at the final actualized cash flow, in the case 3 it is higher. This means that the biggest initial investment is paid back during the operating years thank to the lower need of purchasing electricity from the public grid and from the incentives granted for the self-consumption . It is also possible to see that installing a very big battery is a non-sense from economic point of view because in a lifetime of 20 years is impossible to recover the higher investment.

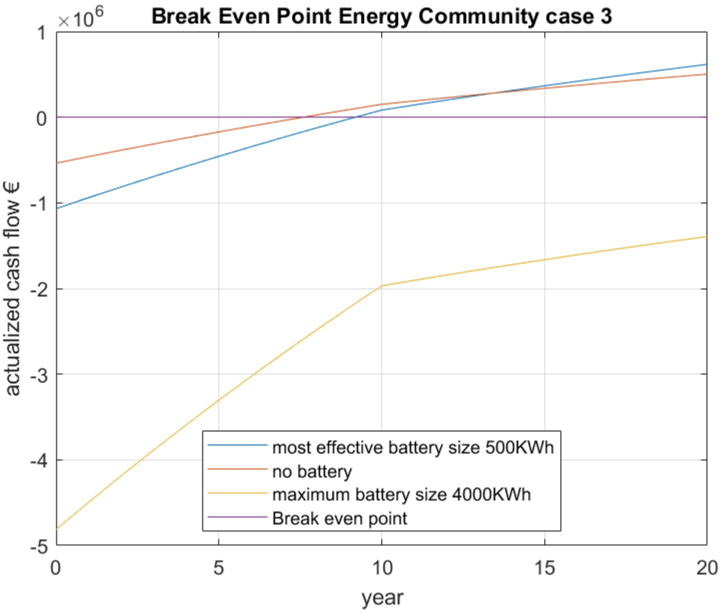


Figure 33: Break even case 3

6.6. Techno Economic Analysis Case 4 - REC with Evs

The fourth case is the final one of the analysis. It represents an upgrade respect to case 3. In this case the effects of Evs station is accounted. Thanks to this case is possible to assess if by adding EVs recharging stations to the condo the REC became more or less profitable. The effects of Evs is increasing the loads of the REC and so increasing also its self-consumption. The Evs in the other hands represent an extra capex because in order to charge them six charging column have to be installed. Each charging column has 2 plugs so each building has one plug available. The investment cost related to the purchasing and the installation of the columns, reminding the unitary cost of 3000 € as seen in paragraph 6.1, is equal to 18000 €. The addition of the Evs influences also the optimization of the battery in fact the same analysis for battery optimization done for case 3 gives different results as it is possible to see in the the graph number 34. Looking also at figure 35, that reports the break even point calculation it is possible to highlight some main differences respect to case 3:

- The battery installation leads to a higher profit during the operating lifetime of the plant;
- The optimal battery size is slightly bigger respect to case 3 in fact the maximum profit is obtained for a battery of 577KWh respect to the 500KWh of case 3;
- The break even point is slightly anticipated because the Evs allows to better exploit the batteries both economically and technically;

