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EXECUTIVE SUMMARY OF THE THESIS

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

LAUREA MAGISTRALE IN ENERGY ENGINEERING - INGEGNERIA ENERGETICA

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1. Methodology

1.1. Monte-Carlo

In this thesis a Monte-Carlo simulations[1] have been adopted. 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.

Two different typologies of Monte-Carlo have been adopted in order to perform different simulations: **Bootstrapped Monte Carlo**,for EV's loads generation and **Inverse Transformation Method**, for generating urban loads.

2. Case Study

2.1. Introduction

The perfect case study in order to analyze the impact of a REC in an urban environment is represented by the condo of *"Villaggio dei Giornalisti"*. In this site the area is highly populated. In fact it is in the Milan northern outskirts. The space available to install PV plant is limited to the building's roof and all the buildings are residential.

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 1. Each building is inhabited by a number of families that can vary from 7 to 10.

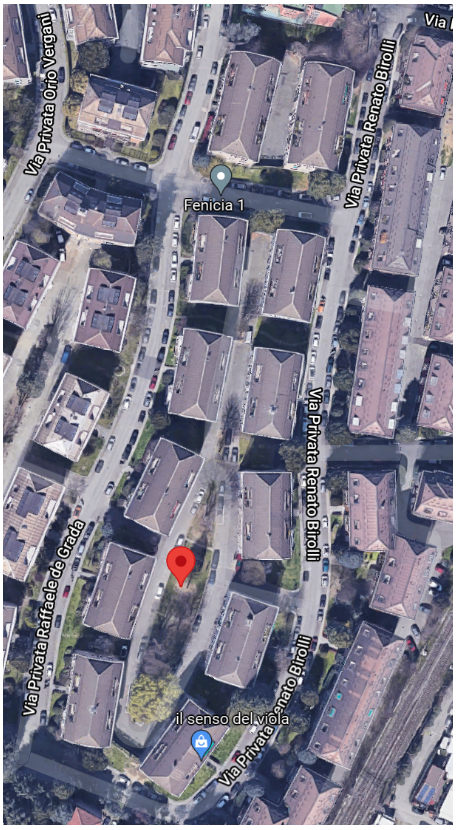

Figure 1: Map of the condominium

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.

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. In order to analyze different aspects the following four scenarios plus the zero 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.

Case	Load	PV	REC	Bat.	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 because people are not very willing to share their private electric consumption ad if they accept to share their private consumption often this are not very useful because report monthly data. The solution to this problem may be provided by the synthetic data generation. In fact to generate artificial data when the real data are not available is one of the main application of it as it is possible to read in the description of What Is Synthetic Data [2], 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 [2]. The synthetic data can be generated in various way:

- Generating according to distribution;
- Fitting real data to a known distribution;
- Using deep learning.

I decided to use it in order to create a data-set of loads for twelve different condo starting from two different data-set: 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 [3].

3.3. 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 [4] the second one is based on random extraction of load profile, both methods are gonna be described in the following paragraphs.

3.4. 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 1

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

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. 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 [5]. It is possible to look at the computed distribution for each hour in figure 2. The boxplot diagram reported below refers to the week day's loads.

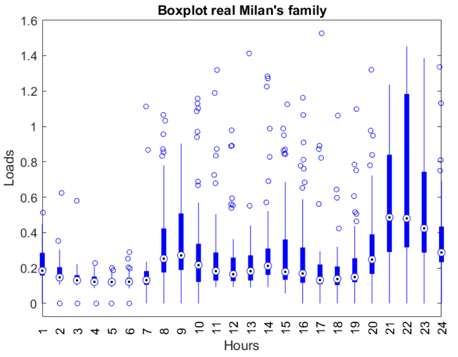

Figure 2: Boxplot real Milan's family.

In the following pictures 3 and 4 it is possible to look at the mean data computed from the starting distributions. Comparing the mean data of the real family of Milan with the data present in figure 5 ,that report a sample day extracted from the starting database, it is possible to note that the data present similar trends. Different data set's origin leads to a different quality of the data. The data collected from a real family in Milan show a marked difference between week days and week-end days, one coming from the data-set generated for a 100 square meters flat doesn't show this difference.

