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Design of an energy information system for renewable energy communities

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Abstract

The current paradigm for energy production is centralized and based on large power plants with a top to bottom configuration. The new challenge is to abandon as soon as possible fossil fuel power plants and to use more renewable energy resources, supporting small power plants where energy sharing and self-consumption are the main milestones. In order to achieve this transition, the best solution is to encourage the spread of Renewable Energy Communities.

This thesis aims to develop an Energy Information System focused on the simulation of the community itself in order to facilitate the evaluation of a potential investment and to make conscious decision. The methodology is thought to facilitate the analysis in the early stage of energy community design.

This thesis is divided in two main parts. In the first section, after a brief explanation of the current European legislative framework regarding Renewable Energy Community with a special focus on Italy, the methodology process is exposed. The simulation is divided in three main steps: in the first step the energy demand of the community is evaluated and is considered to be associated to a small industry and some residential buildings. The process developed allows to have a reliable simulation of the residential energy demand, starting from the number of families included in the community, in order to have a reliable and consistent baseline scenario. Then, the photovoltaic power plant is simulated alongside with the battery energy storage. The algorithm allows to evaluate the size of the PV plant and find the optimal size of the battery electrical storage system to achieve the best exploitation of renewable energy produced also maximising the Net Present Value. The third step includes the calculation of energy consumption/production on yearly scale of the community and the evaluation of the economic investment related to the identified energy systems. In this section the focus is on the analysis of economic investment and incentive to have comparable payback time between residential and industrial members of the community. Eventually, different KPIs are used to benchmark the obtained results.

In the second part of the thesis, a small community composed by a small industry and 50 families is considered as a reference case study. In the community a photovoltaic power plant of 230 kW and a battery storage system of 350 kWh are supposed to be installed. With the configuration proposed the total yearly electricity consumption from the national grid decreases of about 68% in comparison with the baseline scenario without PV panels and storage.

The overall research results and the proposed methodology demonstrated to be useful for the evaluation of consistent energy scenarios in RECs particularly useful during their early design stage.

Contents

Abbreviations

Abbreviation	Description
ARERA	Autorità di Regolazione per Energia Reti e Ambiente
ASO	Automated System Optimization
BACS	Building Automation and Control System
CapEx	Capital Expenditure
CEC	Citizen Energy Community
CEP	Clean Energy Package
CSC	Collective Self-Consumption
DOD	Depth of discharge
EFR	Energy flexible resource
EIS	Energy Information System
EMD	Electricity Market Directive
EMIS	Energy Management and Information System
EMRP	Equity Market Risk Premium
ESP	Electrical Self-Production
FDD	Fault Detection and Diagnostic
GHG	Greenhouse Gas
GME	Gestore Mercati Energetici
IPEX	Italian Power Exchange
IRR	Internal Rate of Return
IRS	Interest Rate Swap
KPI	Key Performance Indicator
LEC	Local Energy Community
NPV	Net Present Value
O&M	Operations and Maintenance
OpEx	Operating Expenses
PBT	Payback Time
PNRR	Piano Nazionale di Ripresa e Resilienza
PUN	Prezzo Unico Nazionale
PV	Photovoltaic
REC	Renewable Energy Community
RED II	Renewable Energy Directive
RES	Renewable Energy Source
SCI	Self-Consumption Index
SPBT	Simple Payback Time
SSI	Self-Sufficiency Index
WACC	Weighted Average Cost of Capital

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1 Introduction

1.1 Background

Climate change is undoubtedly affected by human activities and our lives are progressively concerned by increasing global temperatures. In specific, the rise of the Greenhouse Gases (GHGs) level, *e.g.,* water vapor and CO_2, drastically increases the retention of heat within the atmosphere. Therefore, the toughest challenge our society is facing is to minimize the rise in temperature, mainly by reducing CO_2 emissions.

Nowadays, the energy production is mainly based on fossil fuels and is centralise in big plants outside the cities (Figure 1, right). These energy sources are extremely detrimental for both human health and the environment. Also, the continuous increase in energy demand due to population growth and urbanization, augments the risk for natural disasters causing weather change, sea level rise and major changes in stable ecosystems [1]. Moreover, since fossil fuels are not uniformly distributed on the planet, full reliance on these resources often leads to very fragile geopolitical balances, causing some countries to be fully dependent on other countries or on the global market.

Consequently, the current paradigm for energy production is no longer sustainable for our society and must be changed in order to keep the planet suitable for human beings.

The transition towards renewable sources is fundamental to reduce CO_2 emissions and tackle the above mentioned scenario. However, in order to produce the needed amount of energy with clean sources and the same scenario there should be immense fields of photovoltaic panels or wind turbines which would disfigure landscapes and would occupy large segments of land. Consequently, small distributed renewable power plants (figure 1, left) represent the best trade-off between clean energy production, and landscape preservation enabling the sustainability of the whole ecosystem.

For the past couple decades, a slow transition towards carbon neutrality has already begun. In particular, the transition tackles sectors producing the most GHGs emissions, such as transportations, residential and industrial energy consumption and electricity production.

With the new energy production paradigm, from a few large fossil power plants where the electricity goes only from the plants to citizens with one-way flow, the energy production will pass to a more distributed and dynamic system. Here, small renewable power plants with electricity flowing in two ways, towards the system and to citizens, will encourage self-production and energy sharing, reducing GHGs production and the load on the national grid. The whole energy system will increase its complexity due to the decentralization. At the core of this reorganization, energy storage systems (thermal or electrochemical) will gain a central role as they would solve the problem of stochastic production of renewable sources and would give flexibility to the whole system.

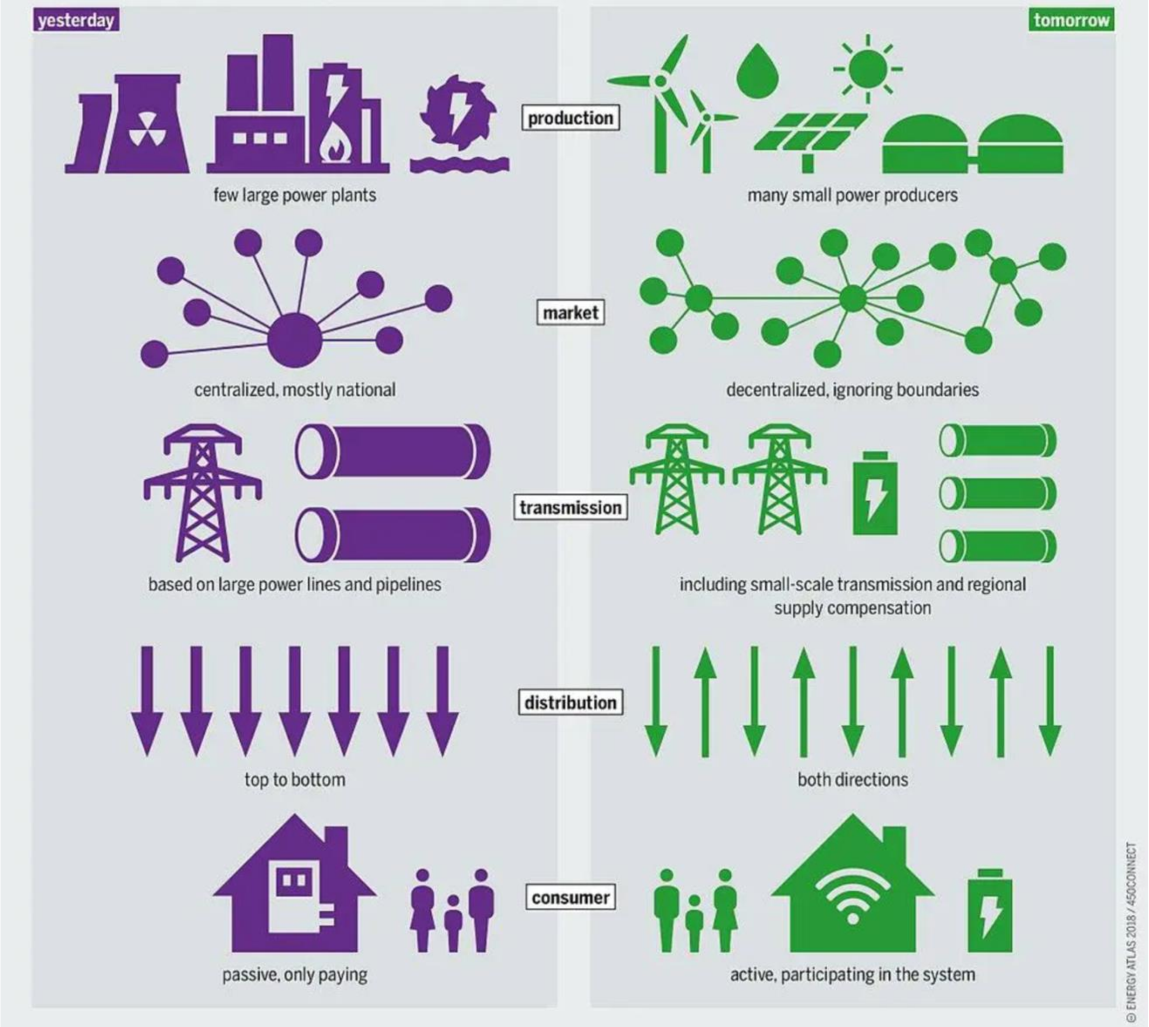

Figure 1 - Expected structural changes in the energy system made possible by the increased use of digital tools. Source: **[2]**

The transition from the old to the new system of energy production and handling cannot be driven by energy producers and politics only. In fact, citizen and industrial enterprises must actively participate for the shift of the system to be fast and effective. To enhance the involvement of inhabitants and businesses , the new energy handling system is based on renewable energy communities (REC), which is an agreement between consumers who decided to collaborate in order to self-produce energy and to share it within the community. The ideal community is composed of big or small industries and activities as well as families. With this structure, the energy production is not centralized anymore, but will be based on several small power plants scattered throughout the country. With RECs, industrial and residential users are encouraged to maximize the self-production and self-consumption in order to minimize the energy purchased from the grid. The members of the REC who produce energy are referred to as "prosumer", as they no longer only purchase and consume energy from the grid, but they actively produce energy, share it within the REC and exchange it with the grid in order to have an economic benefit in return [3]. In conclusion, RECs are based on sharing energy and are opened to whoever wants to join them. Cutting-edge technology RECs and, in particular, helps to manage production and storage of electricity. Photovoltaic panels connected with batteries and supported by specific software and algorithms are the main technology spread. This matching allows to exploit better the energy production and maximize the self-consumption reducing problems linked to the stochasticity of renewable energy production and reduces picks absorptions.

RECs system can be a win-win solution because lead to several economic and environmental benefits. First of all, members of the community have savings on their bills because part of the energy is self-produced, shared and not purchased from the grid. Furthermore, economic benefit could arise both from the construction of the system (purchase of photovoltaic panels and battery) and from shared energy which could be enhanced and paid from the state. Also, producing "in loco" and sharing the energy drastically reduces the CO_2 emissions. Last but not least, RECs fight energy poverty which is spreading worldwide, as being part of a community helps citizens to raise awareness about their consumptions and enables them to purchase energy at better prices.

1.2 European context

The main objective of the European Union with respect to the energy production and consumption is the transition towards climate neutrality. In order to achieve this ambitious goal, the commission of the European parliament agreed on the Clean Energy Package (CEP) which is composed of eight directives. The package follows the previous legislative proposals "Fit for 55" which set targets for reducing emissions by at least 55% by 2030 compared to 1990 and for being the first climate neutral continent by

2050 [4]. Each European country must transpose the directives and set its own objectives in order to achieve the agreed goals.

Another important directive transposed by the end of June 2021 is the Renewable Energy Directive (RED II); it provides an enabling framework for renewable source and, in particular, for RECs [5]. These communities are defined as a legal entity:

a) which, in accordance with the applicable national law, is based on open and voluntary participation, is autonomous, and is effectively controlled by shareholders or members that are located in the proximity of the renewable energy projects that are owned and developed by that legal entity;
b) the shareholders or members of which are natural persons, SMEs or local authorities, including municipalities;
c) the primary purpose of which is to provide environmental, economic or social community benefits for its shareholders or members or for the local areas where it operates, rather than financial profits.

In addiction RED II confirm that in this transition, for energy communities to play a central role, they must follow proper regulations [6] [7].

On the other hand, “citizen energy communities” (CECs) are define in the electricity market directive (EMD) [8] as a legal entity that:

a) is based on voluntary and open participation and is effectively controlled by members or shareholders that are natural people, local authorities, including municipalities, or small enterprises;
b) has for its primary purpose to provide environmental economic or social benefits to members of the community, shareholders or to local areas where it operates, rather than to generate financial profits; and
c) may engage in generation, including from renewable sources, distribution, supply, consumption, aggregation, energy storage, energy efficiency services or charging services for electric vehicles or provide other energy services to its members or shareholders.

Both communities, RECs and CECs, are based on open and voluntary participation and their primary purpose is not financial profit but to provide environmental, economic and social benefits (as shown in the definition above). However, CECs are not strictly related to renewable energy sources (RES), they are simply a new entity that has access to the electricity market as a group rather than as single entities. On the other hand, RECs have more stringent requirements and are limited to renewable energy sources. Self-consumption is their main goal, rather than making profit by selling energy to the market. Another difference is the geographic limitation: CECs have no limitation while to be a member of a RECs you must be in proximity of the community [9].

Scientists argue that considering the diversity of the 27 EU Member States "one-size-fits-all" approaches are not the right solutions [10]. On the contrary an interesting way to introduce the directives is to follow some key aspects, such as to encourage complementary amongst renewable energies (RE), to support energy sharing as a new option for RECs and to ensure that business models and policy designs allow for the full participation of disadvantaged and vulnerable communities.

However, despite all the differences the greatest benefit of energy communities is the reduction of CO_2 emissions and the increase in self-consumption and efficiency [11]. In order to maximize these advantages a data-driven approach is mandatory, an advanced energy management and information system (EMIS) manages all the whole component of the community, from generation (*e.g.,* photovoltaic panels (PV) or micro wind turbine) to storage and final uses.

Without the fine-tuned energy management system provided by EMIS, even the best technology available on the market cannot exploit their maximum potential. Also, this system allows to optimize multi-objective problems such as the minimization of energy consumption while maintaining thermal comfort in indoor environments [7]. Data analytics approaches are really useful both in the design and operation phase of local energy communities (LECs). In the first phase, open-source database help to estimate the optimal dimension of energy flexible resources (EFRs) such as energy storage systems, electrical vehicles, energy demand and response. During the operational phase it is necessary to optimize power flows and to manage the energy tracking and monitoring. In the end, an efficient use of data is crucial for LECs in energy trading and optimization [7].

1.3 Legislative framework in Italy

According to "Fondazione Utilitatis" [12] and Barroco , Felipe, et al. [13] from the end of 2019 and the beginning of 2020 with the introduction of "Legge 8/2020", Italy has embarked on a path of experimentation of self-consumption schemes and RECs, in order to evaluate effects, critical issues and possible drawbacks. The experimentation has some constraints such as:

- renewable energy plants need to be entered into operation after the 1st of March 2020;
- installed power must be lower than 200 kW;
- plants and consumers have to be connected to the same MV/LV transformer station;

Despite these limitations, during this experimentation phase, some incentives where introduced by the government which awarded collective self-consumption (CSC) and RECs. First of all, a discount of fee was implemented and a return of 9 €/MWh of energy produced was given as a refund of the costs not incurred for the management of the electricity system, moreover 100-110 €/MWh were also given for the energy shared into the community.

Finally with legislative decree n.199 / 2021, following the request of stakeholders some changes are introduced:

- Maximum power of single plant upgraded from 200 to 1000 kWp;
- Increase of the perimeter: from secondary station to primary station;
- Services provided: added home automation, energy efficiency and EV charging;
- Subjects involved: added religious institutions, research and third sector bodies.

Hopefully, with these adjustments, RESs and RECs will widely spread across the country and will contribute to achieve the European RED II goals.

Last but not least, in July 2021 the “Piano Nazionale di Ripresa e Resilienza” (PNRR) was approved, which include 60 billion of investments in “green revolution and ecological transition”. More precisely, 23.78 billion are for renewable energy, of which 2.2 billion specifically for investments in energy communities. The main goals of PNRR are to increase RESs exploitation and to enhance and digitize network infrastructures in order to have a solid framework for the RESs themselves.

In Italy the incentive for the RECs is 110 €/MWh [14] and it is given for 20 years considering the lower between the energy produced within the community and the energy shared and consumed within the community. Without any storage support the inconsistency between the moment of energy production and consumption causes great losses and waste. In fact, for the majority of RECs with are only based on photovoltaic energy production, during the day, energy is produced but not consumed. In the contrary, during the evening, energy is consumed but not produced. The situation can be explained in the figure 2. On the left the daily situation is shown, characterized by a surplus of energy production by PV panels and contained consumption. On the right, the evening or night situation is presented where the energy produced is almost zero and the consumption is much higher.

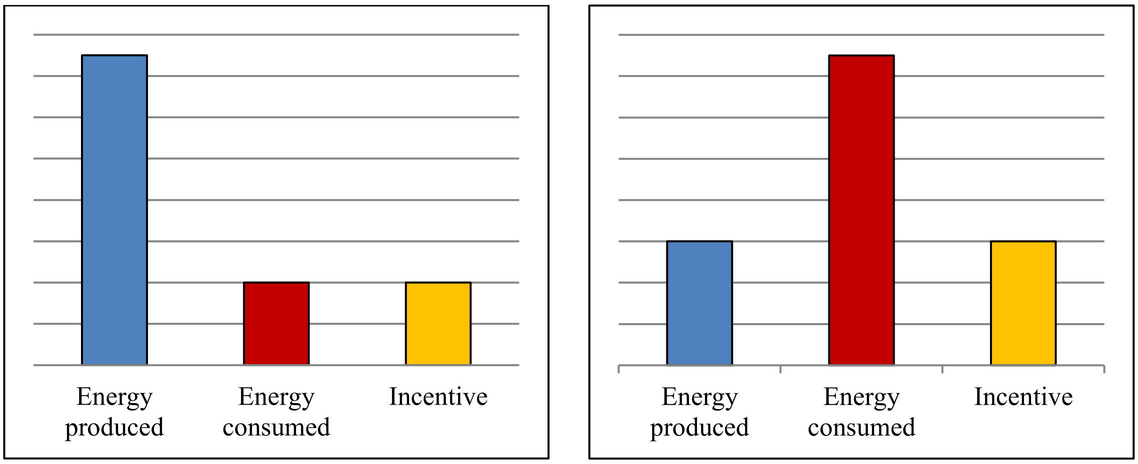

Figure 2 – Comparison of the incentive distribution without any storage system between daytime (left) and night time (right)

Consequently, without any energy storage device, the incentive is not maximised and the system is not exploited to the maximum. An electric storage could solve this problem because during the day it would charge and work like a load, which is discharged in the evening when energy is more needed. Thus, with an electric storage the situation changes drastically and the incentive can be increased. This new operation system is shown in the figure number 3: on the left the daily situation and on the right the discharge phase during evenings or nights.

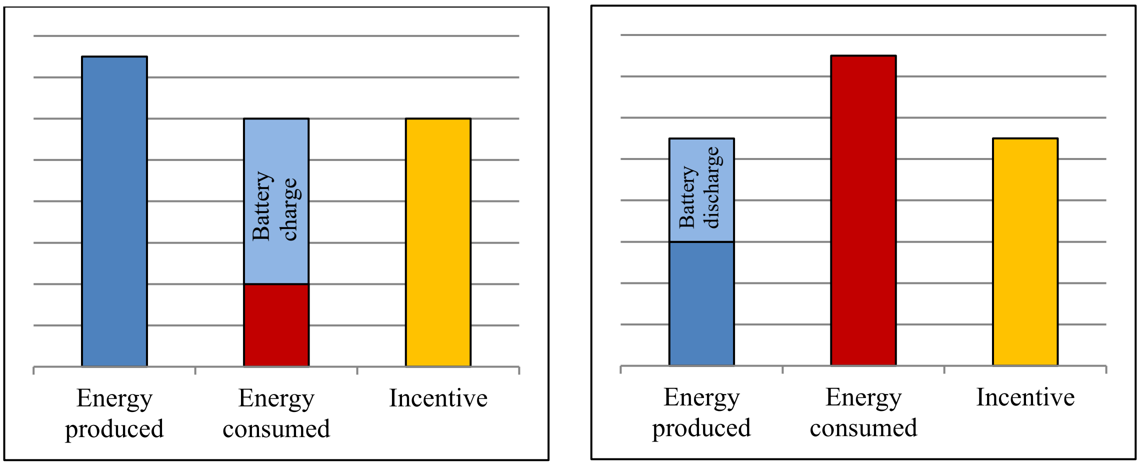

Figure 3 – Comparison of the incentive distribution with a storage system between daytime (left) and night time (right)

1.4 Energy system and technologies in energy communities

Since RECs energy production is mainly based on RESs, the stochasticity of its generation represents the main problem for these communities. The impossibility of planning or estimate energy production does not always allow to fulfil the users' requests.

Moreover, the energy production from RESs and energy request often do not match. New technologies improve by far the efficiency of the energy plants and they can partly solve some problems. For example, the introduction of storages allows to produce energy when is available, save it in stock and use it when needed [13], solving the temporal mismatch between energy production and need. RESs bring the advantages and usefulness of REC one step forward, as the latter can take advantage from the former technologies to be self-sufficient, increment self-consumption and reduce energy waste. However, even the best technologies without a specific support are basically useless because they cannot fully exploit their value. In the previous example, the storage needs to be correctly controlled in order to minimize (or maximize) the desire objective function (*e.g.,* reduce costs, increase self-consumption). Traditional controllers based on reactive rules are not able to solve multi-objective problems and they need to be supported by more advance controllers based on artificial intelligence and data-driven models. As mentioned above, the best strategy is to use EMIS which is composed by Building Automation and Control System (BACS) plus artificial intelligence. This includes Energy Information System (EIS), Fault Detection and Diagnostic (FDD) and Automated System Optimization (ASO). EISs include software and hardware to analyse and visualize big data providing information about the system and its status. ASO encompasses predictive control processes and the output is an action within the system, while FDD provides information on anomalies and their causes.