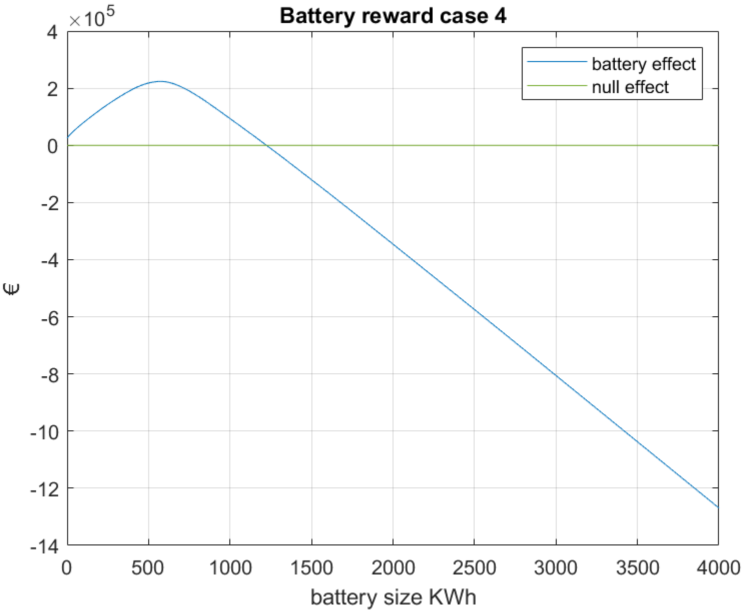


Figure 34: Battery effect case 4

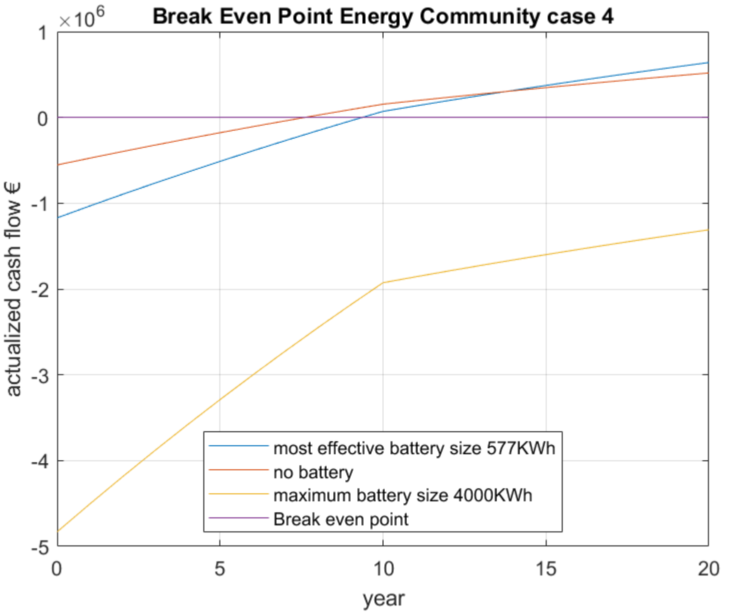


Figure 35: Break even case 4

6.7. Techno Economic Analysis Case 4 - Today's price of energy

All the previous cases has been analyzed assuming an average electricity cost, as sad in sub-paragraph 6.1, equal to 0.173 [€/KWh] In the first quarter of 2022 the energy price jumped to 0.4603 [€/KWh] as it is possible to see in figure 27 and also on Arera's website [27]. The simulation performed for the case 4 are now calculated with the new energy price. First of all as is possible to see from figure 36 the optimal battery size changed. It moved from 577KWh to a size of 698 KWh. This happens because when the electricity price is higher it is convenient to face an higher investment at the very beginning in order to have an higher self-consumption in the followings years. It is also possible to note that also the parameter that was adopted to define the optimal battery size in formula 17 increased. It happens because in a market where the energy price increases and the battery price is assumed nearly constant the savings correlated to a battery installation are higher.

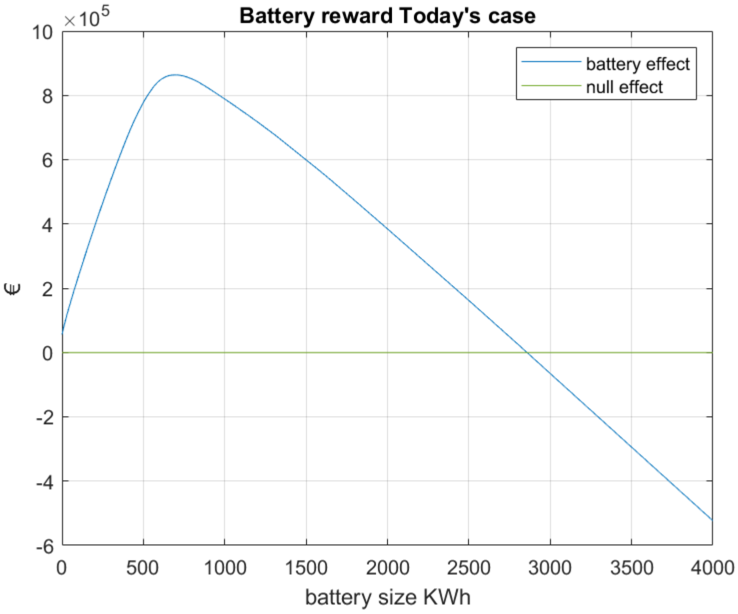


Figure 36: Battery effect case 4 Today

Looking at figure 37, reporting the result of the break even point calculation,t some observations can be done.