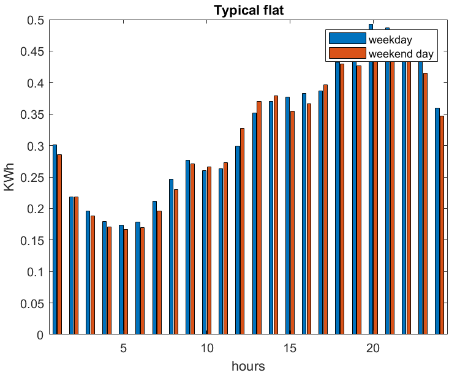

Figure 3: Typical flat mean load.

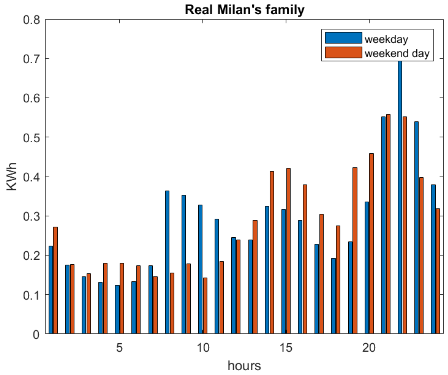

Figure 4: Milan's family mean load

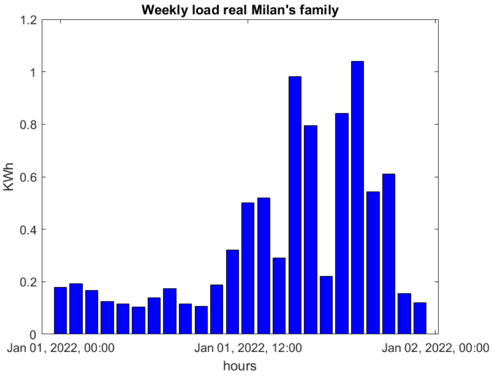

Figure 5: Weekly load real Milan's family.

The data for the traditional flat were available all year long and this made possible to keep a monthly difference in the synthetic data 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, but the synthetic year will not show different monthly trends as it is possible to see in figures 6 and 7.

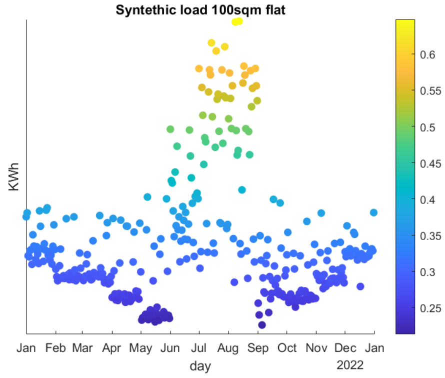

Figure 6: Syntethic load 100sqm flat.

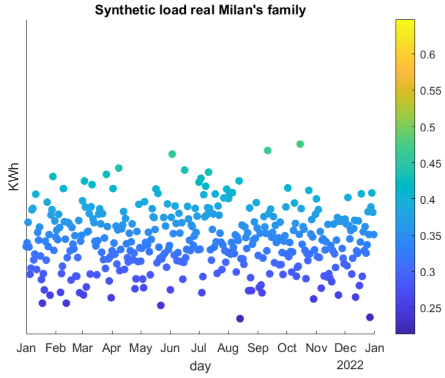

Figure 7: Synthetic load real Milan's family.

3.5. 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. 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[1] approach.

In figure 8 the average charging session computed from the Caltech database is reported. Comparing figure 8 with an example of real charging session in figure 9 it is possible to confirm as anticipated that a mean value between different sessions is not an accurate model of a real one.

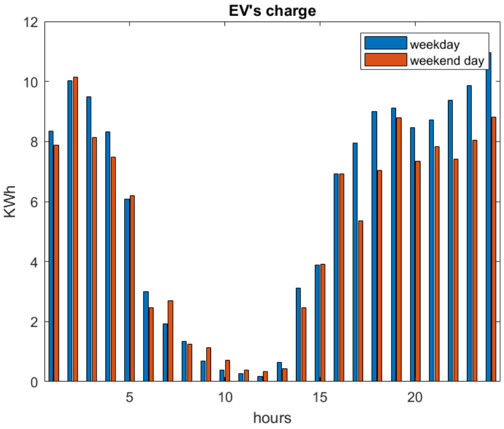

Figure 8: EV's mean charge

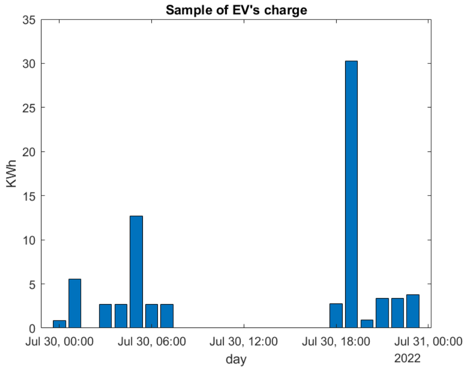

Figure 9: Sample of Ev charging

3.6. REC creation

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 and one of the two synthetic load profiles is assigned at each family.