1.5 Challenges in design of an energy community

Decide to create an energy community from scratch is not an easy task, as many different parties are involved. Install PV panels and share the electricity between residential and industrial site is an excellent solution for the environment but it brings up problems regarding the division and employment of the electricity produced. In fact, if the industrial energy consumption is mainly during hours of the day and the residential energy consumption in mainly during evenings, the industrial is significantly favoured from the PV panels because it mainly uses the electricity self-produced. Also, the needs of all parties involved are very different.

Moreover, as mentioned above a storage system, such as a lithium battery, increases the complexity of the whole community adding the possibility to store electricity when overproduced and to release it during evenings, nights or cloudy days when the production is lower than the consumption. But how to decide when and to whom to release the energy stored in the battery? If the battery is shared between the community there must be an agreed sharing and balance between the electricity used from residential and from the industry site. Another issue could be the distribution of the incentive gained from the shared energy. All these problems need to be solved as well as the division of the initial investment.

A simulation of the community could help to understand how the REC works and how the energy produced is divided between residential and industrial absorption, eventually avoiding the issues just mentioned above. However, in order to have a great simulation with reliable results, a robust model needs to be built. The model can be divided into industrial site and residential consumer, the first one can be estimated or, even better, pretty easily measured by an industrial smart meter. Regarding the residential consumers, it is really hard to make a proper simulation of the electricity consumption as more variables are involved such as the type of families with their number of components, the facilities in the house and the use of them which has less consistency and predictability. From electrical bills the monthly consumption can be evaluated but it is useless considering the hourly operation of the PV production. Nowadays, residential houses seldom have a smart meter and it is almost impossible to create a model starting from the field. However, in order to have a robust model the residential energy consumption profile is needed and to create a reliable trend remains a great challenge. In addition, the model needs to compare the total consumption with the photovoltaic energy production in order to visualize advantages and disadvantages for the whole community. If a storage system is implemented the model must evaluate the trend of the battery and the logic behind in the operational phase according with the decisions taken within the community.

1.6 Aims and objectives of the thesis

This thesis will be focused on Energy Information System, and in particular it aims at contributing to the new researches of energy management of energy community. Consequently an EIS for energy community will be developed and in particular a methodology to simulate an energy community composed by residential houses and an industry is proposed. In the end, an economic analysis as well as key performance indicators (KPIs) will be calculated to assess the community. The REC is thought to be composed by 50 families and a small industrial site, as these dimensions are the best representation of common RECs. However, the methodology proposed is suitable for RECs of different sizes.

2 Methodologies

The REC is simulated in three steps: first of all, the residential energy consumption is addressed, then the industrial energy consumption and finally the photovoltaic energy production is simulated thanks to PVGIS tool [15]. Once the total consumption and the electricity production has been simulated the self-consumption, the virtual self-consumption of the REC and eventually the surplus will be quantified/evaluated. Adding the battery to the model with a specific capacity, energy stored and charge/discharge cycle will also be simulated. Next, savings, gains from incentive and earning from sales are calculated in order to define the annual earnings for the REC. Finally, considering the size of the photovoltaic power plants installed and the size of the battery, the net present values (NPV) and the internal rate of return (IRR) are extracted. In figure 4, the flow chart describes the process exposed above.

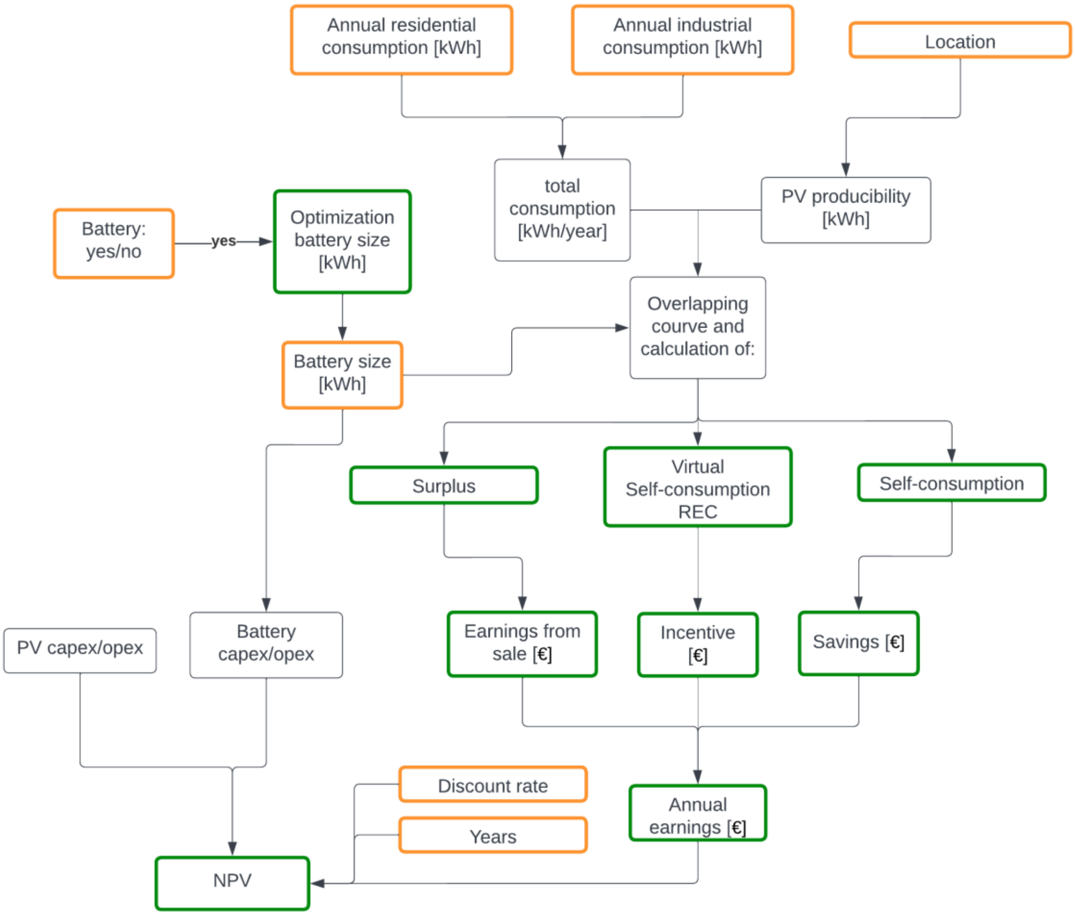

Figure 4 – Flow chart of the methodology, input data in orange and outputs in green

3 Key Performance Indicators (KPIs)

The REC efficiency will be evaluated by KPIs in order to have a solid overview on the scenario and not only take into account the economical aspect. The KPIs used will be: electrical self-production, self-consumption and self-sufficiency, as well as environmental impact.

3.1 Electrical self-production

The firs KPI addressed is the overall Electrical Self-Production. According to [16] it evaluates the electrical performance of the community and is defined in equation 1. It is calculated on a yearly basis and it represent the ratio between self-produced electric energy (E_p^r) and the total electricity demand (E_c). Zero means that there is no production of electricity and 1 means that the electricity self-produced is equal to the demand. However 1 does not means that the community is self-sufficient because it does not analyse how the energy produced is used. Values higher than 1 indicate that the production is greater than the consumption.

Equation 1 – Electrical self-production

$$ESP = \frac{E_p^r}{E_c}$$

3.2 Self-consumption and Self-sufficiency

In addition, other two KPIs proposed by [17] are calculated to evaluate the energetic behaviour of the community: the Self-Consumption Index (SCI) and the Self-Sufficiency Index (SSI).

The first one addresses how much of the renewable energy produced in loco is exploited (E_{ex}^r) and is a percentage indicator computed both instantly and yearly.

Equation 2 – Self-consumption index

$$SCI = \frac{E_{ex}^r}{E_p^r}$$

where E_p^r is the renewable energy produced. SCI is included between 0 to 1, where 0 means that no renewable energy produced is exploited and 1 means that it is all used. A community with a small renewable production respect to the need has higher value than the same community with a larger plant.

The second one indicates how much the REC is dependent from the grid and the outside production.

Equation 3 – Self-sufficiency index

$$SSI = \frac{E_{ex}^{r}}{E_{c}}$$

where $\mathrm{E_c}$ is the total energy needed by the community. SSI ranges from 0 to 1: SSI equal to 1 means that the renewable energy produced in loco exploited is able to fulfil the REC energy needs.

3.3 Environmental impact

Finally, according [16] an environmental KPI is addressed in order to evaluate the impact of the renewable community on the CO_2 level, in particular it quantifies the tons per year of CO_2 emissions avoided. The equation 4 indicates the CO_2 avoided thanks to the community (ΔCO_2^{site}) over the CO_2 of an equivalent site supplied by traditional grid ($CO_2^{site,tr}$).

Equation 4 – CO_2 avoided

$$ECO_2 = \frac{\Delta CO_2^{site}}{CO_2^{site,tr}}$$

To evaluate both the CO_2 avoided and the CO_2 of an equivalent site supplied by traditional grid the value of 268.6 [gCO_2/kWh] is used; this value was taken from the yearly ISPRA report [18], in particular from the 2021 report every kWh avoided saves 268.6 gCO_2.

4 Economical analysis

For the analysis two economic indicators will be used to make evaluation on the final scenario. The indicators used are the Net Present Value and the Internal Rate of Return.

4.1 Net Present Value

The Net Present Value (NPV) is a methodology used to evaluate investments, it takes into consideration cash flows at different years and it actualized them in order to calculate today's value of a future cash flows. For a specific time period, the cash flows and the discount rate are extracted. If at the end of the period the NPV is greater than zero the investment is profitable, otherwise it is not convenient. The equation 5 shows the methodology just described.

Equation 5 – Net present value

$$NPV = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t}$$

Where:

R_t = net cash inflow-outflows
i = discount rate
t = time period when the inflow-outflow occurs
N = years of the investment

4.2 Internal Rate of Return

The Internal Rate of Return (IRR) is a methodology used to evaluate the potential of an investment. IRR represents the discount rate that makes the NPV of all cash flows equal to zero. It is based on the same equation as NPV, however, the unknown is the discount rate. The IRR is interesting because if two projects are evaluated the one which has the highest IRR is the most desirable from investors perspective. In the equation 6 the IRR is shown.

Equation 6 – Internal rate of return

$$0 = NPV = \sum_{t=0}^{N} \frac{R_t}{(1+IRR)^t}$$

Where:

R_t = net cash inflow-outflow

t = time period when the inflow-outflow occurs
N = years of the investment

4.3 Payback time

The payback time can be calculate in two different ways, the first one more simple and the actualized which is a bit more complex. The simple payback time (in short simple payback “SPBT”) is the amount of time, usually years, needed to return of the initial investment. It is represented from the following equation:

Equation 7 – Simple payback time

$$SPBT = \frac{Investment}{AverageAnnualCashFlow}$$

The actualized payback time (PBT) is a bit more complex because also considers the discount rate. The equation becomes:

Equation 8 – Payback time

$$-I + \sum_{t=1}^{\tau} \frac{R_t}{(1+i)^t} = 0$$

PBT and SPBT are used to evaluate an investment, and investments with PBT longer than 5 to 8 years are addressed. The shorter is the return of the investment the more is interesting, however it is appropriated to not consider only the PBT because even though the PBT is short the investment could be meaningless with a NPV really low.

5 Input data

In order to build a reliable model as close to reality as possible, data were taken from the Italian ISTAT census, an European study for residential energy consumption as well as from real data of loads for industrial energy consumption. This will allow to tackle above mentioned problems with a solid load profile to rely on enabling a robust and accurate analysis.

5.1 Residential inputs and total energy consumption

To have a generic and concrete division of the number of families which are included in the community the best starting point is the Italian 2022 ISTAT report that addresses the number of components per family and the percentage of families themselves [19]. The report is shown in the following table 1. Taking into account the year 2021, the majority of families were composed from one individual only (33.2% of the total families), followed from families of two people (27.7%). Families with three or four components are less common and represent respectively 18.9% and 15.2% of the total number of families. In the end, families with five or more components are considered together with a percentage of 5%.

Table 1 – Percentage families with different family members. Source: **[19] [20]**

	Family - two-year average [%]				
Number of components of family	2017	2018	2019	2020	2021
1	31.9	33	33.3	32.9	33.2
2	27.5	27.1	27.1	27.7	27.7
3	19.6	19.5	19.3	19	18.9
4	15.7	15.1	15.1	15.3	15.2
5	4.1	4	4	3.9	3.9
6 o more	1.2	1.2	1.3	1.3	1.1
Total	100	100	100	100	100

Once the number of families is chosen, to estimate their energy consumption, the average consumption of Italian families is determined from a comparator of energy producers shown in appendix 1 [21]. This analysis allows to evaluate the total yearly consumption of a chosen energy community of 50 families. The following table 2 summarizes the methodology just described.

Table 2 – Yearly consumption of families depending on the number of family members

No. of family members	Fraction	Yearly consumption [kWh/year]	Number of families	Consumption [kWh/year]
1	0.332	1400	17	23240
2	0.277	2500	14	34625
3	0.189	3300	9	31185
4	0.152	3600	8	27360
5	0.050	5200	2	13000

The annual residential energy consumption for 50 families is 129,410 [kWh/y].

The next step is to characterise the total yearly consumption in terms of daily energy behaviour. To access the step results from an European study were taken into consideration.

The European project wants to raise the awareness of consumers thanks to smart meters, classification and data representation [22]. For this latter study smart meters are used, they show a two-way communication between the device and the operator and, more important, they can reach a data reading frequency really up to one measurement per minute. However, the most common is every 15 or 30 minutes. In the European study considered, the data of 1020 Italian households are addressed with a frequency of one measurement every 15 minutes for two years, from the 1st of January 2011 to the 31st of December 2012.

The study identified 5 different clusters of consumers that differ from each other in their daily energetic consumption behaviour (Figure 5) .

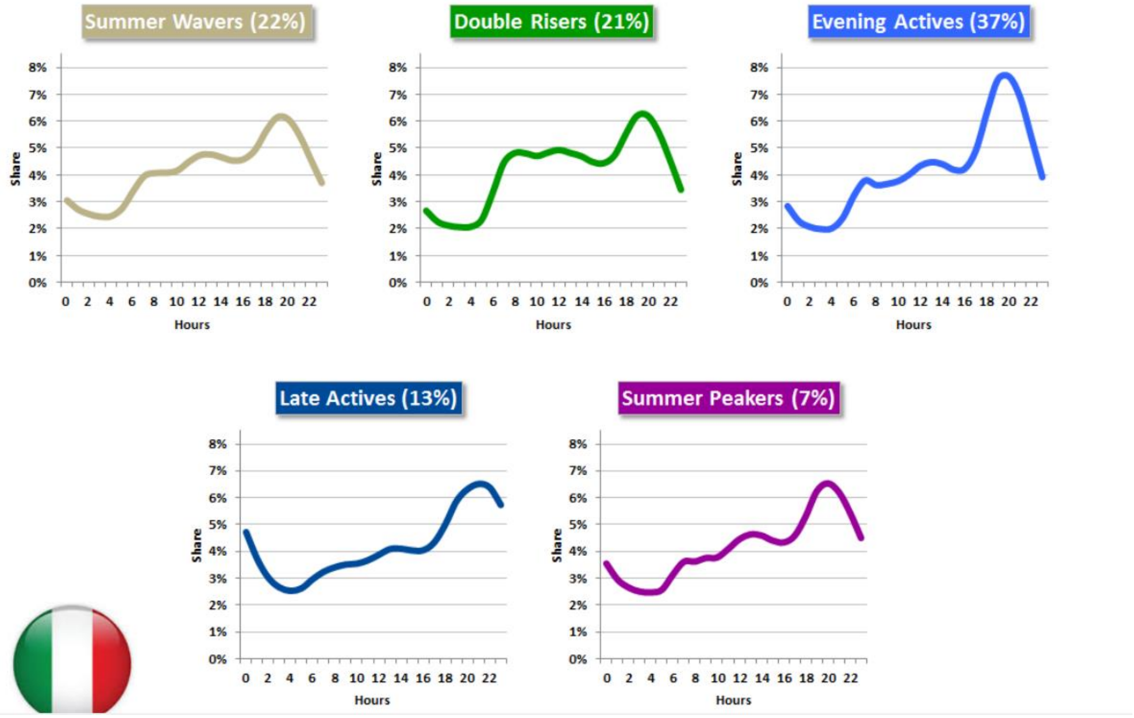

Figure 5 – Different clusters of consumers. Source: **[22]**

The main share of the sample (37%) is represented by “Evening Actives”, they have such a name due to their higher energy consumption during evening hours. “Summer Wavers” and “Summer Peakers” have barely the same daily consumption. They are characterized by a small peak after lunch around 2 p.m., followed by a local minimum and a rise in the evening around 8 p.m. However, Summer Peakers compared to “Summer Wavers” have a much higher peak during the summer than the others (Appendix 2). The third share of the sample is represented by “Double Risers” (21%), they have almost the same behaviour of the ones just described, but they differ in the steep rise in consumption the morning around 7 a.m. The last group is represented by “Late Actives”, their consumption starts to increase at 6 a.m. and goes up till 10 p.m. when there is the peak. People in this sample stays up late and likely go to bed just before noon. Regarding the weekly share, all the segments follow almost the same trend with a visible rise on Sunday (figure 6). Moreover, “Double Risers” have a trend more regular and do not have a slight drop in the middle of the week.

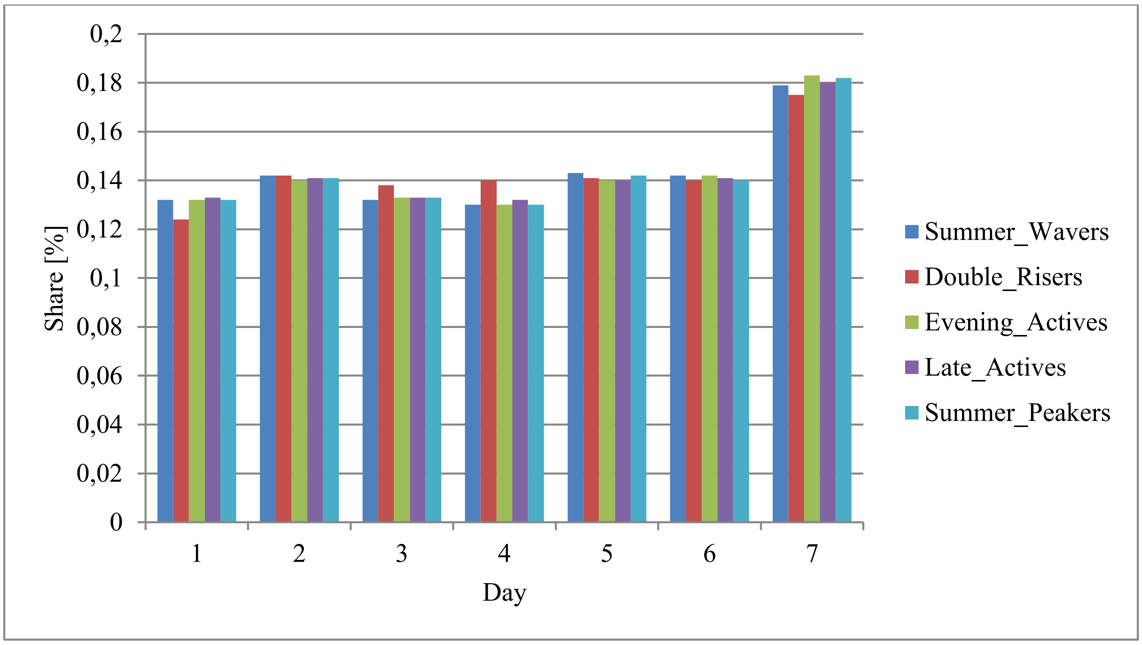

Figure 6 – Daily share of the weekly total energy

More interesting is the seasonal swing between different groups visible in figure 7. *Late Actives* and *Evening Actives* have almost the same trend during the whole year. They only differ in December where Evening Actives have higher consumption, otherwise after the high consumption during Christmas holiday they both present a low in February followed by a small peak in March and then a relative strong decrease until April. *Double Risers* have a slight increase from October to January and remain nearly flat for the rest of the year. The last two groups, as the names suggest, have a marked peak during the summer, in particular the *Summer Peakers* nearly double their average consumption.

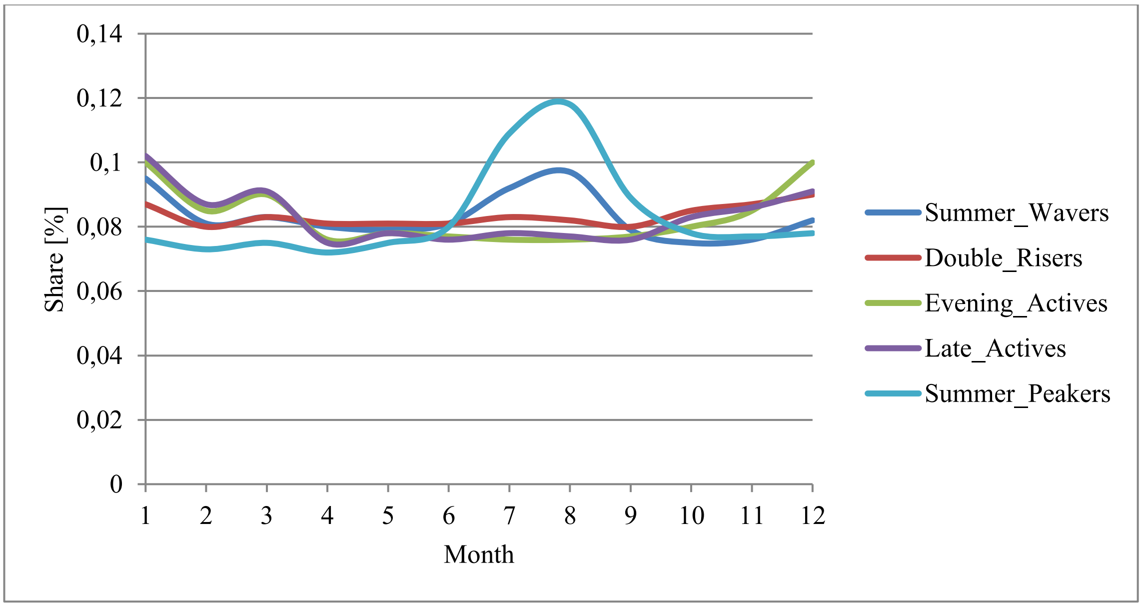

Figure 7 – Annual consumption trend for different users

Combining this European study with the Italian 2022 ISTAT report it is possible to evaluate the residential energy consumption of several families and to have both the yearly consumption and the daily trend. Based on this data, the model for a REC will be built.