- Looking at the break even point computed for the case without battery and comparing it to the one in figure 35 is possible to highlight two different aspects. First, the final benefits coming from the establishment of an energy community are higher. Second, the break event point is anticipated. This is related to the higher savings allowed by the REC that increase with the electricity price;
- Looking at the blue curve, the one reporting the data of the most effective battery implementation and comparing them with the ones of figure 35, it is possible to highlight that the decision of installing a battery is much more rewarded by today energy price. The profitability of the battery installation become higher respect to the base case after seven years, respect to the case of figure 35 where thirteen years were needed to appreciate this overtake;
- The yellow curve, reporting the break even point for the configuration with the highest capacity battery, now reaches the break even in 20 year while, as is possible to see in figure 35, the break even was never reached for this configuration for the previous electricity price. Even if the break even is reached the investment related to the size of battery is non justified by the final capital earning.

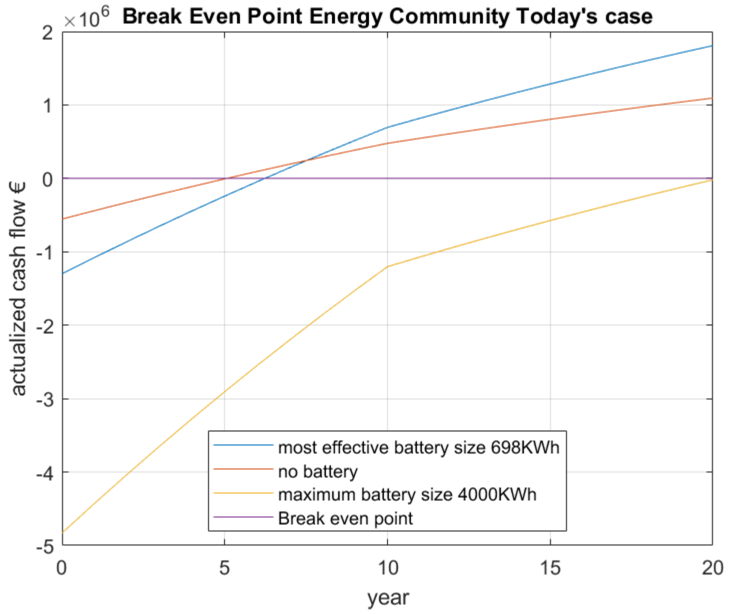


Figure 37: Break even case 4 Today

In figure 38 the break even graphs for all the others previous cases in today's condition are reported. Case 4 is reported with a battery size equal to 577KWh.