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 that the site coordinate are defined 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.

4.2. PV production

The production of the PV field's was computed exploiting two different software. The first one was PVsyst 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 10. The chosen PV panel is long 1.776 meters and wide 1.052 meters. It is mono-crystalline with a Pnom of 370W. The total install-able PV power is 488.4KW. The second one was to compute the near shadowing losses coefficient that is equal to 21.57%.

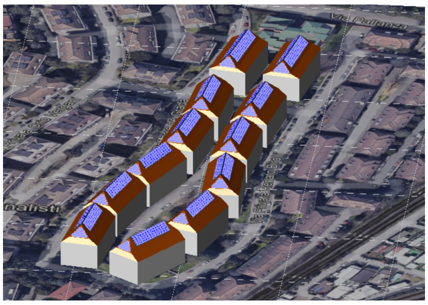

Figure 10: 3D model

The final step is to compute the PV generation curve, it has been done through PVGIS's tool. PVGIS is the acronym of Photovoltaic Geographical Information System, it is a European Community's website where is present a tool [6] that having as input: the tilt, the location, the azimuth of the field and the PV panel technology of the PV plant allow to evaluate its typical year and to compute its energy production.

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 11 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.

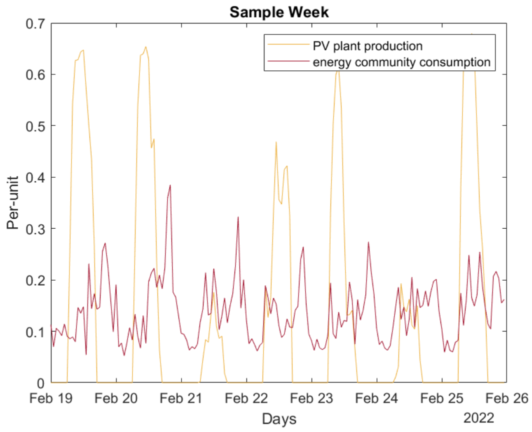

Figure 11: PV production REC

5. Cases simulation

Finally after the calculation of the load curve and the PV production curve is possible to simulate all the cases that were defined in table 1. For sake of brevity in the executive summary only case 0, 1 and case 4, that are the easiest the first improvement and the most complex, are reported.

5.1. Case 0 - No investment only loads

The case 0 is the starting one. It comprehends 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 an algorithm whose 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. Control if all the year's hours are processed or if some are still missing;
4. End the algorithm producing the vector purchased energy that store all the loads. It represent the amount of electric energy that the REC must buy from the grid in order to feed its needing.

This case is the easiest one. It is needed in order to define the condo traditional expenses.

5.2. Case 1 - PV installation

Case 1 comprehends 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 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 normative that rules the private PV plant installation. The energy can be consumed only in the building where it is produced and it is not possible to share it with the other buildings. All the overproduction is sold to the grid. The simulation is performed through an algorithm. 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. Decide 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 the one that 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.

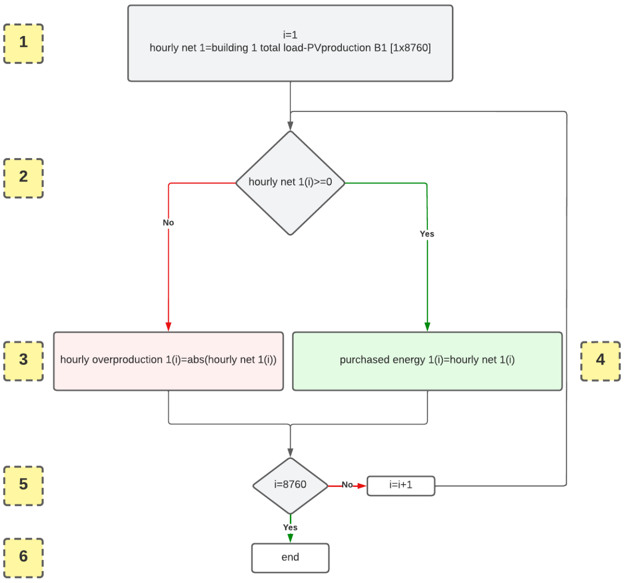

Figure 12: Case 1 Load & PV for B1

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 accordingly to the collective self-consumption configuration. The incentive is 100 €/MWh [7].