The two following figures 8 and 9 represent the flow charts of whole methodology described above.

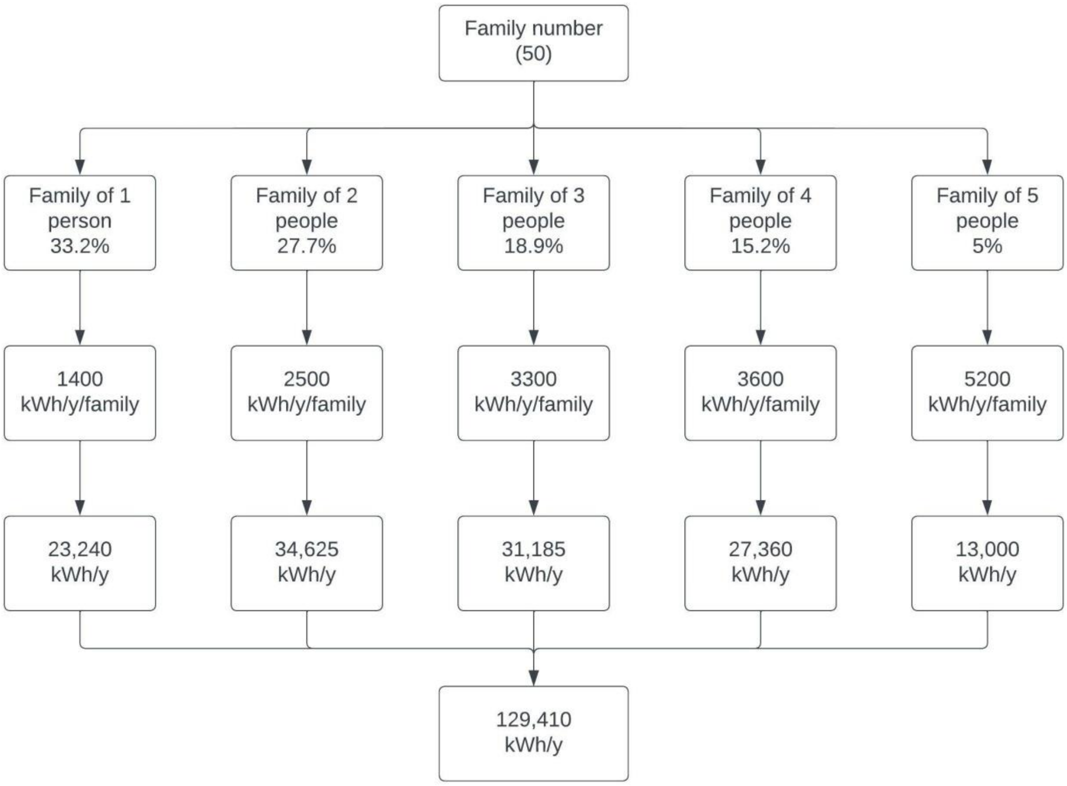

Figure 8 – Flow chart of the residential annual energy total consumption

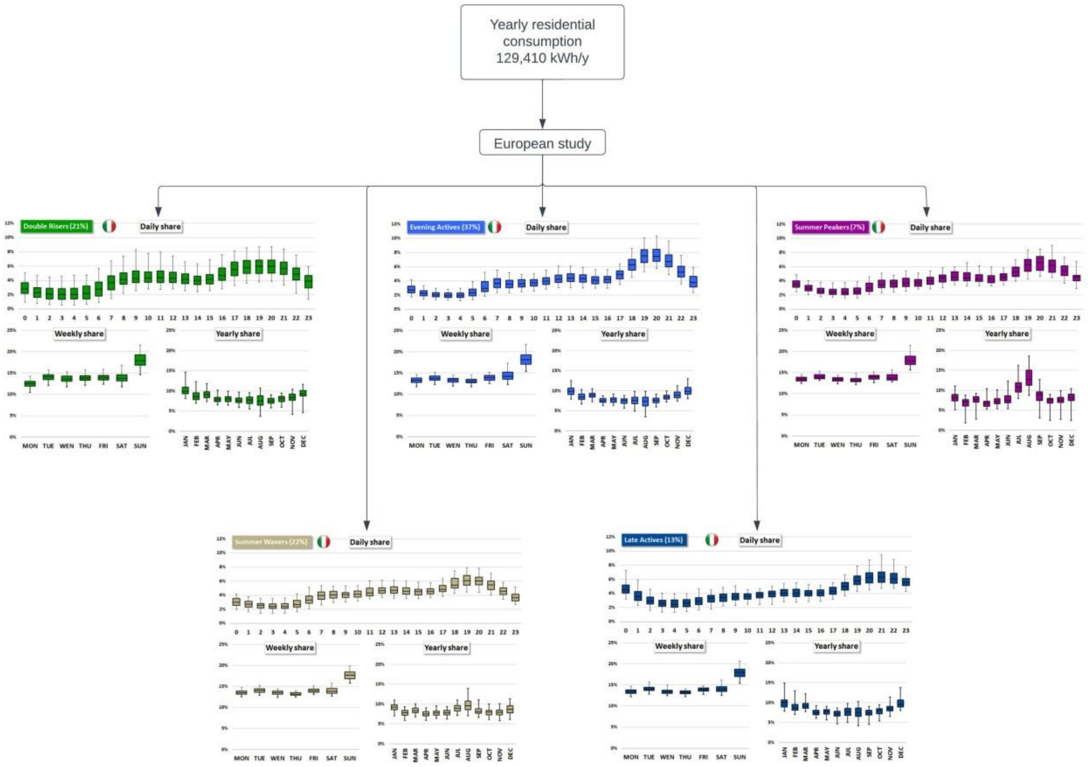

Figure 9 – Flow chart of the share of the annual total consumption in different users

5.2 Industrial inputs and total energy consumption

Regarding the industrial energy consumption, it is easier to collect data from the field due to an advanced regulation spread in Italy which imposes mandatory meters in all facilities in order to reduce waste. In this thesis, for the case study, a small industrial site is chosen because it is easier to find a small enterprise willing to participate in a REC. The total consumption of the company is 205,900 [kWh/y]. In the section 6.1.2 it will be shown in detail.

5.3 Photovoltaic inputs

For the evaluation of the photovoltaic energy production the European PVGIS tool is used [15]. This software calculates the hourly PV production merging several crucial factors: desired location (*i.e.,* coordinates) and year, the solar radiation database, which has hourly time resolution, the mounting type of the panel (*i.e.*, fixed, vertical or inclined axis or two axis). Also, in the case the PV panel is fixed, the slope and the azimuth have to be specified. Lastly, the tool needs as an input the installed peak PV power and the system loss in order to give reliable results.

6 Case study

6.1 Demand estimation

In order to develop an EIS for energy communities, an hypothetical REC is modelled employing data from 50 families and a small stone factory, whose name will be protected by privacy. These conditions are chosen to propose a methodology feasible for the most part of the citizens. The location chosen for the study is Castel Maggiore, a small town near Bologna, with coordinates 44.564N and 11.370E. The city has about 18,000 inhabitants, an area of 30.9 square kilometres and it perfectly fits as possible model for energy community due to the small enterprise situated in the south-eastern part of the town.

6.1.1 Residential energy consumption

According with the methodology described before, the residential energy demand is simulated considering 50 families which form about 3 condominiums. The number was chosen in order to have a small energy community suitable in different areas and feasible for the majority of the citizen without the necessity of gather too many volunteers.

Results from the simulation of the community show that the whole residential energy consumption is highly dependent on the month, the day and the hour. The maximum demand was found to occur on Sundays of January whereas the lowest consumption was achieved in May with peaks of 27 kW during Sundays. With respect to weekly consumptions, in January, the peak has the same trend for every day from Monday to Saturday with an evening peak of 25 kW. On Sunday, the maximum peak is achieved, where energy consumption reaches almost 35 kW.

The following figure 10 shows a week of January. During the week, from Monday to Saturday, the consumption has almost the same trend, the peak is always in the evening and it is around 25 kW. The maximum peak is reached on Sunday evening where energy consumption reaches almost 35 kW. Every day there is a rump up starting from 5 a.m. till 8 a.m., then a small peak around lunch at 1 p.m. followed by a low at 4 p.m., finally the consumption rises quickly till its maximum around 8 p.m. The lowest consumption is reached every day around 4 a.m. and it is around 8 kW.

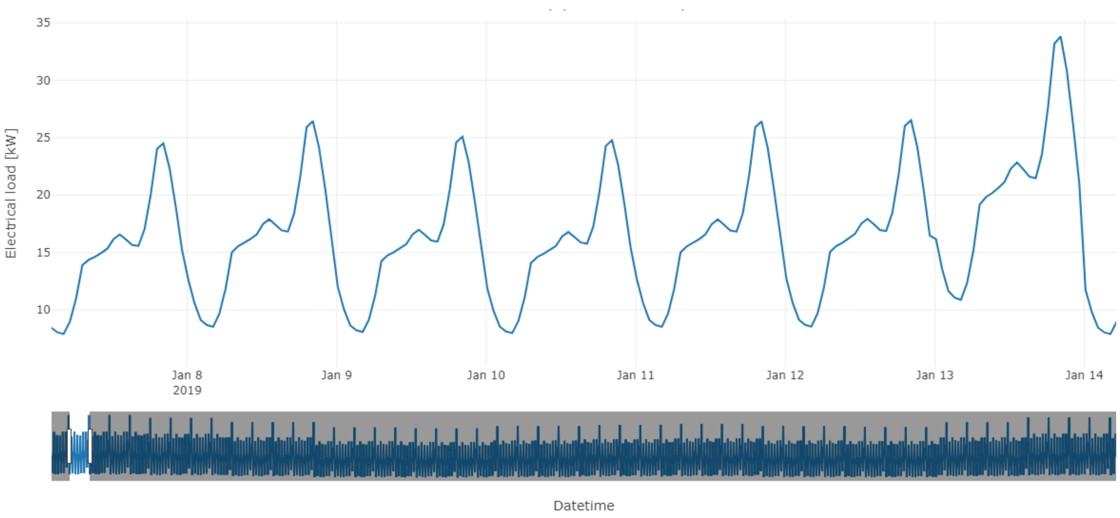

Figure 10 – Electrical load trend in a week of January

Throughout the year the weekly trend is the same but the intensity changes according to the month. In the figure 11 the annual consumption is represented.

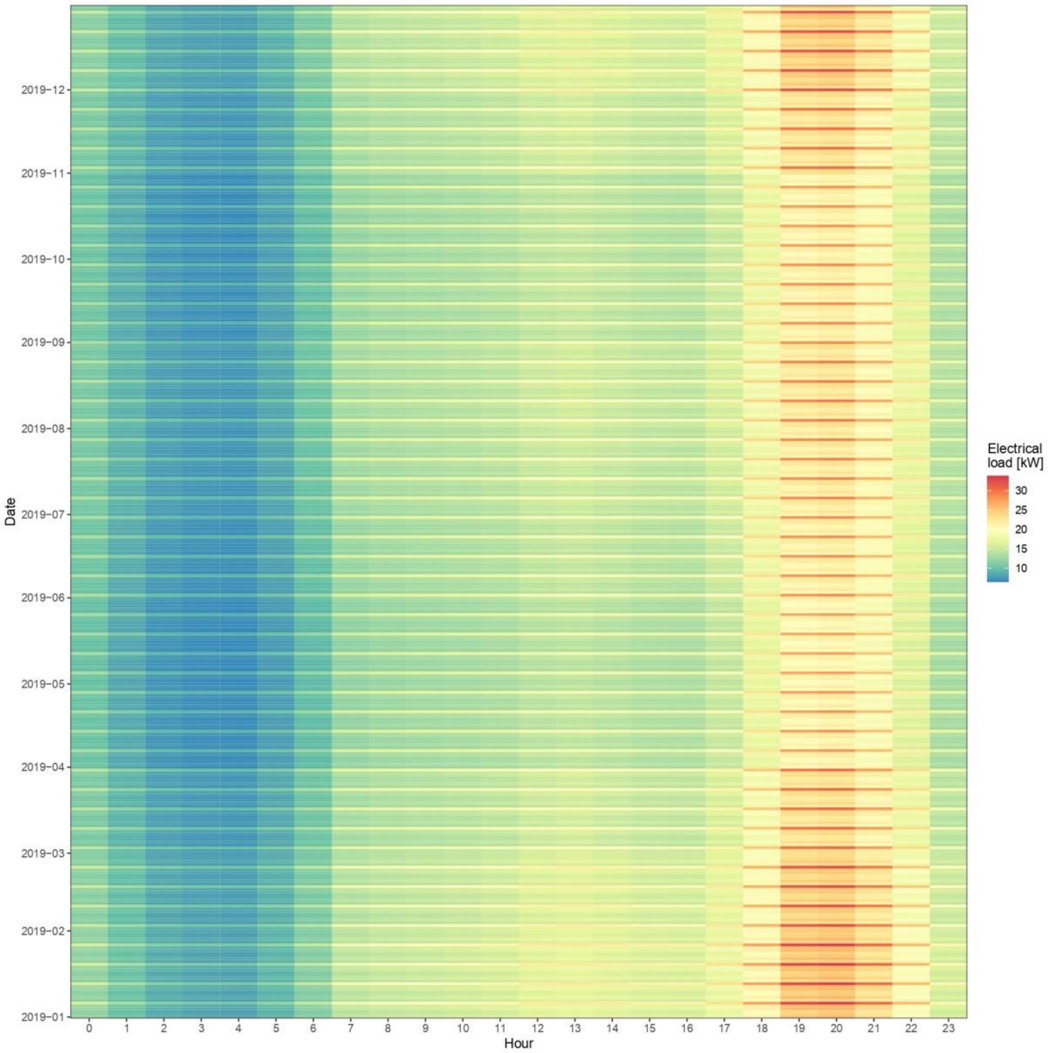

Figure 11 – Carpet plot of the annual residential REC consumption

6.1.2 Industrial energy consumption

The industrial electricity absorption is based on a real site and for this reason it is not uniform as the residential one, nevertheless it is possible to recognize some similarities in the pattern. The whole year consumption is represented in the carpet plot in figure 12.

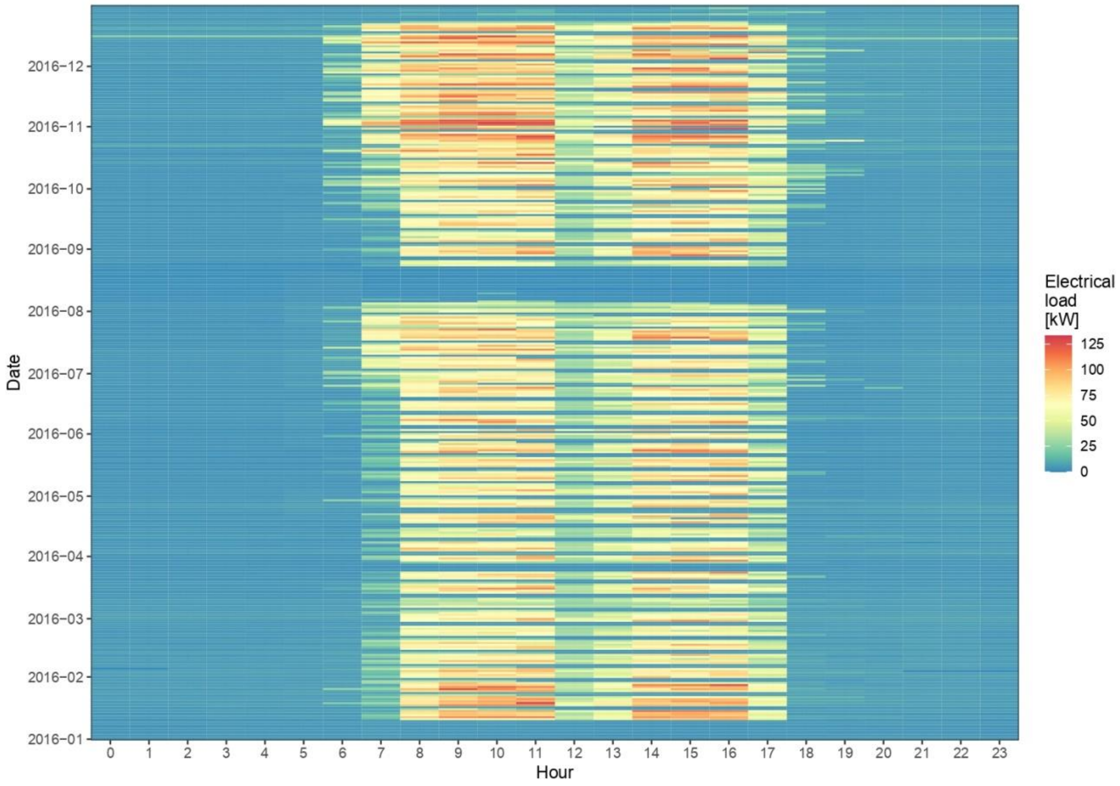

Figure 12 – Carpet plot of the electrical load of the industry

From the carpet plot, it is clear how the factory has two main stops, the first one during Christmas holiday and the second one in August. During these two periods the consumption goes from 100-120 kW to 3-5 kW which is the base load of the industry. The highest peak, 132 kW, is reached in January. During the rest of the year, before the summer break, peaks stay below 120 kW, while during November and the beginning of December some peaks reach 125-130 kW.

With respect to weekly consumption, despite single irregularities, it is possible to follow a pattern with two peaks during the day, the first one in the morning and the second one in the afternoon. The working days are mainly Monday-Friday (five consistent peaks) but since sometimes the company works Saturday morning as well, a small peak follows the five peaks of the working week.

In the figure 13 workdays (Monday – Friday), Saturdays and Sundays are gathered by month in order to highlight the differences between these days. The first clear thing is the visualization of the two daily peaks during workdays, these peaks usually reach 65-75 kW except for August where the industry has a closure for the summer break and the average is extremely lower (around 30 kW). Sundays are generally characterized by a small peak in the morning except for August and November where the peak is intense as the first peak of workdays. Despite this difference all Saturdays have only one peak. In the end, Sundays are characterized by a flat profile, except December where there is a small peak in the morning.

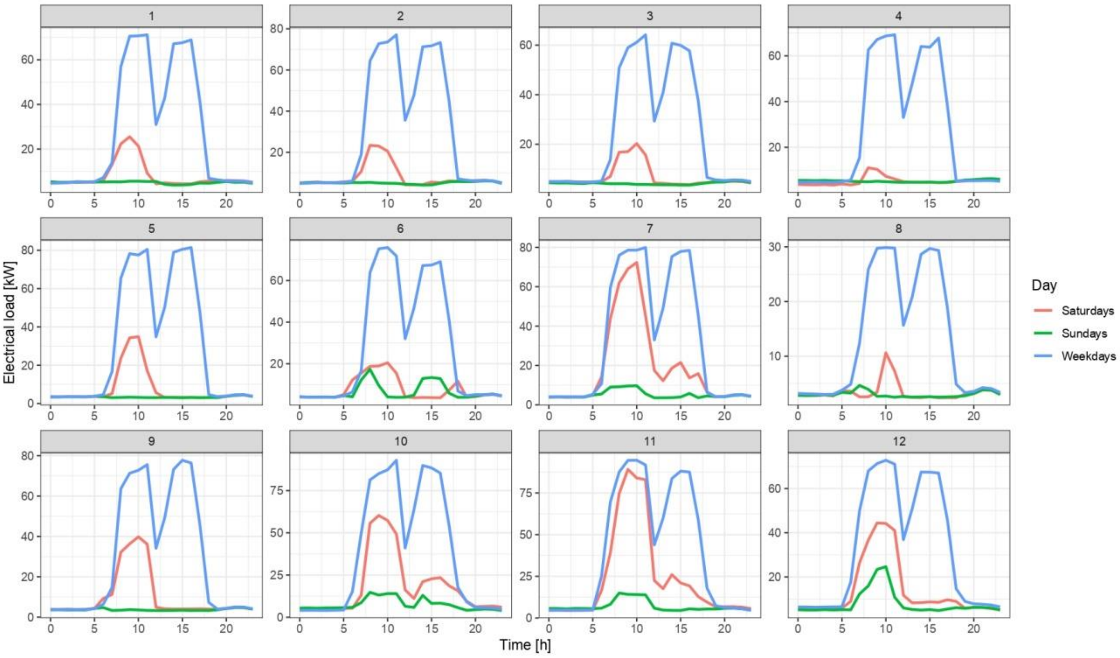

Figure 13 – Monthly electrical load of the industry gathered by workdays, Saturdays and Sundays

Continuing the analysis in figure 14, for every month mean consumption and standard deviation are calculated in order to visualize changes in different months. From this visualization it is clear that there are not particular differences between every month, excepted for August where the trend is the same but it is lower due to the closure for summer break. The standard deviation (SD) is extremely wide for every month because in all the months are contained different trends such as working days, Saturdays, Sundays and sometimes also holidays.