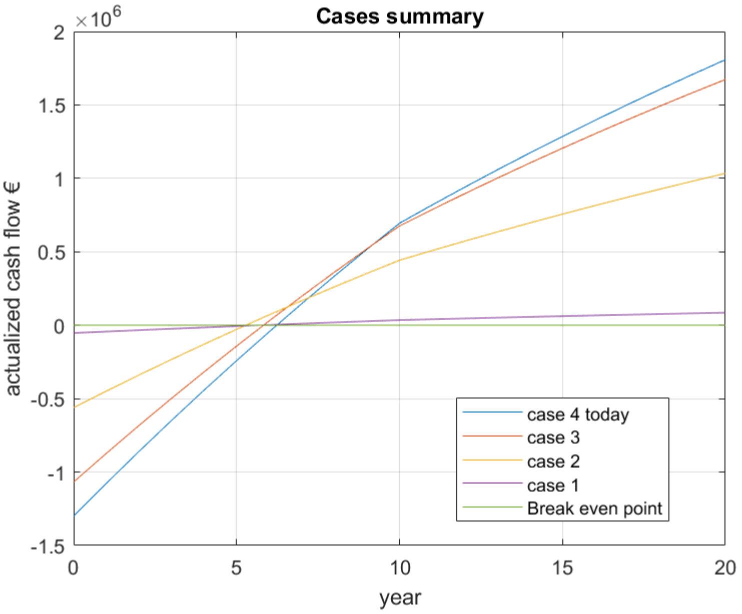


Figure 38: Cases summary

Conclusions

Thesis conclusions

Nowadays in Italy, due to the incredible high increase in the electricity bill, people are becoming more and more interested in the REC and it is important to spread information about them in order to increase their diffusion on Italian territory. The main aim of this thesis is to understand how a REC architecture could work in a highly urbanized context like the one of Milan's suburbs because this model is most of the time available in rural ambient . One of the most complex aspects highlighted during the developing of this thesis has been collecting the real electric loads. This problem has been overcame thank to the Monte-Carlo simulations, based on reals electric loads, that have been adopted in this thesis. In the first case as shown in paragraph 5.2 the brake even point was after 7 years. This result is the first evidence that even without any further computation nowadays installing a PV plant in an urban area is quite economically profitable and generates welfare for the condo. The project has been profitable even if the design of the plant was not based on the most effective size for an economic return, actually, even installing the most possible PV power the techno-economic analysis showed that the project is profitable. Further evaluation highlights that return of the investment of the REC configuration respect to the one of a self-consumption configuration are almost the same. The difference between the two configuration, in this case study, is only in the incentive that varies respectively from 110 to 100 [€/MWh]. Despite that, it is important to remind that a main difference exists between the two configurations and that this difference could leads to important advantages for the REC in the future. The REC configuration allows that in the future new players outside the condominium can join the community and this is beneficial for the community founder. It has to be reminded that, if from the beginning the choice is to not accept new players in the configuration, a self-consumption is optimal. If on the other hand, at the beginning, there is no certainty regarding this aspect when starting the project the REC configuration is more flexible. From the condominium meetings that I attended it appeared that nowadays people are more willing to install PV plant for three different reasons:

- The initial investment is blunted by the ecobonus;
- More awareness of one's own environmental impact;
- It stems the impact of the rise in the price of electricity.

The decision whether to install batteries or not from an economic point of view, tends to move towards their adoption. This is true up to a reasonable battery size as it is possible to see in figures number 32, 34, 36. This is particularly true in this analysis where I assumed to install all the possible PV power and so I obtained an oversized plant respect to the REC loads. Looking at the results coming from the fourth case with the current energy price it is necessary to highlight how the strategic decisions regarding the creation of a REC are strictly dependent on the energy market. The final economic return, in a time horizon of 20 years, is estimated equal to 2 millions € whereas for the electricity price computed on the period 2004-2020 was less than a million. It is also important to recall that the penetration of the Evs in the market make the REC even more profitable. Another interesting aspect is that comparing the results obtained with literature[28] similar results are obtained, in some case identical for the break even point. The PV plants analyzed in that article are much smaller respect to the one of this thesis and they are aimed to provide electric energy only to the starting members of the project. Having ascertained that similar economic results can be achieved with oversized plants, to design a small plant could represent a major limit to the diffusion of the REC. Once a REC is established one of its main strength is the possibility to accept new members inside and to act like a driving force in shifting the energy production to a cleaner one. Concluding the answer at the question: *"Is a REC suitable in an European Metropolis context?"* is yes without any doubt. Both the architectures, self-consumption or energy community, lead to a positive effect; it is important to decide case by case which fit better the will of the investors.

Further Development

In this thesis all the analysis has been carried out assuming to install the maximum PV power without considering what is the best nominal power with respect to the REC needs. It could be interesting to assess how the results would change by varying the PV installed accordingly to the REC loads. In the thesis, the members of the REC are assumed the same for all the lifetime whereas in reality REC architecture contemplates that members can change during the years both joining the community and leaving it. An interesting development could be to consider what could change if new players, both consumer and prosumer, in future years decide to join the energy community. Finally, the benefits coming from the energy community have been assumed equally distributed between all the families belonging to the condo and this means that each family is expected to participate equally at the initial investment, which is not at all mandatory. In fact, people can decide to join the community as only consumer and not participate in the PV plant investment. When people participate with different share in the initial investment it is necessary to define different methods for distributing the income coming from the incentive. It could be interesting to analyze how the initial decision made by people finding and joining the community leads to different rewards for them and what different role they have in the REC running.

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