5.3. Case 4 - REC with EVs

Case 4 comprehends the REC and EVs loads the PV generation and the batteries installation. The installation 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 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 constrains changes from one to another. For the sake of conciseness only one is reported in figure 13, but the variations that must be made in order to perform the different simulations are highlighted in the following lines. The algorithm's the steps 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 a 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 in battery path is stored the battery level;
6. Decide if the battery level is higher than the net battery size;
7. Battery level remain 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 the state of charge higher than the net battery size is not allowable,
9. Control if all the year's hours are processed or if some are still missing;
10. End the algorithm exporting self-consumption overproduction purchased energy and battery path;

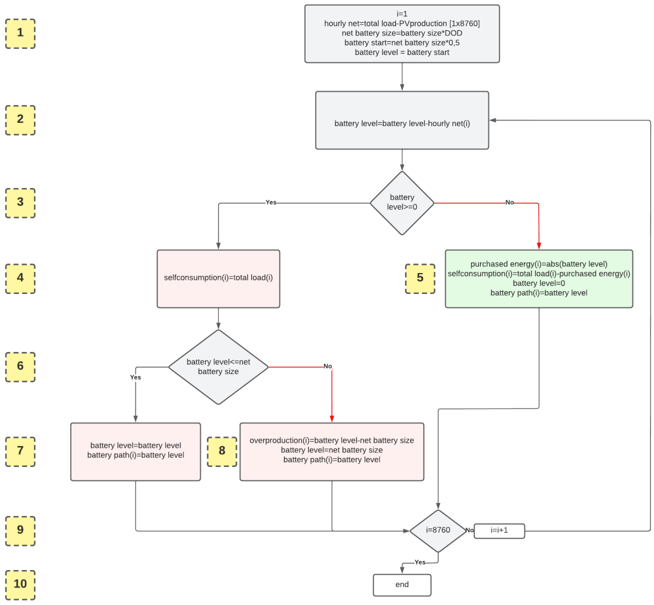

Figure 13: Case 3 REC and Batteries

Between the different algorithms linked to the different battery size what changes is simple the starting value of battery size that affects the starting battery level.

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 cases 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 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 purchase energy for a typical year, computed from the case 0 simulation, is multiplied by the electrical energy cost.
The total cost in year one, assuming an electricity cost of 0.173 [€/KWh] ,that is a mean of the last ten years, 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 lead to a realistic electricity expenditure and also in order to have an idea of the single consumption of a family.Recalling that 8 families live in building 1 the mean family expenditure is equal to 502.58 €. I want to compute also the total cost in a time horizon equal to 20 years that is the expected lifetime of the REC plant, this is done in order to make a comparison with the following cases. This computations are also done for a different electricity price equal to 46.03[c €/KWh] that is the highest recorded in 2022. That 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 price was caused by external unpredictable and unusual phenomena, despite that this studio is useful because it 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 are equal to 0. The table 2 summarize some results computed for traditional electricity price for three different buildings.

	B1	B2	B3
Total Cost	4.02	3.52	4.52
Mean Cost	502	503	502

Table 2: Total Cost in [K €] & Mean Cost in [€]

6.3. Techno Economic Analysis Case 1 - PV installation

In the case 1 the first active choice of the investors is analyzed. I 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 14 are used in order to evaluate this costs (the incomes are considered as a negative cost).

$$
\begin{aligned}
Electricity_{Cost} &= \sum_{i=1}^{i=8760} PurchasedElectricity_i \cdot ElectricityPrice \\
Incentive &= -\sum_{i=1}^{i=8760} SelfConsumption_i \cdot 100 \\
Earnings &= -\sum_{i=1}^{i=8760} Overproduction_i \cdot GreenEnergySellingPrice \\
YearlyCashFlow &= Electricity_{Cost} + Incentive + Earnings
\end{aligned}
$$

Figure 14

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 the previous formula. 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 the previous formula. The total earnings are computed multiplying the overproduction by the green energy selling price.

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 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. 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 [8]. 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 15 that are less of the expected ones in the 20 operating years.