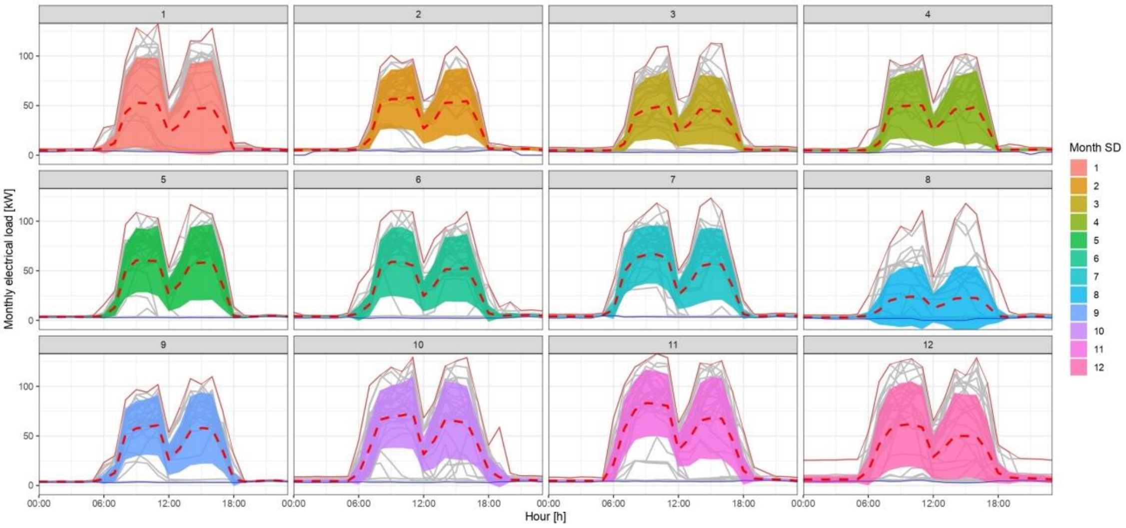

Figure 14 – Average industrial monthly electrical load with standard deviation

The last step of this short evaluation is to address a cluster analysis in order to highlighted different trends which are presented within the dataset. The analysis is carried out utilizing unsupervised learning, in particular the hierarchical clustering with agglomerative algorithm approach has been used. In order to link the different trends as linkage method the "ward.D2" has been used, this method creates groups in which the variance is minimized within clusters. Once the dendrogram is created the best number of clusters is calculated utilizing the package of R "NbClust". The package provides around 30 indices for determining the number of clusters and propose to the user the best ones [23] [24]. In this case the number of clusters proposed by NbClust and then utilized is 4. In the figure 15 the dendrogram and the division are represented.

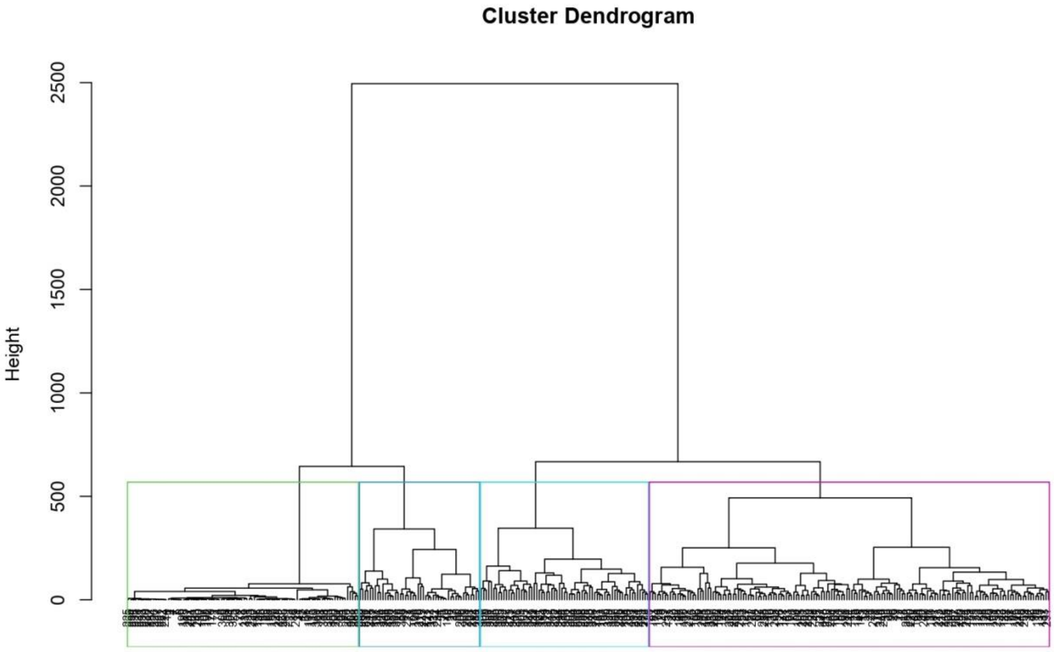

Figure 15 – Dendrogram with its division in 4 clusters

Collecting all the profiles in the four clusters (figure 16) once again differences between days are extremely clear. The first cluster is characterized by a flat profile and represents Sundays and holidays, while in the second and in the fourth clusters the two working peaks are recognizable and characterized them. Lastly, the third cluster gathers all Saturdays characterized by a small peak in the morning.

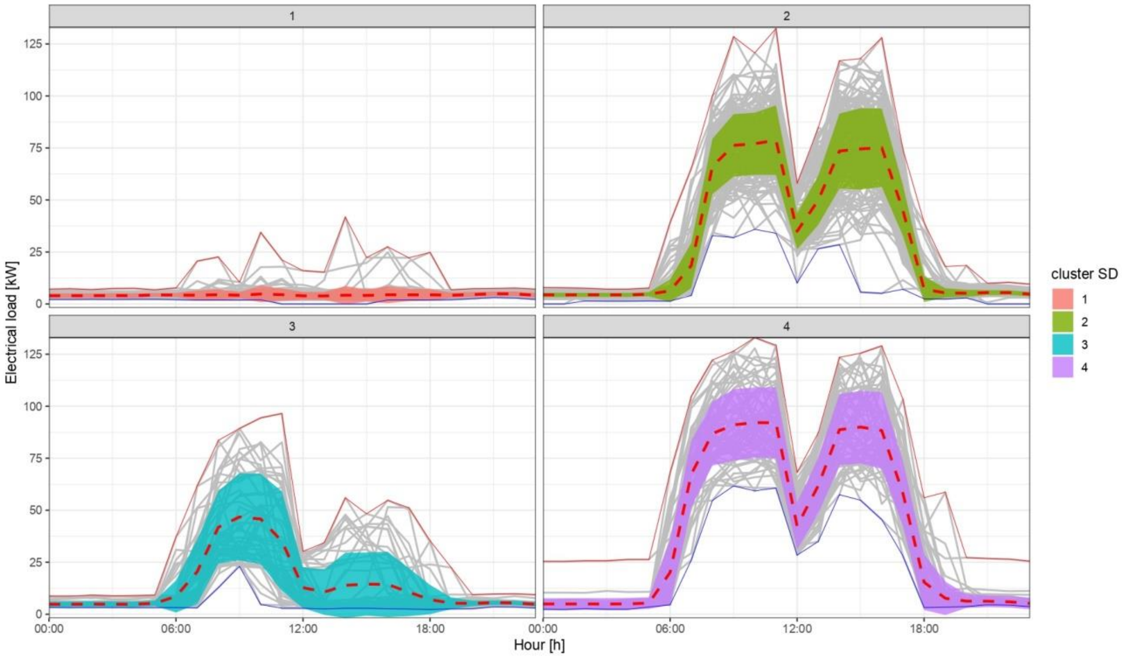

Figure 16 – Electricity electrical load trends divided into 4 clusters with average and standard deviation

6.1.3 Estimation of the Photovoltaic energy production

In this assessment, the location chosen is Castel Maggiore, a small town near Bologna, with coordinates 44.564N and 11.370E. The solar radiation database is the satellite-based PIVGIS-SARAH2 which is produced by CM SAF[1] [25] and it covers Europe, Africa, most of Asia, and parts of South America with a temporal range from 2005 to 2020. For the purpose of this thesis the year 2019 is selected. PV panels are designed to be fixed with both the slope and azimuth optimized, in this location the optimal slope is 39 degrees and the optimal azimuth is -3 degree. The PV power considered for the simulation/model is designed bases on the equation 9 [26] and the system loss is considered to be 14 %.

Equation 9 – Photovoltaic power calculation

$$P_{pv} = \frac{E_{tot} \cdot STC}{Z \cdot WKN \cdot WW} = \frac{335241.9 \left[\frac{kWh}{y}\right] \cdot 1 \left[\frac{kW}{m^2}\right]}{1502.2 \left[\frac{kWh}{m^2 \cdot y}\right] \cdot 1.13 \cdot 0.84} = 229.6 \approx 230\ kWp$$

where E_{tot} is the total amount of electricity consumed by both residential and industrial [kWh/y], STC is the solar irradiance at standard test condition (1 kW/m^2), Z is the global horizontal irradiation at the location [kWh/m^2/y], WKN is the irradiation correction factor and WW is the performance coefficient.

Considering the PV power plant just described the carpet plot in figure 17 shows the production of the site. From the carpet plot it is visible how the production is extremely low in January, November and December, probably due to poor irradiation and cloudy days. On the other hand, in April and May the irradiation is really strong but cloudiness greatly reduce the production. The overall monthly production is represented, in [kWh], in the figure 18 and the observations made on the carpet plot are confirmed by lower overall production in January, April, May, November and December.

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[1] European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) - Climate monitoring

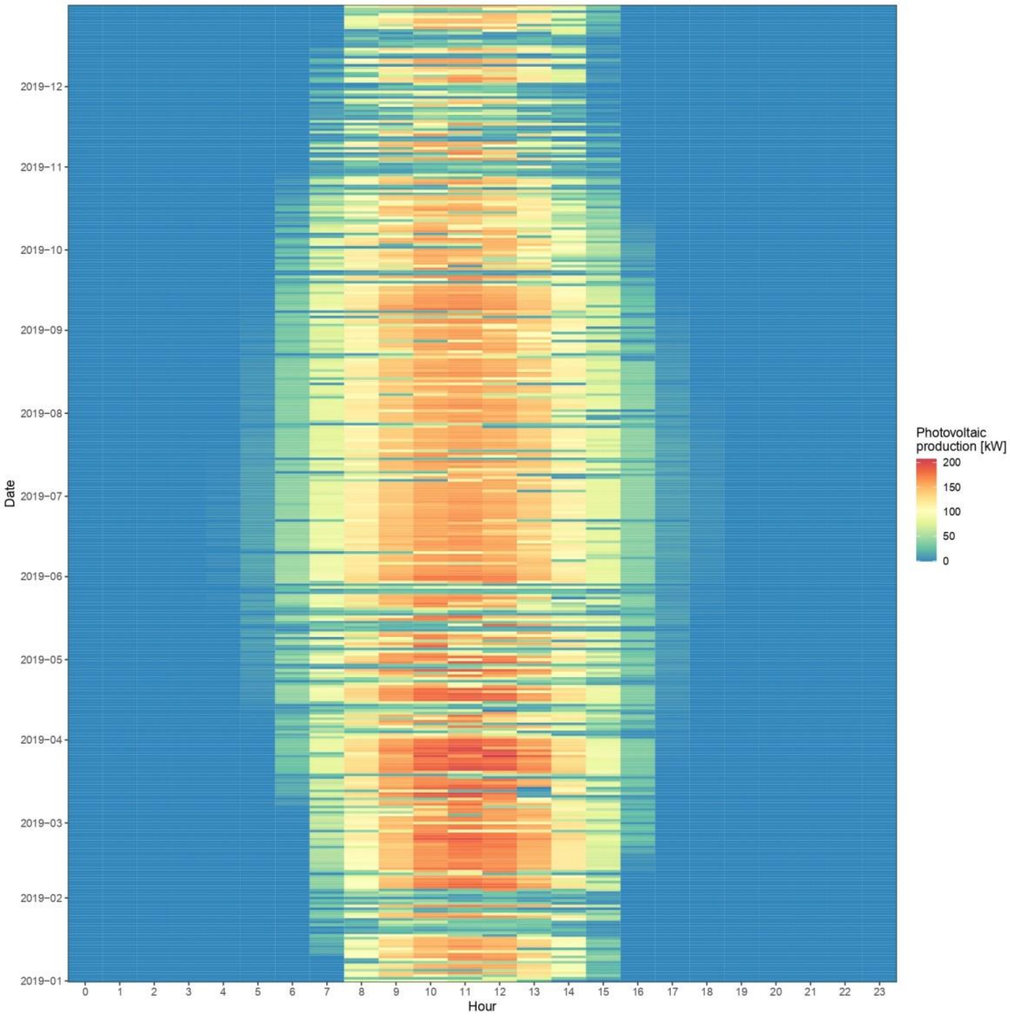

Figure 17 – Carpet plot of the production of the photovoltaic system installed in the REC

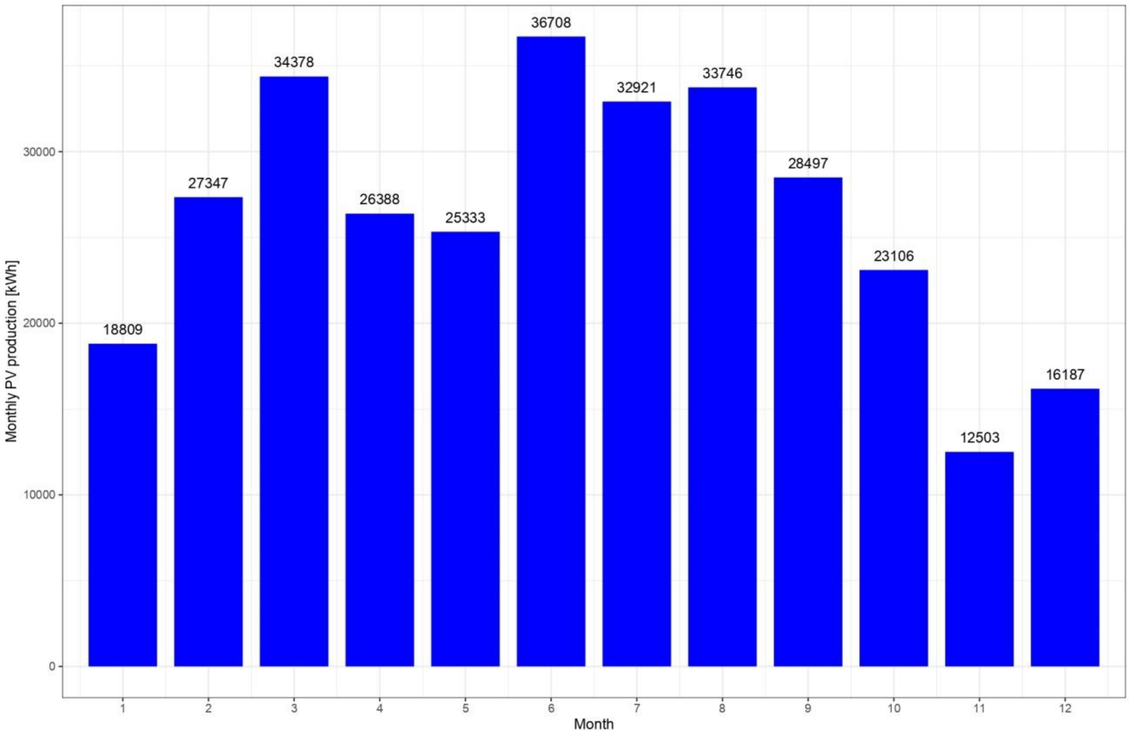

Figure 18 – Monthly production in [kWh] of the photovoltaic system installed in the REC

6.2 System configuration and operation

6.2.1 REC as a Prosumer

In the configuration chosen, the PV power plants and the battery are installed and founded by the whole community, thus the battery operation is in favour of the whole REC. Consequently, PV panels and the battery are thought to maximize the benefit of the community and not the industrial ones, in other words the battery is charged when there is a surplus of production related to the total REC consumption and it is discharged when the PV production is not enough to cover the community electricity demand. Moreover, the system considers both for purchase and selling the hourly electricity price. It is taken in consideration also an almost impossible scenario, if the selling price of the market is higher than the incentive, instead of charging the battery the energy could be directly sold and inserted in the grid in order to increase the economic gains. Figure 19 shown the flow of the energy produced from the PV panels and how it is employed and distributed within the community.

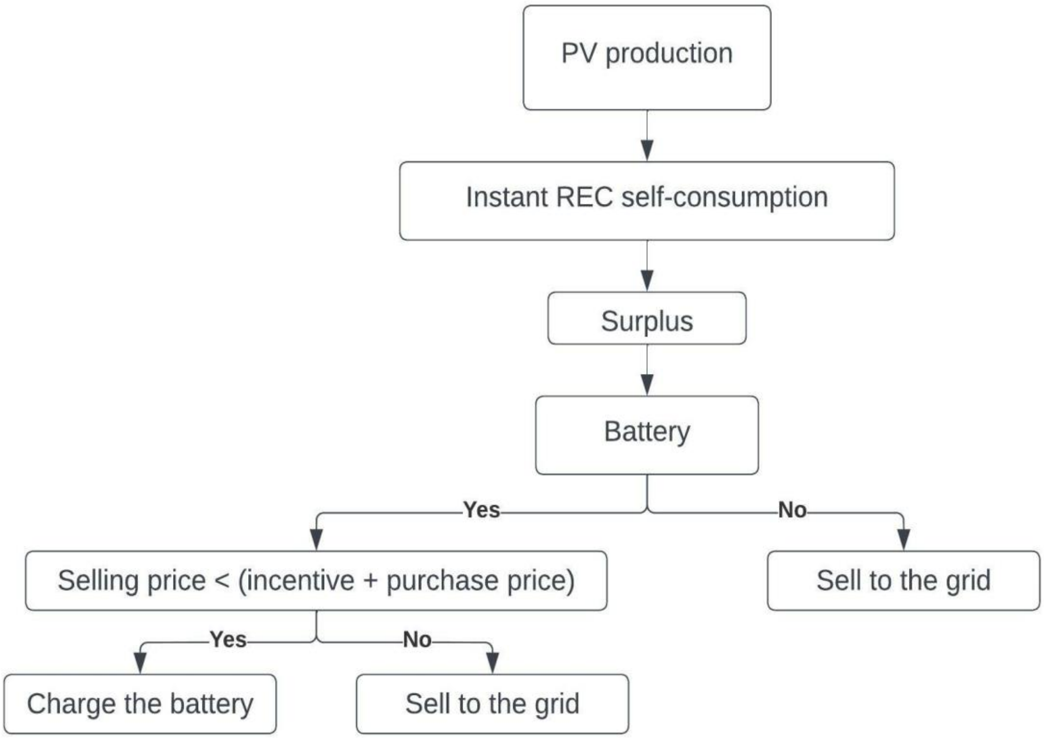

Figure 19 – Flow of the energy produced by PV panels

Another scenario occours when the battery is fully charged and the PV production is higher than the REC consumption, in this case the surplus is directly sold to the grid. Regarding the surplus sold to the grid it was considered the guaranteed minimum prices provided by ARERA[2] for the photovoltaic energy production. The price for electricity withdrawn on an annual basis until 1,500,000 kWh is 39.9 €/MWh [27]. If the battery is fully charged but the consumption is higher than the production, the system self uses all the PV electricity production and covers the remaining demand discharging the battery. The process occurring in the second scenario is shown in figure 20.

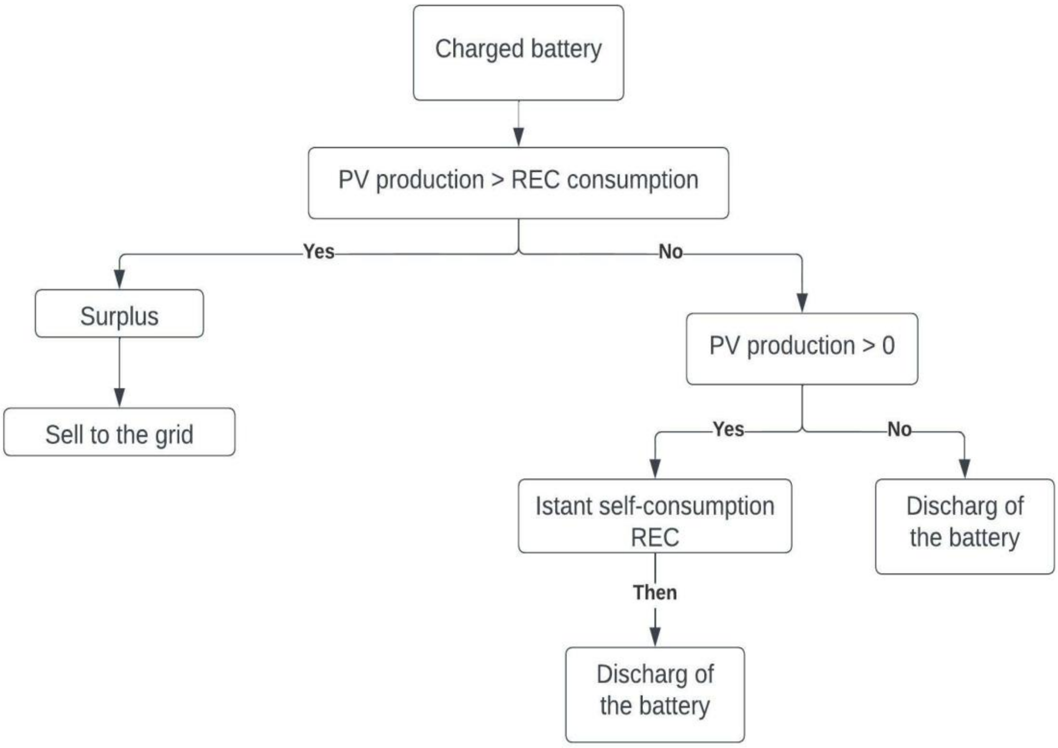

Figure 20 – System operation with battery charged

When REC consumption is lower than PV production, electricity is purchased from the grid considering a variable price of electricity, this variable price is based on the “Prezzo Unico Nazionale” (PUN) which is the wholesale reference price of electricity purchased on the Italian Power Exchange (IPEX - Italian Power Exchange) market. The PUN considered is from the year 2021 and in table 3 its growth during the year due to geopolitical situation is shown [28]. However, the PUN consider only the energy part of electric bill, so it has been considered to be the 40% of the whole electricity bill which the final user pays (Appendix 3).