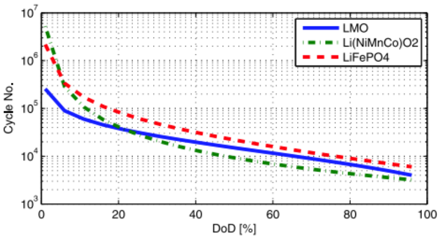

Figure 15: Depth Of Discharge

The Capex for the building 1 is equal to 53014 €. This is the total investment needed to build the plant. 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 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. In picture number 16 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.

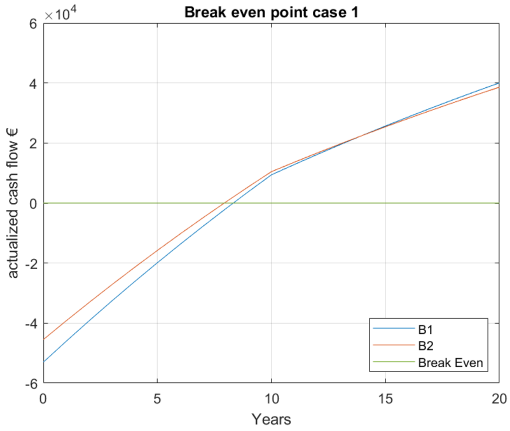

Figure 16: Break even case 1

6.4. Techno Economic Analysis Case 4

Computation similar to the previous ones have been done in case 4. The differences are that:

in this case all the buildings have been considered as one accordingly to REC's normative, the EVs charging has been added to the loads and batteries have been installed. The optimal battery size is defined accordingly to a parameter called battery reward that account how much profitable is the battery installation respect to the size as it is possible to see in figure 18. The brake even in this case happens slightly earlier, with respect to the previous case as is possible to see in figure 17. For the case with the batteries, as is also possible to see in figure 17, the brake even is little further in time but the final net present value is higher.

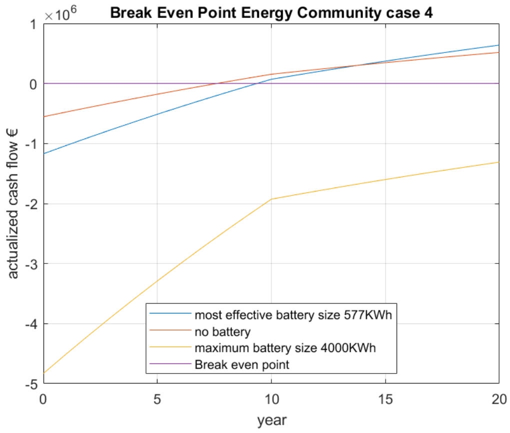

Figure 17: Break even case 4

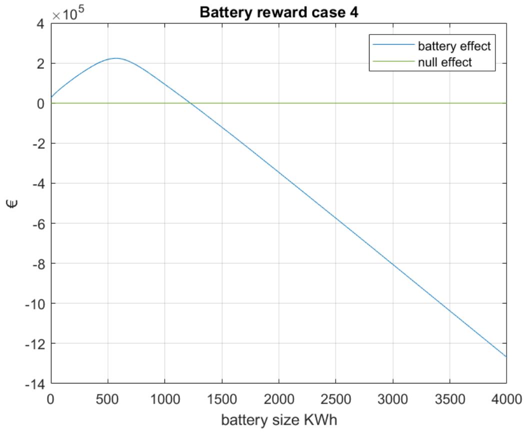

Figure 18: Battery effect case 4

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

The same computation made for case 4, but this time done with today energy price, lead to a much earlier break even point as is possible to see in figure 19

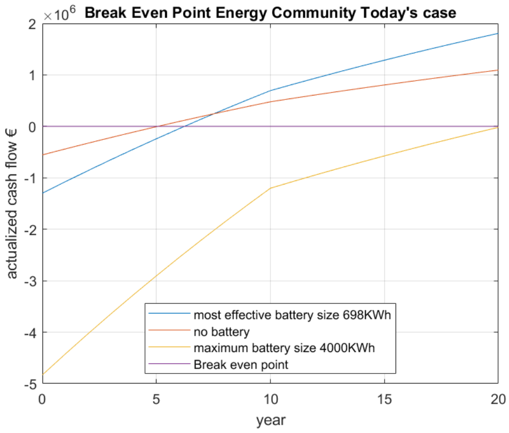

Figure 19: Break even case 4 today

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 6.3 the brake even point was after 7-8 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 figure number 18. 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[9] 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.

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Giovanni

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