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[2] Autorità di Regolazione per Energia Reti e Ambiente

Table 3 – PUN trend of the year 2021. Source: **[28]**

Month	Purchase price PUN (€/MWh)		
	Average	**Min**	**Max**
January	60.71	30.76	101.01
February	56.57	10.00	108.57
March	60.39	31.71	100.87
April	69.02	3.49	118.08
May	69.91	3.00	99.50
June	84.80	42.67	139.07
July	102.66	60.00	148.59
August	112.40	60.09	156.96
September	158.59	60.06	256.29
October	217.63	130.50	380.00
November	225.95	119.00	400.00
December	281.24	94.48	533.19

6.2.2 Battery design and operation

Besides the mechanism explained above where the Battery Energy Storage System (BESS) maximizes the incentive, the main function of the battery in a solar PV system, is to maximize the self-consumption of the PV production and to shift the surplus of the daytime production to the night-time consumption. The energy in surplus from the PV production, not sold to the grid, goes into the battery and charges it. The efficiency factor of the battery allows to calculate the exact and final amount of energy stored in it. In fact, the battery discharges when the community needs energy and also releases some energy in the whole process (charging efficiency). The energy which goes in or out at a time step "t" is added or subtracted to the energy in the battery at time step "t-1". The operation of the battery during its cycle is expressed in the equation 10 as explained by [29]:

Equation 10 – Energy stored in the battery an time "t"

$$E(t) = E(t-1) + \left[E_{PV}(t) \cdot \eta_{ch} - \frac{E_{dis}(t)}{\eta_{dis}} \right]$$

Where:

$E(t)$ is the energy in the battery at time t;

$E(t-1)$ is the stored energy in the battery at time t-1;

$E_{PV}(t)$ is the energy generated from the PV panels in one hour;

η_{ch} is the charging efficiency of the battery;

$E_{dis}(t)$ is the energy discharge from the battery to the community demand in one hour;

η_{dis} is the discharging efficiency of the battery.

Furthermore, the battery has a few more constraints such as the Depth of Discharge (DOD) and the maximum charge and discharge power. The first one, is the percentage of battery capacity which is not recommended fall behind in order to not damage the battery. The maximum charge power, represents the maximum power at which the battery can store energy for one hour. On the other hand, the maximum discharge power is the maximum energy that the battery can yield to the system in one hour. For the purpose of this case study, it was a DOD of 80% was used, a maximum discharge power of 25% and a maximum charge power of 50%.

The DOD is represented by the following equation:

Equation 11 – Depth of discharge

$$DOD = 0.8 \cdot C_{bess}$$

where C_{bess} is the battery capacity.

The maximum charge and discharge are represented by:

Equation 12 – Maximum charge energy

$$E_{ch,max} = 0.5 \cdot C_{bess}$$

Equation 13 – Maximum discharge energy

$$E_{disch,max} = 0.25 \cdot C_{bess}$$

In conclusion, the battery starts empty, it charges when a surplus occurs and every cycle it discharges until the DOD when the system asks for electricity. In the whole cycles the two constraints are applied and there are some losses due to heating of cables.

6.3 Scenario 1 – REC with only photovoltaic panels

The first configuration considered is the baseline scenario with only photovoltaic panels and without any storage systems. In this case, the electricity produced by the PV panels is either instantaneously self-consumed or sold to the national grid. This configuration is easier to implement and cheaper, but it does not optimize the self-consumption nor the

REC savings. Figure 21 shows in orange the REC total electrical demand and in blue the PV production during the whole year. The first visible thing is how the surplus is much higher during the summer month and lower in November, December and January. It is also clear that when there is clear sky the production is sufficient to cover the peaks of the electricity demand.

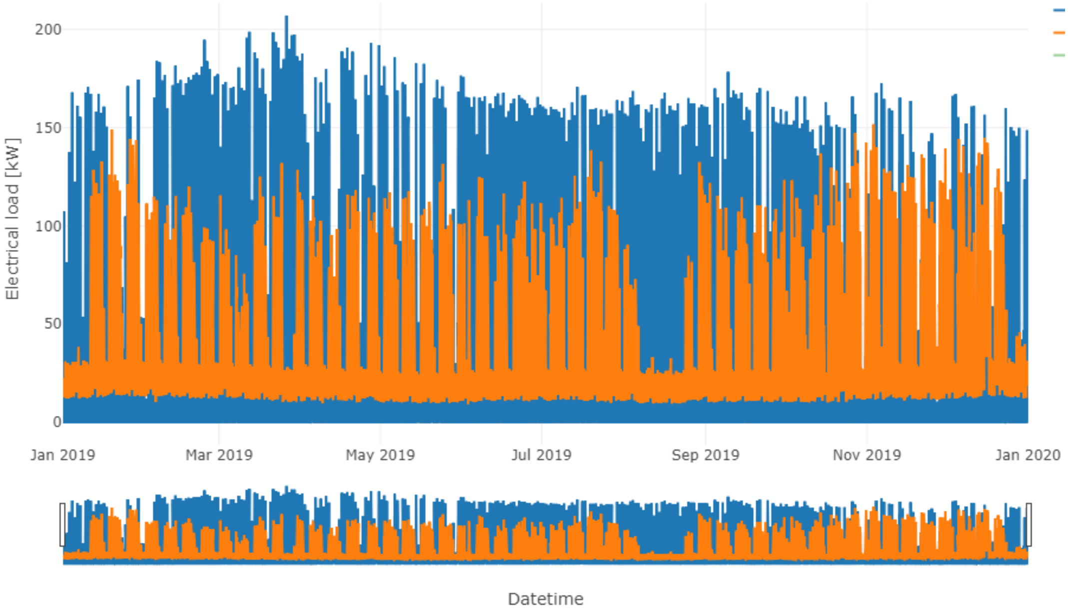

Figure 21 – REC total electrical demand (orange) and PV production (blue)

When zooming considering single weeks, *e.g.,* in June when there is high chance for a clear sky, the PV production covers almost the total daily electrical demand except for some consumption during late afternoons. However, late residential activities during the evenings in this configuration are never covered by PV production (figure 22).

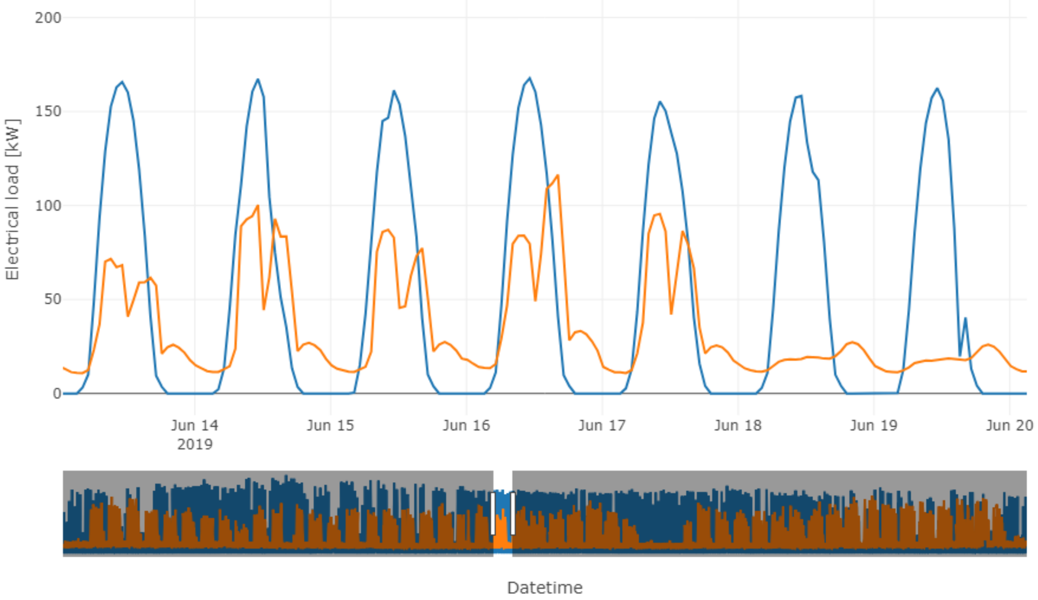

Figure 22 – Zoom of the PV production (blue) and REC consumption (orange) on a week of June

In the table 4 results of scenario 1 are shown. Looking at the table and comparing the total monthly consumption with the PV monthly production, it could seem that they are balanced and that the community is almost self-sufficient.

However, the production is not synchronised with the consumption and most of the electricity is not self-consumed but added to the grid.

In fact, for the whole year the monthly surplus is nearly half of the monthly production and as mention before it is all sold to the grid due to time mismatch.

The energy from which the incentive is calculated in this scenario is always the energy self-consumed. In fact, the calculation considers the minimum between the production and the consumption, but in this scenario consumption and production occur simultaneously, thus the energy supported by the incentive is the energy self-consumed.

Anyhow, all the energy self-consumed is energy which will be not purchased from the national grid, this mechanism generates earnings for the community that saves money. Moreover, in the table is visible an increasing in REC savings during the year due to the increase of the PUN trend. Adding together REC savings due to energy not purchased, the incentive and sales earnings the monthly earnings of the REC emerges. In this scenario the annual earnings are 73,574 euro.

Table 4 – Monthly results of the baseline scenario

Month	**Residential monthly consumption [kWh]**	**Industrial monthly consumption [kWh]**	**Total monthly consumption [kWh]**	**PV monthly production [kWh]**	**Surplus [kWh]**	**Energy sold to the grid [kWh]**	**Instantaneous self-consumption REC [kWh]**	**Energy incentive [kWh]**
1	12198	15727	27924	18809	8974	8974	9835	9835
2	10675	15664	26339	27347	14734	14734	12613	12613
3	11220	14941	26160	34378	19781	19781	14597	14597
4	9988	15086	25074	26388	13744	13744	12644	12644
5	10125	17512	27637	25333	11348	11348	13985	13985
6	10272	16562	26834	36708	19068	19068	17640	17640
7	10753	19683	30436	32921	14034	14034	18887	18887
8	10955	7944	18900	33746	23126	23126	10620	10620
9	10243	17026	27269	28497	13925	13925	14572	14572
10	10326	22128	32454	23106	8172	8172	14934	14934
11	10723	24123	34846	12503	2758	2758	9745	9745
12	11864	19507	31371	16187	7672	7672	8516	8516
Month	**REC saving [€]**	**Incentive [€]**	**Earnings sale [€]**	**Electricity bill [€/kWh]**	**Industrial energy consumption post [kWh]**	**Residential energy consumption post [kWh]**	**Monthly earnings REC [€]**	**Monthly earnings REC with incentive [€]**
1	1710	1170	350	0.151781	9218	8871	2060	3231
2	1966	1501	575	0.141432	6597	7129	2541	4042

3	2137	1737	771	0.150971	4802	6761	2909	4646
4	2187	1505	536	0.172584	6198	6233	2723	4228
5	2322	1664	443	0.174785	7296	6356	2765	4429
6	3781	2099	744	0.212071	3768	5426	4524	6623
7	4980	2248	547	0.256679	5398	6151	5527	7774
8	2953	1264	902	0.281062	2359	5920	3855	5119
9	5792	1734	543	0.396673	6257	6439	6335	8069
10	8295	1777	319	0.544156	10396	7124	8614	10391
11	5904	1160	108	0.564882	16325	8775	6011	7171
12	6539	1013	299	0.7031	13657	9198	6839	7852

6.3.1 Collective Electrical Self-Production of the baseline scenario

Ideally the PV panels could cover almost the total electrical demand because the yearly production is 315,923 kWh/year while the consumption is 335,243 kWh/year. In fact, the Electrical Self-Production is 94%. Looking at the monthly ESP in table 5, the only period below 1, where the consumption is higher than the production, is from October to January and May which it was uncommonly cloudy and the production is significantly below the average. In August the industrial is barely open and the electrical consumption is significantly less, thus the ESP is more than 1.5.

Table 5 – Overall and monthly Electrical Self-Production

Overall ***ESP***	0.942
Month	***ESP***
1	0.674
2	1.038
3	1.314
4	1.052
5	0.917
6	1.368
7	1.082
8	1.756
9	1.045
10	0.712
11	0.359
12	0.516

6.3.2 Collective Self-Consumption Index of the baseline scenario

The ESP does not take into consideration the electricity really self-consumed within the community but the entire production regardless the final use. Consequently, it is more interesting to analyse the SCI which considers the electricity effectively consumed from the community and gives a reliable indication on the use of the energy produced. Looking at the table 6, as it might be expected in this scenario, the SCI is barely over 50%. This fact is due to the shifting between the PV production and the residential demand mainly during evenings. Analysing the monthly SCI it is higher during the winter months due to a lower production and it is really low in August when the production is at its maximum and the consumption is at its minimum due to the industrial vacation. In order to improve this index, reduce waste and increase the energetic efficiency of the community, the installation of a BESS (e.g. lithium battery) would allow to store the energy and exploit it during evenings, with this configuration the energy self-used will increase drastically.

Table 6 – Overall and monthly Self-Consumption Index

Overall ***SCI***	0.502
Month	***SCI***
1	0.523
2	0.461
3	0.425
4	0.479
5	0.552
6	0.481
7	0.574
8	0.315
9	0.511
10	0.646
11	0.779
12	0.526

6.3.3 Collective Self-Sufficiency Index of the baseline scenario

Another interesting indicator is the Self-Sufficiency Index which considers how much the REC is self-sufficient or dependent from the grid. In this scenario, without any storage system this index is quite low, as almost half of the energy needed (47%) is purchased from the grid. The REC does not even produce and use half of the energy needed. The worst period is, as expected, winter where the SSI is around 30% because the production is very low compared to the demand (table 7). Again, a BESS system could help to consume much more energy produced.

Table 7 – Overall and monthly Self-Sufficiency Index

Overall ***SSI***	0.473
Month	***SSI***
1	0.352
2	0.479
3	0.558
4	0.504
5	0.506
6	0.657
7	0.621
8	0.562
9	0.534
10	0.460
11	0.280
12	0.271

In conclusion, the configuration of a REC with installed only the PV panels is a good starting point but not the best solution. The most electricity produced by PV panels is put into the grid and not self-exploited reducing a lot the advantages of the community such as shared energy, incentives and self-consumption.

6.3.4 Environmental impact of the baseline scenario

The environmental impact is measured thanks to the tons of CO_2 avoided with the new configuration. Considering the comparison between the baseline scenario of the REC with just the PV system and the actual situation where both the industry and residential families purchase energy from the national grid, the amount of CO_2 avoided by just installing PV panels and self-consuming the energy is about 42.6 tons per year. The environmental impact index is about 0.47.

6.4 Scenario 2 – Hypothesis of REC with photovoltaic panels and optimized BESS

Until now, the system considered is composed by 50 residential users, a small enterprise and a photovoltaic plant of 230 kWp. For the second scenario a battery is installed in the system in order to maximize the exploitation of the energy produced by PV panels and possibly to overcome all drawbacks presented in the previous scenario. In order to maximize the economic and energetic gain the correct size of the battery has to be evaluated.

The battery size optimization is addressed taking into account residential and industrial load profiles and the PV power plant considered before. With the combination of demand and production it is possible to calculate the NPV in different situation.

The optimization algorithm is thought to maximize the NPV[3] after 10 years finding the best size of the battery in the configuration chosen. The algorithm developed, takes into account demand and production and evaluates the NPV thanks to the calculation of annual earnings. These are calculated considering the annual savings from the generation and the incomes due to the incentive and from sales minus the operational costs. Considering that the function that maximized the NPV is a linear and continuous function there will be one maximum only. Hence, it is possible to find the best NPV with a general investigation and lately fine-tune the best size within the ones which return the best NPV.

Thus, the algorithm calculates the NPV for sizes every 200 kWh from zero to 5000 kWh finding the size with higher NPV. Then, starting from the best size, it runs again and calculate the NPV from the best size founded with a size-step of plus/minus every 20 kWh and so on until it finds the size that maximises the NPV.

With the parameters selected the best size is 356 kWh with a NPV after 10 years about 435,073 euro, however to facilitate the battery purchases on the market a battery of 350 kWh is selected.

In figure 23, the REC consumption (orange), the PV production (blue) and the battery trends (green) are represented. PV production and REC consumptions are the same as before while the battery trend is completely new.

The first visible thing regarding the battery is its specification: 350 kWh maximum capacity and the DOD of 80% of the maximum capacity (70 kWh). Another interesting thing is that the battery charges and discharges almost every day when the production is greater than the consumption, this phenomenon confirm the fact that consumption and production do not occur at the same time and, at least the residential energy consumption, discharges the battery in the evenings and nights. If the PV production is low and the surplus is not enough to completely charge the battery, the battery itself is a bit useless. This happens especially in November and December, nevertheless during

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[3] Calculations of NPV are explained in section 6.5

the rest of the year the battery is extremely useful. In August the battery does not completely discharge due to a lower industrial energy consumption and a small battery could fit better, but still in the rest of the year a 350 kWh battery is the best.

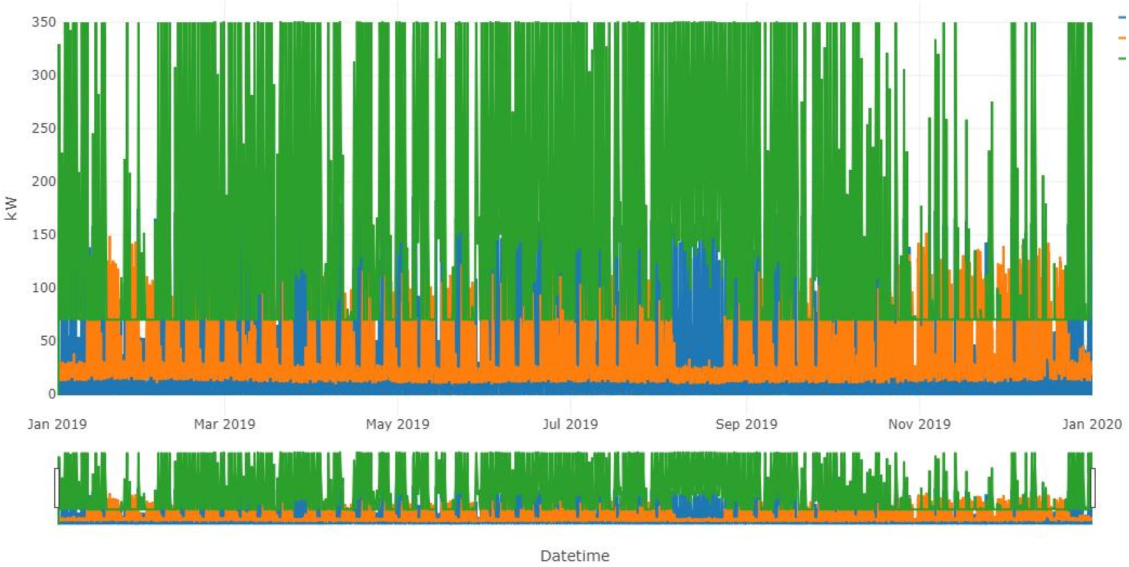

Figure 23 – REC total electrical demand (orange), PV production (blue) and battery trend (green)

The figure 24 shows the same week of June analysed in the previous scenario (scenario 1), including the battery trend. As just mention for figure 23, in normal condition, the battery charges and discharges every day going up to 350 kWh and discharging all the way down to 70 kWh respecting the rules of maximum charge and discharge power. In the morning when the PV production starts and the consumption are still low, the battery start charging adding at the previous energy already stored the PV production minus the instantaneous REC self-consumption. Apart from weekends, where the consumption is lower and the battery does not completely discharge, during week days the battery is well exploited and completely charges and discharges keeping as short as possible those moments when it is fully charged or discharged. Extreme cases still occur, where *e.g.*, the system has surplus and cannot store it or when the system requires energy and it have to buy it from the grid because the battery is already discharged.

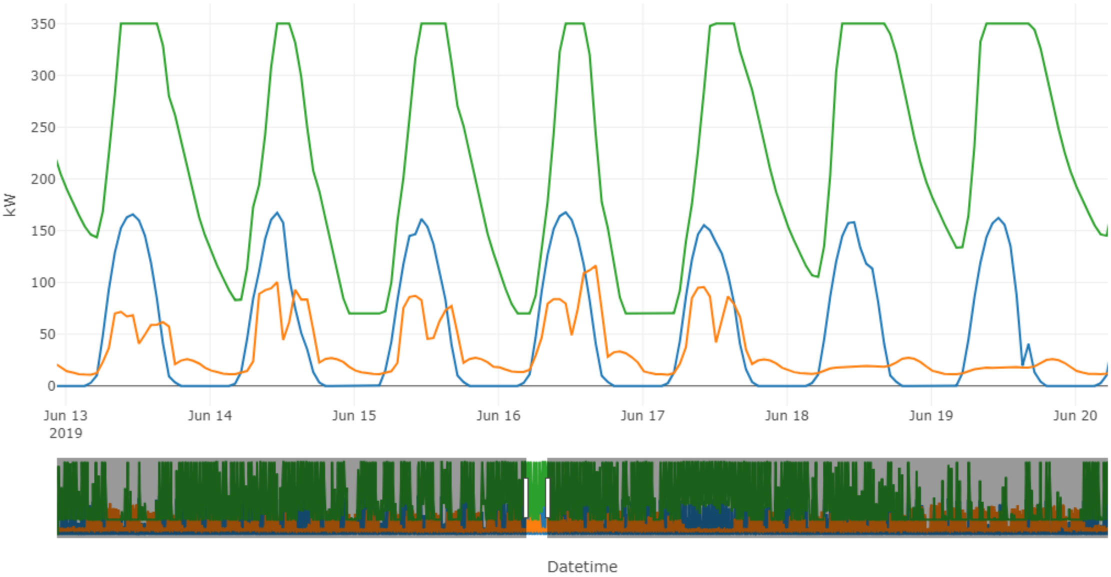

Figure 24 – Zoom of the PV production (blue), REC consumption (orange)
and battery operation (green) on a week of June

The following table 8 summarizes results of this scenario. Residential and industrial monthly energy consumption as well as the total consumption are the same as the previous case since the demand is not changed. The monthly photovoltaic energy production and the surplus are the same too because the plant remains of 230 kWp. The first big change occurs in the annual energy sold to the grid, it is drastically decreased due to the battery used which stores energy to use it afterwards instead of selling it to the grid. In specific, the earning from the selling passes from 6,136 €/year to 3,361 €/year and decreases of 44.2 %. Also the REC instantaneous self-consumption remains the same due to the same production and consumption. Using more PV self-produced energy the REC purchases less energy from the grid and it makes more savings, in particular the yearly savings goes from 48,566 €/year to 69,860 €/year in this new scenario with the battery. Compared to the previous case the savings are increased up to about 44%. Another advantage of this latter case is the function explained in the section 1.3 where the battery works both as demand or as production depending on its phase. In this way the yearly shared energy (energy incentive) is nearly doubled passing from 158,589 kWh/year to 302,364 kWh/year. Thus, also the annual incentive is almost twice and pass from 18,872 €/year to 35,981 €/year increasing of 90.7%. The absorption from the grid after the photovoltaic energy self-produced and self-used is less is this latter case with the battery and the REC is more independent. In conclusion, the annual earnings goes from 73,574 €/year to 109,202 €/year and despite the earnings from energy sold to the grid which decreases, all the other components are improved.

Table 8 – Monthly results of the scenario 2 with PV panels and BESS

Month	Residential monthly consumption [kWh]	Industrial monthly consumption [kWh]	Total monthly consumption [kWh]	PV monthly production [kWh]	Surplus [kWh]	Energy sold to the grid [kWh]	Instantaneous self-consumption REC [kWh]	Energy incentive [kWh]
1	12198	15727	27924	18809	8974	3864	9835	20109
2	10675	15664	26339	27347	14734	8421	12613	25290
3	11220	14941	26160	34378	19781	11890	14597	30644
4	9988	15086	25074	26388	13744	7960	12644	24215
5	10125	17512	27637	25333	11348	5897	13985	25095
6	10272	16562	26834	36708	19068	11499	17640	32971
7	10753	19683	30436	32921	14034	6834	18887	33339
8	10955	7944	18900	33746	23126	15835	10620	25460
9	10243	17026	27269	28497	13925	7360	14572	27852
10	10326	22128	32454	23106	8172	2794	14934	25826
11	10723	24123	34846	12503	2758	322	9745	14689
12	11864	19507	31371	16187	7672	3502	8516	16875

Month	REC saving [€]	Incentive [€]	Earnings sale [€]	Electricity bill [€/kWh]	Industrial energy consumption post [kWh]	Residential energy consumption post [kWh]	Monthly earnings REC [€]	Monthly earnings REC with incentive [€]
1	2546	2393	151	0.151781	7323	5725	2697	5090
2	2960	3010	328	0.141432	3766	3743	3289	6298
3	3450	3647	464	0.150971	1250	2326	3914	7560
4	3206	2882	310	0.172584	3668	3102	3517	6398
5	3350	2986	230	0.174785	4741	3371	3580	6566
6	5556	3924	448	0.212071	539	1052	6004	9928
7	6921	3967	267	0.256679	2274	2176	7188	11155
8	5195	3030	618	0.281062	286	601	5812	8842
9	8579	3314	287	0.396673	3025	3107	8866	12181
10	11437	3073	109	0.544156	6870	5271	11546	14619
11	7364	1748	13	0.564882	14778	7886	7376	9124
12	9295	2008	137	0.7031	12125	6633	9432	11440

Focus the attention on the battery is possible to calculate the total energy that goes in and out from it, the annual amount is 145,076 kWh/year and the total self-consumed energy is 72,466 kWh/year. The energy self-consumed is not exactly half due to the charge and discharge efficiency factor that are considered. The following table 9 represents the monthly division of these two parameters.

Table 9 – Monthly energy charged and discharged into the battery and energy discharged and self-consumed

Month	Energy charged and discharged in the battery [kWh]	Energy discharged and self-consumed [kWh]
1	10358	5144
2	12786	6344
3	16201	8149

4	11678	5776
5	11215	5652
6	15482	7759
7	14591	7243
8	14983	7543
9	13398	6699
10	10976	5488
11	4972	2486
12	8435	4180

6.4.1 Collective Electrical Self-Production of the scenario 2

The ESP depends from the PV production and the electrical demand and not from the energy effectively consumed, it is just a parameter that compares the demand with the production. For this reason it does not change from the previous scenario.

Table 10 – Overall and monthly Electrical Self-Production

Overall ***ESP***	0.942
Month	***ESP***
1	0.674
2	1.038
3	1.314
4	1.052
5	0.917
6	1.368
7	1.082
8	1.756
9	1.045
10	0.712
11	0.359
12	0.516

6.4.2 Collective Self-Consumption Index of the scenario 2

The same thought cannot be applied to the SCI that goes from 0.50 up to 0.73, this is due to majority of the PV energy produced exploited. The battery allows to store energy and to use it when is needed and the production is not enough. Looking at the table 11 and comparing with the figure 23 is clear that the months with higher SCI are the months where the PV energy production is low such as January, October and November or those months with a great consumption. On the other hand in August and March where there is a lower energy demand but still a good PV production and the index goes drastically down.

Table 11 – Overall and monthly Self-Consumption Index

Overall ***SCI***	0.731
Month	***SCI***
1	0.796
2	0.693
3	0.662
4	0.698
5	0.775
6	0.692
7	0.794
8	0.538
9	0.746
10	0.884
11	0.978
12	0.784

6.4.3 Collective Self-Sufficiency Index of the scenario 2

Also the SSI increase a lot and goes from 0.47 to 0.69. In this case the best months are those with lower demand or really high production such as August where both the conditions are satisfied and the SSI is 0.96. On the other hand, when the production is low like in winter month the SSI decreases a lot even if a battery is installed. However, the decreasing is less than the previous scenario. These consideration are shown in the following table 12.

Table 12 – Overall and monthly Self-Sufficiency Index

Overall ***SSI***	0.689
Month	***SSI***
1	0.536
2	0.72
3	0.87
4	0.735
5	0.711
6	0.947
7	0.859
8	0.961
9	0.78
10	0.629

11	0.351
12	0.405

In conclusion, considering energetic results and the information given from KPIs the scenario 2 is preferable to the first one due to an increase in both energy and economic factors. In fact, the annual earnings goes from 73,574.12 € to 109,202.19 € and all the KPIs increase more than 20 percentage points.

6.4.4 Environmental impact of the scenario 2

With this configuration the CO_2 avoided is almost 62 tons and it is higher due to less energy purchased from the national grid. The more energy used is self-produced the less CO_2 is released into the atmosphere. The environmental impact index is about 0.69.

6.5 Economic analysis of the REC with photovoltaic panels and optimized BESS

Considering the results shown above, a more detailed economic analysis is carried out for the scenario 2. In this chapter capex and opex of the configuration as well as NPV and IRR are addressed. Moreover, a solution for the division of the total investment and the incentive is proposed.

Remembering that in this scenario are installed a photovoltaic power of 230 kWp and a battery of 350 kWh it is possible to continue with all the calculations.

6.5.1 Capex of the scenario 2

A capital expenditure (CapEx) is amount of money needed to purchase long term physical or fixed assets used in a business's operations.

Photovoltaic

For the calculation of the PV capex are considered panels of 400 Wp with a cost, based on the actual market, of 370 €/panel considering capital cost, commissioning and construction. In order to have 230 kWp 575 panels are required for a total price of 212,750 €. Considering another 0.75% for the insurance [30] the final cost is 214,346 €. The studies of IRENA [31] and National Renewable Energy Laboratory [32] propose for a site from 20 kWp to 1 MWp a price of 934.2 €/kW, if this latter price is considered the CAPEX would be of 214,866 € which does not differ too much from the previous one, thus the consideration of 370 €/panel is reliable.

Battery

Regarding the battery a report from HydroWIRES – U.S. Department of Energy [33] is considered and looking the table 13 the final total project cost for the selected lithium battery is 400 €/kWh. Hence, the total cost for the battery is 140,000 €.

Table 13 – Summary of compiled 2018 findings and 2025 predictions for cost and parameter ranges by technology type – BESS.(a) Source: **[33]**

	Sodium- Sulfur Battery		**Li-Ion Battery**		**Lead Acid**		**Sodium Metal Halide**	
Parameter	**2018**	**2025**	**2018**	**2025**	**2018**	**2025**	**2018**	**2025**
Capital Cost – Energy Capacity ($/kWh)	400-1000 **661**	(300-675) **(465)**	223-323 **271**	(156-203) **(189)**	120-291 **260**	(102-247) **(220)**	520-1000 **700**	(364-630) **(482)**
Power Conversion System (PCS) ($/kW)	230-470 **350**	(184-329) **(211)**	230-470 **288**	(184-329) **(211)**	230-470 **350**	(184-329) **(211)**	230-470 **350**	(184-329) **(211)**
Balance of Plant (BOP) ($/kW)	80-120 **100**	(75-115) **(95)**	80-120 **100**	(75-115) **(95)**	80-120 **100**	(75-115) **(95)**	80-120 **100**	(75-115) **(95)**
Construction and Commissioning ($/kWh)	121-145 **133**	(115-138) **(127)**	92-110 **101**	(87-105) **(96)**	160-192 **176**	(152-182) **(167)**	105-126 **115**	(100-119) **(110)**
Total Project Cost ($/kW)	2394-5170 **3626**	(1919-3696) **(2674)**	1570-2322 **1876**	(1231-1676) **(1446)**	1430-2522 **(2194)**	(1275-2160) **(1854)**	2810-5094 **3710**	(2115-3440) **(2674)**
Total Project Cost ($/kWh)	599-1,293 **907**	(480-924) **(669)**	393-581 **469**	(308-419) **(362)**	358-631 **549**	(319-540) **(464)**	703-1274 **928**	(529-860) **(669)**
O&M Fixed ($/kW-yr)	10	-8	10	-8	10	-8	10	-8
O&M Variable (cents/kWh)	0.03		0.03		0.03		0.03	
System Round-Trip Efficiency (RTE)	0.75		0.86		0.72		0.83	
Annual RTE Degradation Factor	0.34%		0.50%		5.40%		0.35%	
Response Time (limited by PCS)	1 sec		1 sec		1 sec		1 sec	
Cycles at 80% Depth of Discharge	4000		3500		900		3500	
Life (Years)	13.5		10		2.6	(3)	12.5	
MRL	9	(10)	9	(10)	9	(10)	7	(9)
TRL	8	(9)	8	(9)	8	(9)	6	(8)

(a) An E/P ratio of 4 hours was used for battery technologies when calculating total costs.

MRL = manufacturing readiness level; O&M = operations and maintenance; TRL = technology readiness level.

The final investment cost is 354,346 €.

6.5.2 Opex of the scenario 2

Operating expenses (OpEx) are the day-to-day basis expenses that a company spends to keep its business operational.

Photovoltaic

The opex for photovoltaic system are calculated based on Renewable Energy Report written by Politecnico di Milano [30]. The report suggest to consider 25 €/kW of installed power, considering the 230 kWp installed the annual operational cost for the PV panels is 5750 €/year.

Battery

Regarding the storage fixed and variable operational and maintenance (O&M) are considered, the first one includes all the necessary to keep the storage system operational during its lifetime that do not depend on energy used, and it is normalized respect the power of the storage system and is expressed as €/kWh-yr. The second one includes all costs necessary to operate the storage during its lifetime and it normalized respect the annual discharge energy throughput. It is expressed as cents/kWh.

The HydroWIRES report [33] has been used and the fixed O&M is considered to be 2 €/kWh-yr. This value is taken from table 13 considering an E/P ratio of 4 hours is. The E/P ratio is the battery energy capacity divided by its power rating. The E/P ratio represents the duration the storage can operate while delivering its rated output. The variable O&M is considered to be 0.03 cent/kWh. Considering the size of the battery of 350 kWh and the annual total energy discharge 72,465.96[4] kWh the fixed opex are 700 €/year, while the variable opex are 21.7 €/year.

The following table 14 summarizes all the cost explained.

Table 14 – Capex and opex of the investment in the scenario 2

<table>
<tr><th colspan="3">Photovoltaic</th></tr>
<tr><td>Capex [€]</td><td colspan="2">Opex [€/year]</td></tr>
<tr><td>214,346</td><td colspan="2">5750</td></tr>
<tr><th colspan="3">Battery</th></tr>
<tr><td rowspan="2">Capex [€]</td><td colspan="2">Opex [€/year]</td></tr>
<tr><td>fixed</td><td>variable</td></tr>
<tr><td>140,000</td><td>700</td><td>21.7</td></tr>
<tr><th colspan="3">Total</th></tr>
<tr><td>Capex [€]</td><td colspan="2">Opex [€/year]</td></tr>
<tr><td>354,346</td><td colspan="2">6,472</td></tr>
</table>

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[4] Sum of the column “Energy discharged and self-consumed [kWh]” of the table 9

6.5.2 Net Present Value

The lifetime of the investment to address the NPV is considered to be 10 years because after this time the performance of the battery could change and a replacement might be needed. Once capex and opex are evaluated, in order to calculate the NPV, cash flows and discount rate need to be addressed. The cash flows are considered to be constant during the whole lifetime of the investment, they are calculated as the annual earnings of the REC (due to savings, sales and incentive) minus the yearly opex of the system. While, the discount rate is calculate considering the Weighted Average Cost of Capital (WACC):

Equation 14 – Weighted Average Cost of Capital

$$WACC = K_e \cdot \frac{E}{D+E} + K_d \frac{D}{D+E}$$

Where K_e is the equity cost and K_d is the debt cost and E and D represent the division of the investment.

Equation 15 – Equity cost

$$K_e = R_f + R_s + \beta \cdot (R_m - R_f)$$

R_f is the real risk-free discount rate referring to other possible and alternative investment (can be considered as the government bond at short term since it is the less risky investment), R_s is the small stock premium due to reduced liquidity (only for small investors), β is the sensitivity of a the specific investment rate of return to the market modification, R_m is the market return and R_m-R_f is the equity market risk premium (EMRP).

Equation 16 – Debit cost

$$K_d = (IRS + spread)$$

IRS is the interest rate swap, it represents the fraction of a fixed interest rate stock exchanged with a variable interest rate stock. The spread is the increasing of the interest rate depending on the capability of the investor to return the capital.

The table 15 summarizes the parameters chosen.

Table 15 – Parameters for the economical evaluation

Factor	Value

R_f	1.4 %[5]
R_s	0*
β	1*
EMRP	6 %[6]
IRS	1.86 %[7]
Spread	1 %*

Assuming a financial structure of the investment of 50 % equity and 50 % debt the WACC is 0.051.

Considering the equation of the Net Present Value in the section 4.1 and the discount rate just explained it is possible to calculate the yearly cash flows and the NPV after 10 years. In the table 16 results are shown.

Table 16 – NPV calculation results of the scenario 2

Year	Cash flow [€]	Actualized cash flow [€]	NPV [€]
0	-354346	-354346	-354346
1	102730	97745	-256600
2	102730	93002	-163598
3	102730	88489	-75109
4	102730	84195	9087
5	102730	80109	89197
6	102730	76222	165419
7	102730	72524	237943
8	102730	69005	306947
9	102730	65656	372603
10	102730	62470	435073

From the table is visible that the NPV after 10 years is 435,073.49 € and the actualized payback time is around 3.5 years.

The IRR calculated with the equation 6 is 0.26.

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[5] Source: [39]

[6] Source: [40]

[7] Source: [41]

* hypothesis

6.5.3 Share of the investment and incentive between of community members

According to section 1.5 where challenges and issues of the design and operation of the REC are proposed, in this paragraph a solution based on the exploitation of the system is proposed and it tries to address the following questions: how to divide the initial investment and the incentive? The equal division between residential and industrial members is correct? Does it lead to reasonable results?

Share of the Investment

First of all, to evaluate who is the most users of the energy self-produced, it is useful observe the electricity purchased from the grid pre (blue) and post (orange) installation of PV panels connected to a battery proposed in the figure 25. From the graph it is visible a drastically reduction of the energy purchased due to self-production, storage and self-consumption, especially from March to September where the production is more consistent. The total absorption from the national grid goes from 335,243 kWh to 105,638 kWh decreasing of 68.5 %.

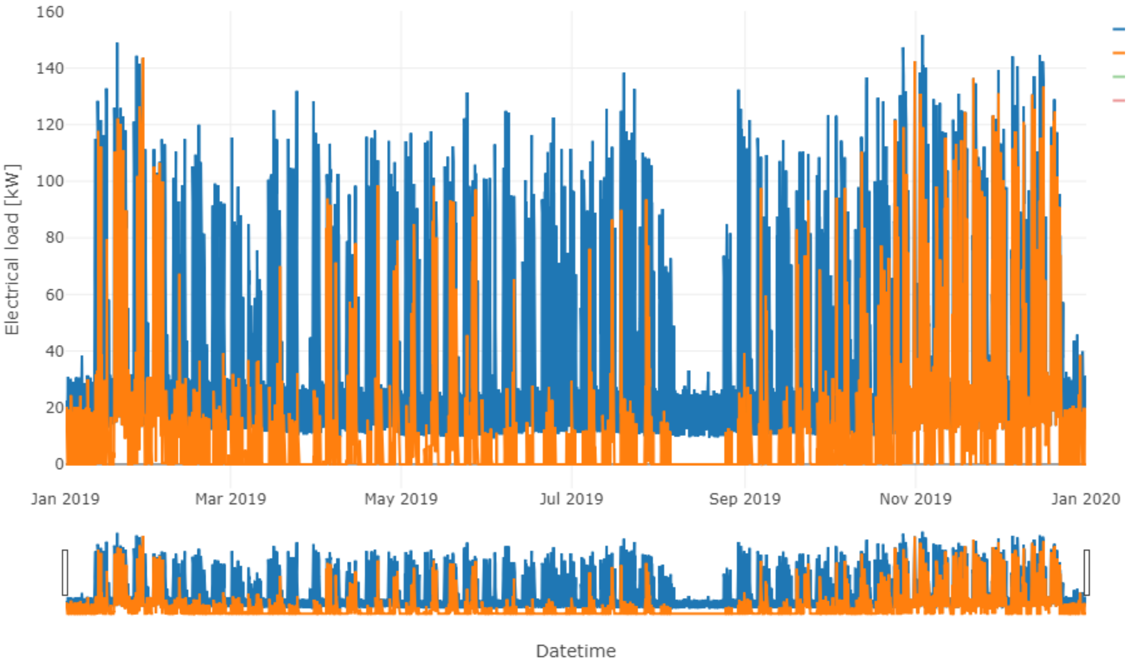

Figure 25 – Electricity purchased from the grid pre (blue) and post (orange) installation of BESS

Zooming on a week in April (figure 26) the reduction is impressive and when the system works at full capacity the industry absorption is reduced to zero, just a small night consumption is still needed from the national grid.

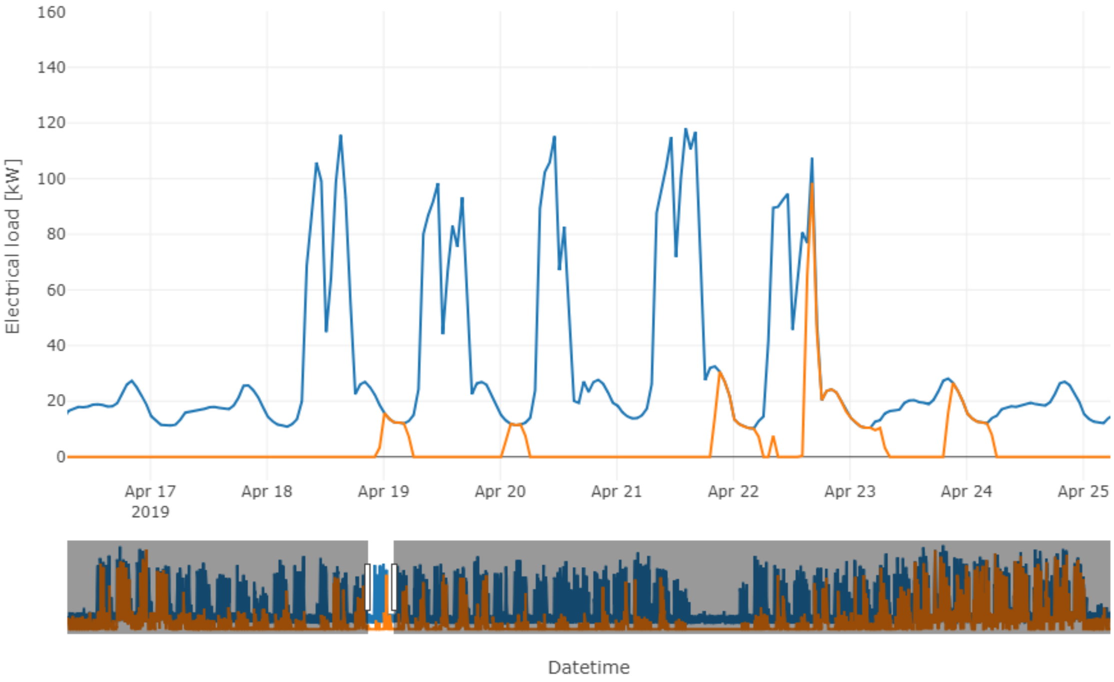

Figure 26 – Zoom of a week in April of the energy purchased from the grid pre (blue) and post (orange) installation of BESS

Looking at the summer the month of August where the industry is closed for vacation and the consumption remain is only residential the system is able to supply the entire amount of energy needed (figure 27).

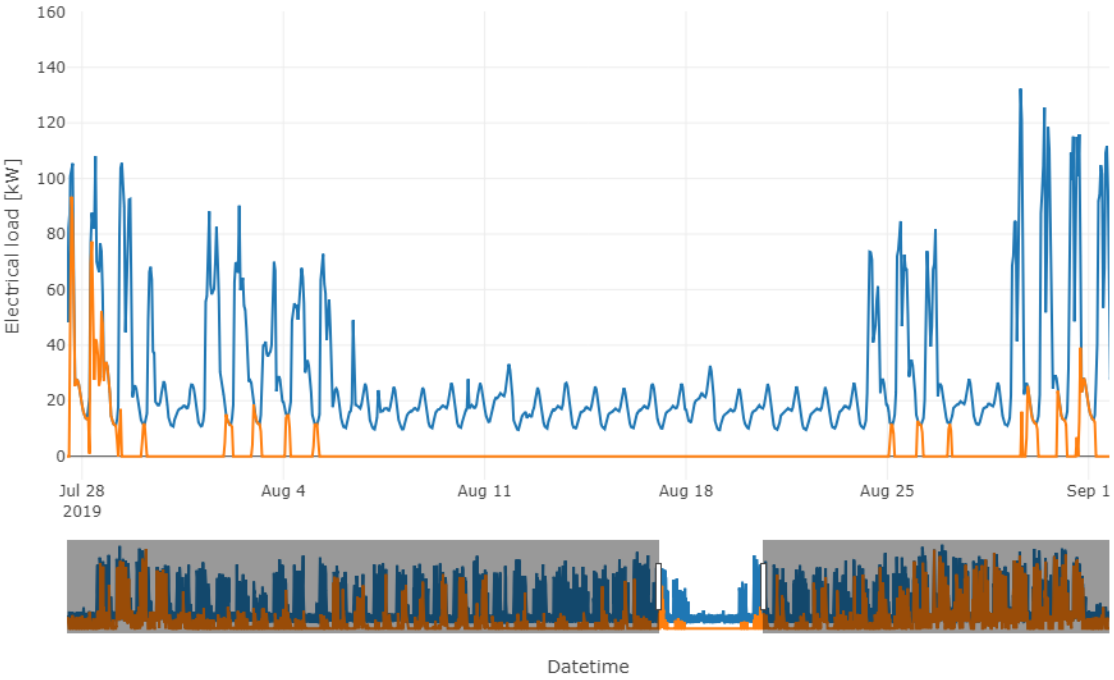

Figure 27– Zoom on the summer holidays of the energy purchased from the grid pre (blue) and post (orange) installation of BESS

However, from only these graphs is difficult to evaluate who uses more energy and how to divide the investment and the incentive. Thus, in order to have a better understanding a deeper analysis on the energy used is carried out. Starting from the baseline, the scenario zero without any PV or storage installations, and knowing residential, industrial and total consumption, it has been calculate the percentage of energy used by residential and industrial every hour. The assumption now made is that this proportion remains unchanged after the installation of PV and storage. This hypothesis is reasonable because the total amount of energy needed before and after the installation is the same and it is assumed to supply energy with PV and storage proportionally with the energy demand. Thus, to understand how much self-produced energy has been used from residential and industrial the proportion has been reported on the final energy purchased from the grid after the installation of PV and storage. The total amount of post energy purchased for residential and industrial is now calculated. In this way, looking on who has the most reduction of energy purchased, is possible to understand who exploits the system the most and has more advantages.

The residential yearly total consumption of grid energy goes down from 129,341 kWh/year to 44,995 kWh/year having a reduction of 65.2 %. On the other hand, the annual industrial total consumption of grid energy goes down from 205,901 kWh/year to 60,643 kWh/year, with a decrease of 70.5 %. In conclusion, looking the column *"Instantaneous self-consumption REC [kWh]"* in the table 8 and the column *"Energy discharged and self-consumed [kWh]"* in the table 9 the annual total energy self-produced and collective self-used (instantaneously or stored and used later on) is 231,055 kWh/year, and the industrial uses 63.3 % respectively 145,258 kWh/year, and the residential uses 36.7 % respectively 84,347 kWh/year. Thus, the system is not equally exploited and the division of the investment proposed is based on this latter calculation.

Considering the total investment of 354,346 € the industrial share is 224,174 €, while the residential share is 130,172 €. Remembering that the residential part is composed from 50 families it is possible to divide the residential share by 50 and to obtain the share of each family which is 2,603 €.

Share of Incentive

According to [34] the incentive could be divided according to three mechanisms. The first one considers the ownership shape of the generation power plant, the second one is proportionally to the actual contribution to self-consume the energy generated by the community members, the last one considers both the ownership and the contribution to self-consume. However, since the initial investment as well as the annual savings are different between residential and industrial, it has been decide to propose a different sharing mechanism where the division of the incentive leads to the same simple payback time for residential and industrial.

In order to calculate the SPB the "earnings" from the use of the energy self-produced are calculated both for residential and industrial. Monthly savings are calculated as the different of the energy used in the baseline (without any system) minus the energy used with PV panels and battery, this difference is then multiplied by the PUN in order to have the cost of the energy saved (equations 17 and 18).

Equation 17 – Industrial savings

$$savings_{ind} = \sum_{i=1}^{12} \left(consumption_{ind,baseline,i} - consumption_{ind,PV+BESS,i}\right) \cdot PUN_i$$

Equation 18 – Residential savings

$$savings_{res} = \sum_{i=1}^{12} \left(consumption_{res,baseline,i} - consumption_{res,PV+BESS,i}\right) \cdot PUN_i$$

At these savings the annual earnings from sales of surplus (equations 19 and 20) are added and the total opex (equations 21 and 22) are subtracted. In order to divided earnings and opex between residential and industrial the percentages of exploitation of the system calculated above are used. Now, the only factor left is the incentive itself which is added with a goal search to have SPBT residential and industrial as equal as possible (equations 23 and 24).

Equation 19 – Industrial earnings from sales

$$earinings_{ind} = \left(\sum_{i=1}^{12} sales_i\right) \cdot exploitation\ fraction_{ind}$$

Equation 20 – Residential earnings from sales

$$earinings_{res} = \left(\sum_{i=1}^{12} sales_i\right) \cdot exploitation\ fraction_{res}$$

Where the exploitation factors are respectively 0.633 and 0.367 (calculated before).

Equation 21 – Industrial opex

$$opex_{ind} = \left(opex_{PV} + opex_{BESS,fix} + opex_{BESS,var}\right) \cdot exploitation\ fraction_{ind}$$

Equation 22 – Residential opex

$$opex_{ind} = \left(opex_{PV} + opex_{BESS,fix} + opex_{BESS,var}\right) \cdot exploitation\ fraction_{,res}$$

Equation 23 – Industrial simple payback time

$$SPBT_{ind} = \frac{investment_{ind}}{savings_{ind} + earnings_{ind} - opex_{ind} + incentive_{ind}}$$

Equation 24 – Residential simple payback time

$$SPBT_{res} = \frac{investment_{ind}}{savings_{res} + earnings_{res} - opex_{res} + incentive_{res}}$$

The goal search leads to have a SPBT of 3.55 years for the industry with an incentive share of 60 %, while the SPBT of the residential is 3.53 with the incentive share of 40 %.

In conclusion, the yearly industrial incentive is 21,589 €, while the yearly residential incentive is 14,393 €. Dividing the residential part it is possible to obtain the single family share which is 288 €.

7 Discussion of the obtained results

In this section a comparison and discussion of the baseline scenario and the scenario 2 is carried out. The discussion aims to highlight advantages and disadvantages of the two configurations. The comparisons analysed are: total energy sold to the grid, total energy collective self-consumed, incentivized energy and total REC savings.

In the following figures the baseline scenario is represented in blue, while the scenario with PV panels and BESS is represented in red. Where is necessary in green is represented the PV production as benchmark for the two scenarios.

The first comparison discussed concerns the energy sold to the grid (figure 28). In the baseline the energy sold to the grid is always more than the scenario 2, this is due to the energy stored in the battery and collectively self-consumed later on. At first impact selling more energy could be seen as an advantage, however selling less energy is better because the energy not sold is collectively self-consumed. The more energy is collectively self-consumed the more is the incentive and the less is the energy purchased to the national grid. In both scenarios the energy is sold the most in August where the production is high while the consumption is low due to summer break. During the winter the energy sold to the grid is extremely low due to less production and high consumption, the limit is reached in November where the energy sold is close to zero.

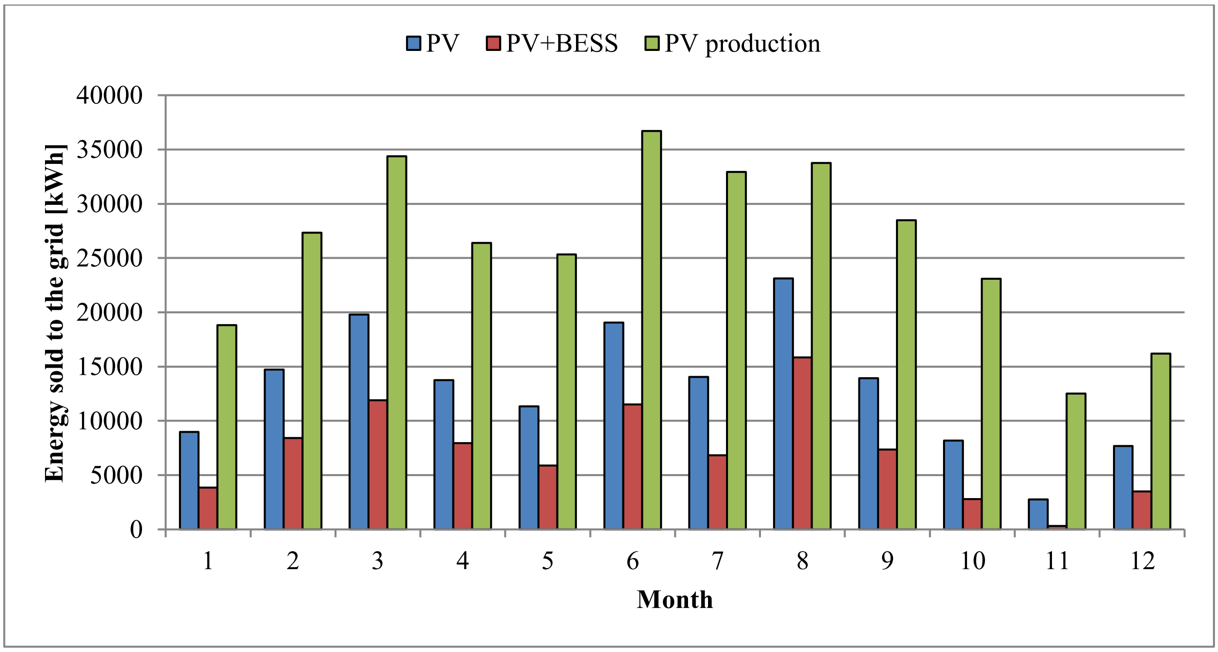

Figure 28 – Comparison of the energy sold to the grind in the two scenarios

With the baseline configuration almost every month half of the production is sold to the grid and the remaining half is collectively self-consumed. The situation change drastically installing the battery, in this case the energy collectively self-consumed increase a lot and brings the advantages mentioned above. The increase in collective self-consumption is clearly visible in figure 29, while the incentive is shown in figure 30.

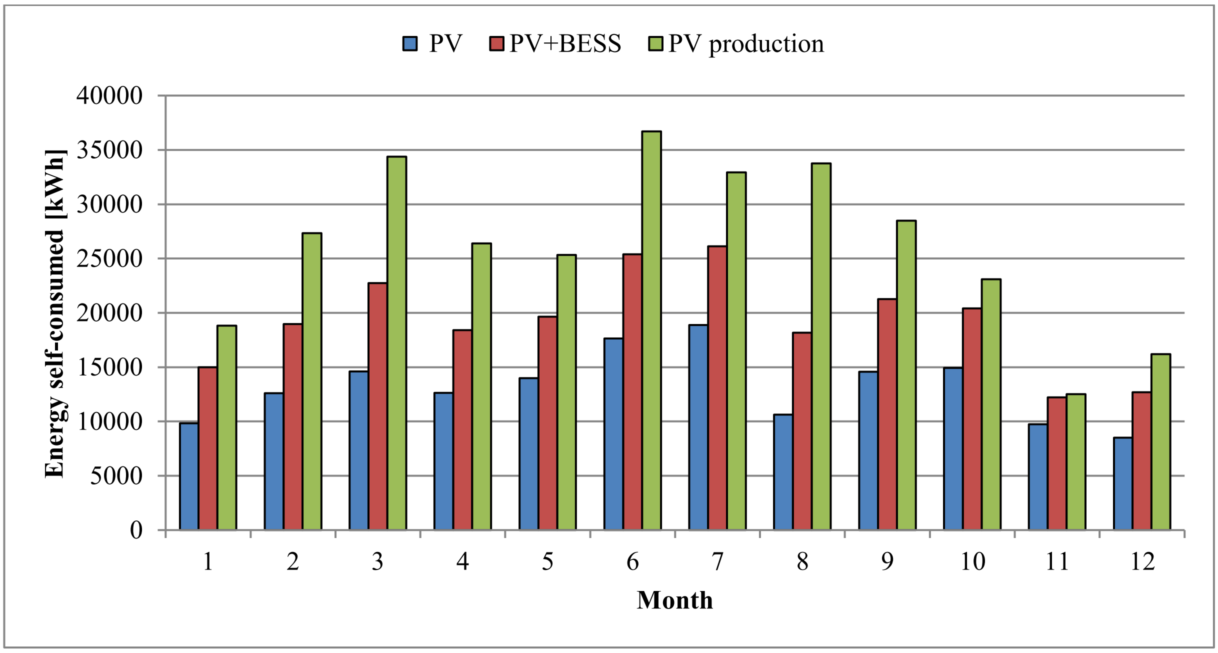

Figure 29 – Comparison of the energy self-consumed in the two scenarios

As mentioned before, the installation of the battery leads to more energy collectively self-consumed. Since the incentive is based on production and energy collective self-consumed (section 1.3) the installation of the battery allows to almost double the incentivized energy. The figure 30 shows the comparison between the two scenarios. In both scenarios the incentivized energy is maximized in June and July where production and consumption are at their highest level because PV panels work at full capacity and the and there are no vacations that stop the industrial production.

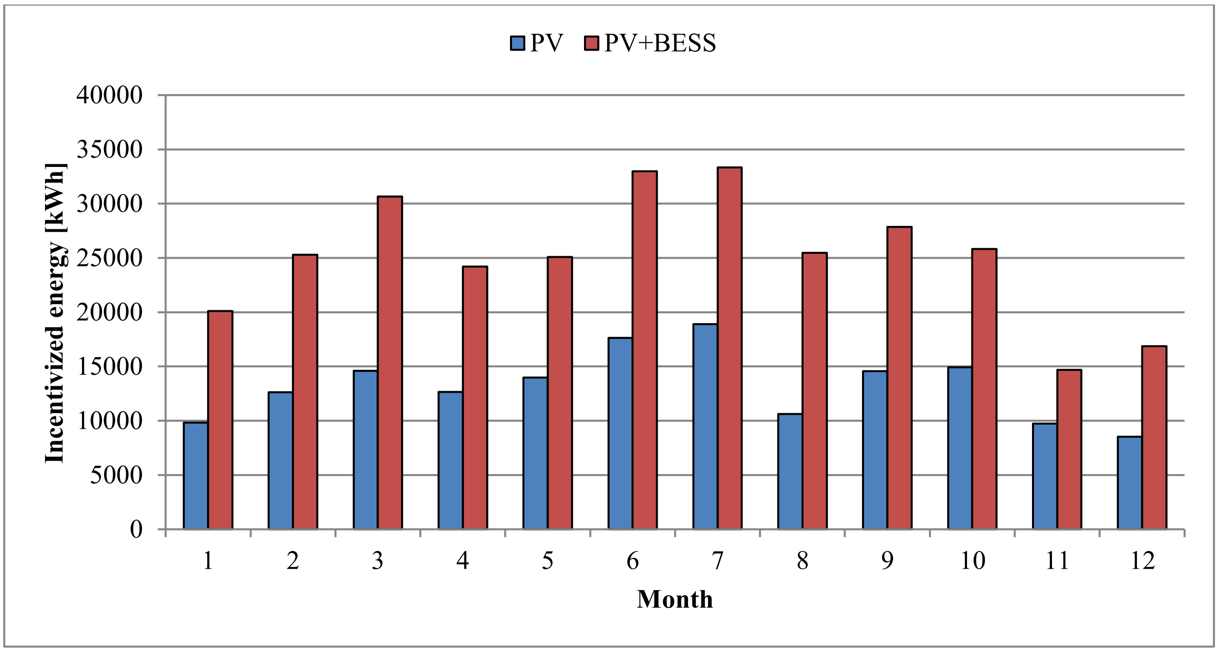

Figure 30 – Comparison of the incentivized energy in the two scenarios

Finally, in the figure 31 the comparison between REC savings in both scenarios is represented. These savings come from the energy self-produced and collectively self-consumed and hence not purchased from the grid. Since the savings depend from the energy purchased the trend follows the PUN swing visible in table 3, with a flat price the savings trend should be exactly the same of the energy collectively self-consumed (figure 29), however in both scenario the trend is distorted by the PUN and the maximal savings is visible the in October where the PUN is higher (figure 31). In conclusion, even in this comparison the installation of a battery leads to better result.

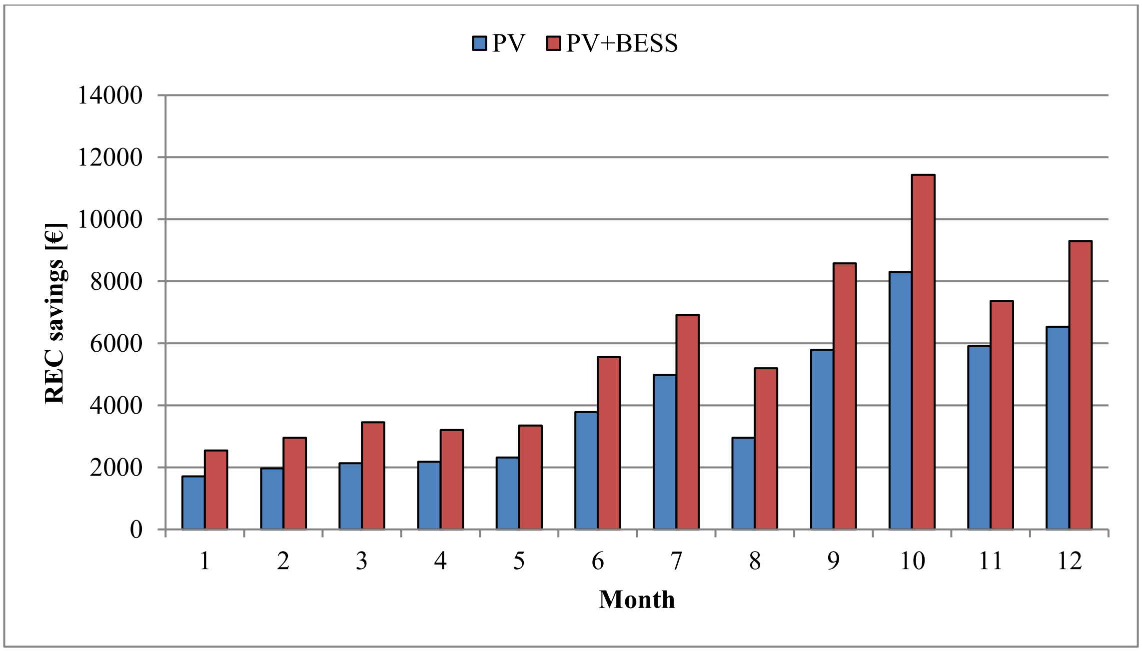

Figure 31 – Comparison of the REC savings in the two scenarios

In conclusion, if the installation of a battery brings only advantages in terms of energy why is not so spread around Italy? First of all, the application of the technology is relatively new and the costs were and still are really high. Moreover, not many studies were carried out and it is not easy to evaluate all the advantages of the storage system. In conclusion, really few investors are willing to pay more than three hundred thousand euros without being sure of the return of the investment. On the other hand, it is easier to evaluate advantages of an investment of only PV panels where the operation of the battery is neglected. In the appendix 4 the economic analysis of the baseline scenario is shown and the investment calculated is extremely lower than the scenario 2 with the battery, furthermore the opex are halved. The payback time of the investment is again around 3.5 years, but the NPV is lower. The last interesting factor is the IRR which is higher in the baseline scenario comparing with the scenario 2. In the first case is 0.29, while with the battery is 0.26. The difference is not much and they are both extremely high meaning that both investment are recommended.

8 Future work and Conclusion

8.1 Limitations, considerations and improvements for future work

In this study some limitations have been found which have restricted the research under few aspects. First of all, the photovoltaic energy production is strictly linked to the climate file and the year considered. Furthermore, the simulation of the residential energy consumption is based on the European study presented and hence can be taken into consideration as main line and not as specific case, in order to have a specific evaluation smart meters need to be installed in the desired buildings. Also the industrial energy consumption obviously depend on the file imported and a different company may lead to a different values.

Beside this aspects, the methodology process proposed is valid and useful for the evaluation of preliminary simulation for energy communities and more important for investors, companies and families who want to evaluate the possibility of a renewable energy community. In fact, knowledge and forecast on energy produced, consumed and shared makes easier the evaluation of the investment and the possibilities of different design scenarios. Companies and investors benefit from such simulations because knowledge of the energy framework of the community and the cash flows related to the investment allows the implementation of targeted strategies to improve growth of the company or to maximize the investment. While families can verified utility and efficiency of the small investment before undertake it.

To improve this study and further analyse the advantages of a renewable energy community a few extra considerations can be addressed. First of all the integration of Superbonus 110% and tax reduction into the economic evaluation. Then, a deeper analysis on specific capex and opex may improve the study. Moreover, a sensitivity analysis on the PV system size could be interesting for the economic and energy evaluation. Successively, in this study the battery and the PV panels are purchased from the whole community and they work for the benefit of the community itself. Hence, the energy charged and discharged depends on the consumption of the whole community. Another interesting scenario that could be interesting to evaluate is when the investment is made only by the industrial thus the PV panels produce and the battery charges based only on the industrial energy consumption. In this scenario the families do not have to pay for the investment and they benefit from the incentive but all the earnings are for the company. The third interesting scenario is an hybrid case where the photovoltaic panels are purchase by the whole community while the battery is purchased by the company. In this configuration families can take advantage from the instantaneous self-consumption but the battery operates only for the company, thus charges and discharges when is needed from the industry. However, in this hybrid configuration, it is necessary to well define some boundaries to avoid exploitation by the company of energy of the families.[8] The last possible scenario is the evaluation of the investment by an external organization of the energy community. In this case the total investment and hence the management of the system is made by and external organization that covers all the expensive based on the agreement decided. Alongside these scenarios, the implementation of other technologies such as micro turbine, micro cogeneration or hydroelectric system can be addressed and evaluated. Finally, different sharing mechanisms could be implemented to improve the study.

8.2 Conclusion

In this study the Renewable Energy Community is proposed and evaluated in order to suggest an alternative way to large power plants dependent by fossil fuels. The diffusion of RECs, and hence the installation of small renewable power plants, may help toward the European target of “carbon neutrality” of 2050. Moreover, the direct citizens involvement in to the energy community improve their awareness of energy savings and the necessity to reduce greenhouse gasses.

In particular, in the thesis is developed an Energy Information System for renewable energy communities which can help on energy and economic analysis in the early stage of an energy community design. The methodology is explained and then utilized to address a case study.

First off all, the problem to have a reliable simulation is addressed. Residential houses seldom have smart meter installed and to know the real trend of the energy consumption is nearly impossible due to lot of variables such as the type of families, the number of components, the household appliances in the house and the use of them. However, by linking together the ISTAT report on Italian families and a European study on the residential energy consumption it is possible to obtain a reliable framework of the

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[8] E.g. if photovoltaic system of the families has a surplus the industry cannot charge its battery even though is better to charge the battery than to sell to the grid.

hourly annual consumption of the residential starting from the number of families. Regarding the industrial energy consumption it is easier to obtain real data from the field since the Italian regulation obliges to install start meters.

Then, after the evaluation of the size of the PV system, an algorithm which maximized the NPV after 10 years propones the best size of the battery storage system.

Successively, the energy strategy of the PV production and the battery storage is exposed. The management strategy takes into consideration that both the PV system and the eventual storage are financed by the whole community and therefore owned by the entire community. It is considered to maximize the instantaneous collective self-consumption of the community and to use the surplus energy to charge the battery. When the battery is fully charged the energy is sold to the national grid. With this configuration it has been demonstrated that the incentivized energy is maximized too. In order to have a fair distribution of the investment it was proposed to divide the costs according to the use of the self-produced energy. Finally, the incentive is divided to have the return of the investment equal between residential and industrial. The NPV is utilized to evaluate the investment in a time period of 10 years that is the life cycle of the battery. In order to evaluate the cash flows are considered as savings the energy not purchased from the grid, the incentive and the earnings from the energy sold, while are considered as costs the initial investment and the operational and maintenance costs.

The methodology proposed is then applied on a case study. The renewable energy community located in Castel Maggiore is composed by 50 families and a small company. The annual energy consumptions are respectively 129,342 kWh and 205,900 kWh. The PV system considers has a power of 230 kWp and the optimization algorithm proposes as best size of the battery 356 kWh, thus a comparison between the baseline scenario without battery and the scenario 2 with a battery of a capacity of 350 kWh is carried out. The analysis shows better performances of the scenario 1 with the battery under basically all the aspects considered. The energy sold to the grid decrease of 54 % and goes from 154,335 kWh/year to 86,177 kWh/year, while the self-consumed energy increase of about 46 % and passing from 158,589 kWh/year to 231,055 kWh/year. These changes leads also to an increase of the incentivized energy of nearly 91 %, from 158,589 kWh/year to 302,365 kWh/year. At last, the total annual savings increase of about 48 % going from 73,574 €/year to 109,202 €/year. Regarding the investment both scenarios present a positive NPV with a return of the investment around 3.5 years. The NPV of the scenario 2 is extremely higher and reaches 435,073 € after 10 years. However, the investment is greater, about 354,000 €, and divided between residential and industrial in shares based on the utilized of the self-produced energy, about 37 % and 63 %. In the end, the incentive is divided in order to have equal return of the investment between residential and industrial with shares of 40 % and 60 % respectively. In conclusion, considering both energy and economical results, even though the initial investment is greater, it is preferable to install a PV system connected with a battery energy storage system in order to maximize collective self-consumption and economical return.

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10 Appendices

10.1 Appendix 1 – Average consumption of Italian families based on number of components

Table 17 – Average consumption of Italian families depending by family components and facilities **[21]**

Family components	Household appliances and electrical appliances	Annual consumption of electricity [kWh / year]
1	TV, computer, fridge, washing machine + 1 air conditioner	1400
2	TV, computer, fridge, dishwasher, washing machine + 1 air conditioner	2000
	TV, computer, fridge, dishwasher, washing machine + 2 air conditioners + electric water heater	2700
3	TV, computer, fridge, dishwasher, washing machine + 2 air conditioners	3300
4	2 TVs, 2 computers, fridge, dishwasher, washing machine + 2 air conditioners + electric water heater	3600
5	2 TVs, 2 computers, fridge, dishwasher, washing machine + 3 air conditioners	5200

10.2 Appendix 2 - Boxplot of load profile segments of the 5 clusters identified in the "Load Profile Classification" by NatConsumers

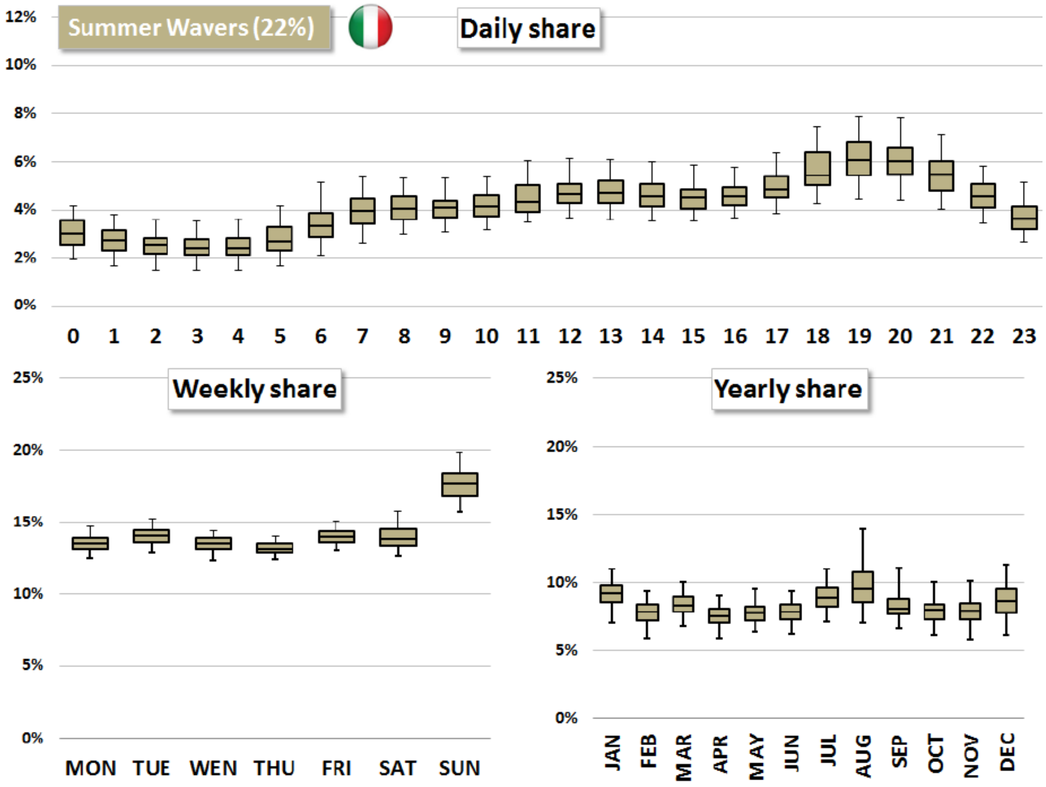

Figure 32 – Boxplot of load profile segments, Summer Wavers segment. Source: **[22]**

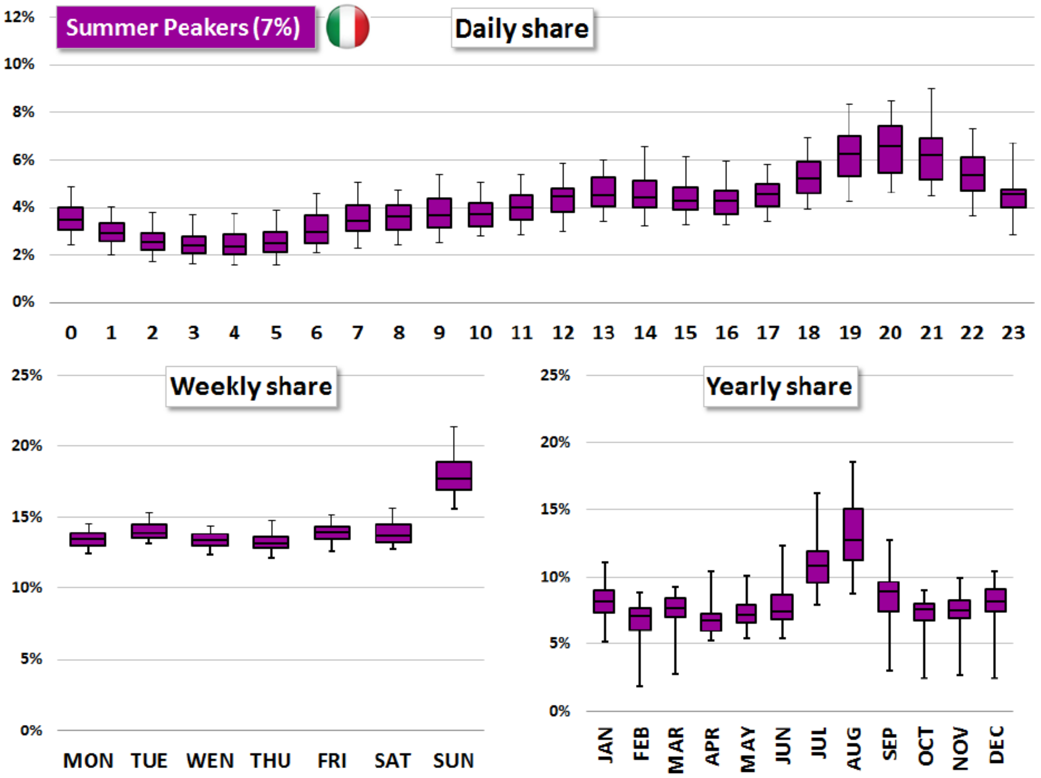

Figure 33 – Boxplot of load profile segments, Summer Peakers segment. Source: **[22]**

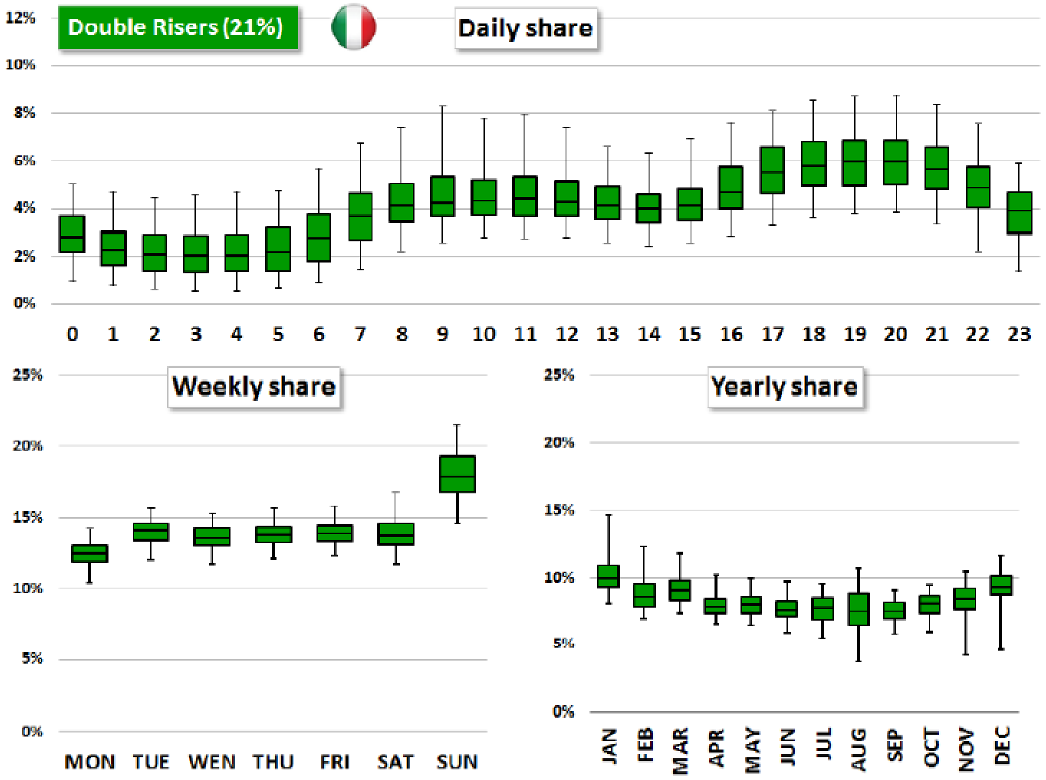

Figure 34 – Boxplot of load profile segments, Double Risers segment. Source: **[22]**

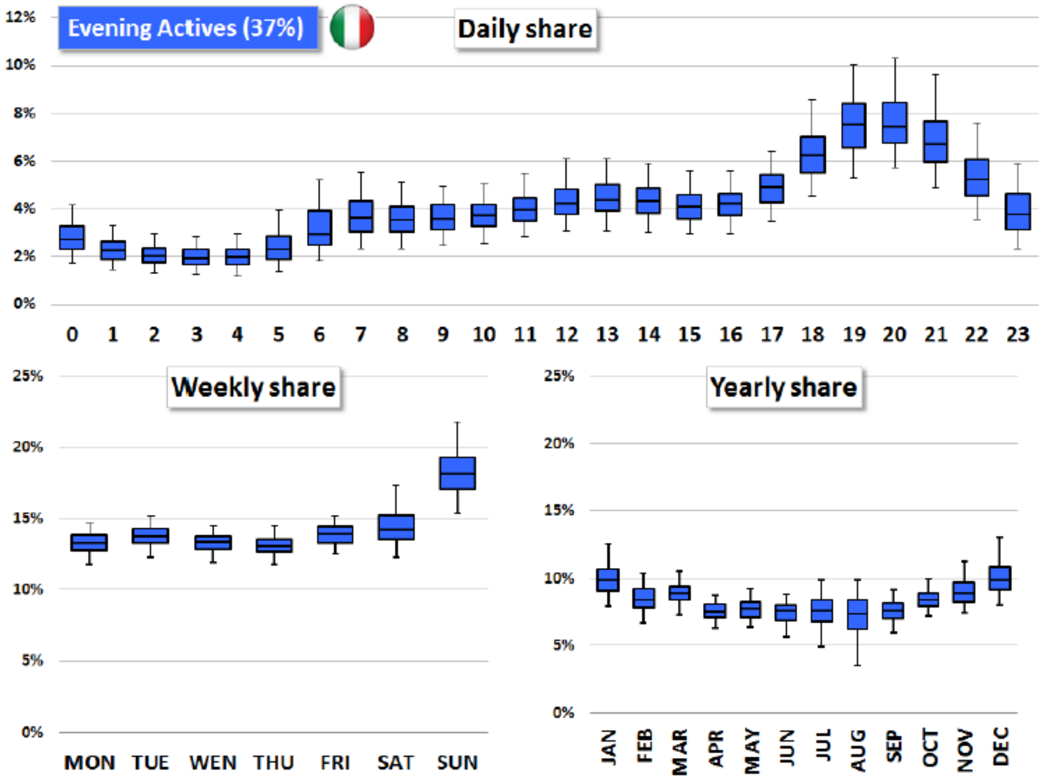

Figure 35 – Boxplot of load profile segments, Evening Actives segment. Source: **[22]**

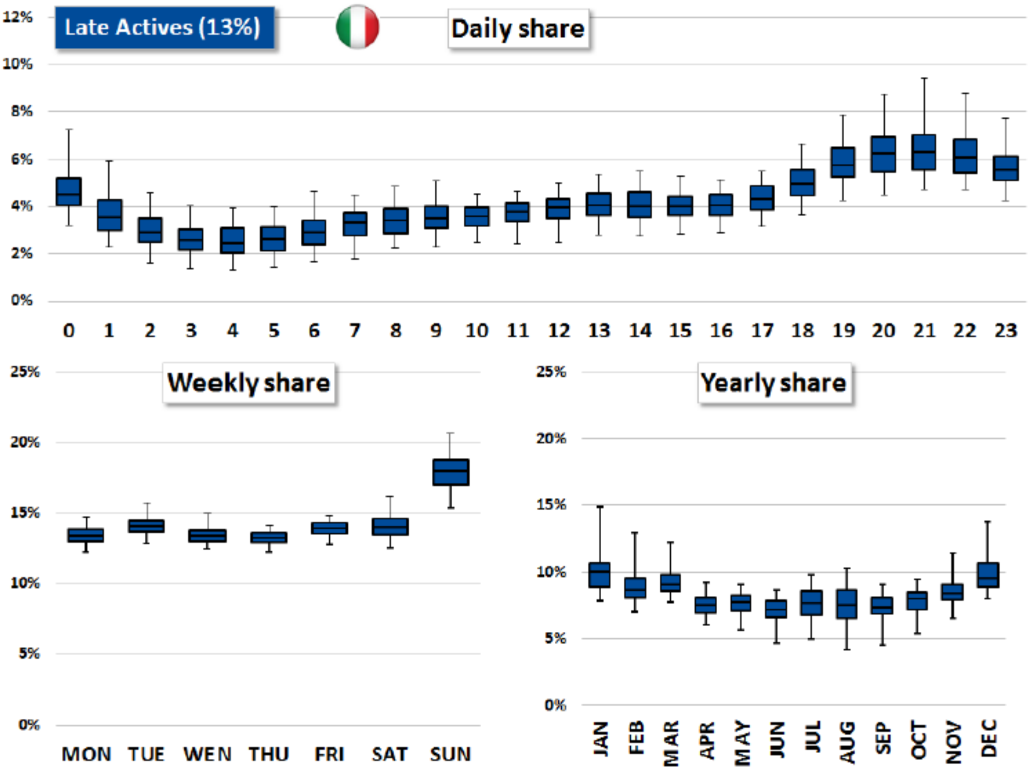

Figure 36 – Boxplot of load profile segments, Late Actives segment. Source: **[22]**

10.3 Appendix 3 – Electric bill structure

Table 18 – Electricity bill structure

Costs	
Sale services	Energy (raw material)
	Dispatching (system regulation)
Grid services	Transport (grid use)
	System charges
Taxes	Taxes

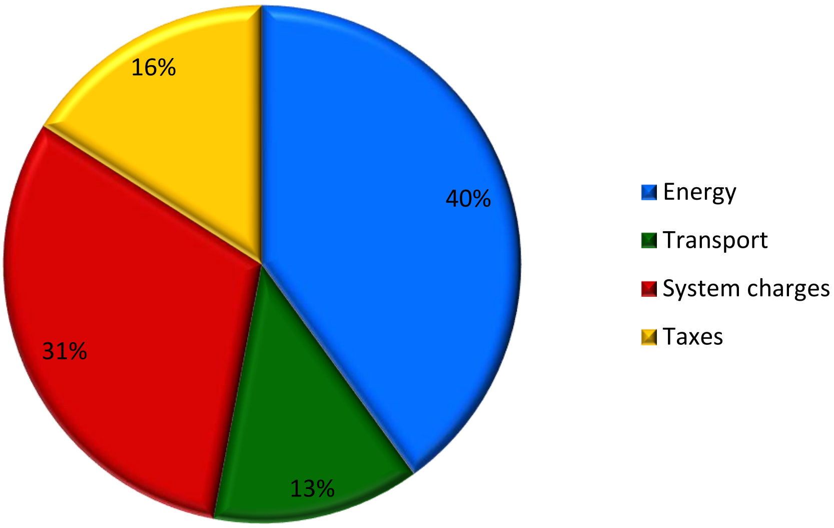

Figure 37 – Example of electrical bill shares

10.4 Appendix 4 – Economic analysis baseline scenario

Table 19 – Capex and opex of the scenario 1

Photovoltaic	
Capex [€]	Opex [€/year]
214,346	5750

Table 20 – Net present value calculation results, scenario 1

Year	Cash flow [€]	Actualized cash flow [€]	NPV [€]
0	-214346	-214346	-214346
1	67824	64533	-149813
2	67824	61401	-88411
3	67824	58422	-29989
4	67824	55587	25598
5	67824	52889	78487
6	67824	50323	128811
7	67824	47881	176692
8	67824	45558	222249
9	67824	43347	265597
10	67824	41244	306840

Internal rate of return: 0.29