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Energy Engineering

CRITERIA FOR THE OPTIMAL AGGREGATION OF USERS IN AN ENERGY COMMUNITY

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ABSTRACT:

The thesis delves into the economic feasibility of energy communities, initially focusing on a specific type, where an investor, with available space, installs a photovoltaic system and is willing to share a portion of the energy produced. The primary goal is to establish criteria for selecting users to form an energy community. As the incentive plays an important role in the economics of the EC, a critical discussion about the values of incentives set by governments is carried out. The findings highlight the strong dependence of incentives on electricity prices, and it emphasizes how the criterion used to identify the best energy community evolves when there are changes in the allocation of the money earned from the shared energy incentive among community users. If the earnings are divided equally among all the aggregated users and the investor, the optimal energy community comprises the aggregation of office users, given their peak electrical demand during daylight hours. In this scenario, users can save approximately 18%, in respect to their expenses with all imported energy from the grid. However, a single office can save an additional 15% by installing its own photovoltaic system and self-consuming electricity, resulting in a total savings of 30% compared to an all-imported energy scenario. By changing the way earnings from incentives are allocated, the criterion for selecting users becomes clearer. A portion of the money obtained from energy sharing among users needs to be guaranteed to community members to convince them to join. This guaranteed amount is calculated as the difference between business-as-usual operation (all energy imported) and the optimal single-user operation (imported energy + photovoltaic system). In this scenario, the investor prefers to aggregate residential users due to their lower ability to self-consume electricity (residential saves 22% by installing PV, while office saves 34%, and commercial saves 29%). Given the strong dependence of the incentive on the price of electricity, if the incentive is fixed, energy communities become less effective. With 110 €/MWh incentive and electricity price set at 250 €/MWh, the best energy community results in only exploiting 7% of the total energy produced by the PV system (i.e., 93% is not used locally but spread on the grid), leading to a meagre earning of 120 €/y for the investor. Moreover, from an environmental standpoint, the results are not favourable, as the indirect emissions caused by the imported energy + photovoltaic system installed (life cycle) are more than double in the "best" energy community compared to the single operation of the same number of users (16148 kgCO2/y in the best energy community operation and 7630 kgCO2/y

in the single residential user operation with 5 users), due to the lower percentage of photovoltaic energy exploited. Considering all these factors, a new incentive is proposed at the end of the thesis. The incentive comprises a fixed part and a variable one that changes in relation to the amount of energy produced by PV that is effectively exploited (both changing linearly with the electricity price). With this new incentive, if at least 60%-70% of the photovoltaic energy is shared inside the community, both on the economic point of view and on the environmental front, results are more convincing. Indeed with:

- 150 kW PV installed.
- 250 €/MWh electricity price.
- 110 + 9 €/MWh fixed part of the incentive.
- 70 €/MWh * % exploited PV energy produced (incentive variable component).

the investor earns around 1000 €/y with 56 residential users aggregated, while emissions are equal to 85436 kgCO2/y. On the other hand, the same 56 residential users operating alone emits, overall, 85456 kgCO2/y.

NOMENCLATURE:

- Agg = aggregation of user
- COM/comm = commercial user
- EC/ECs = Energy community/communities
- HP/hp = heat pump
- Mmg = minimum money that the investor has to guarantee to the users in the EC
- OFF = office user
- PV = Photovoltaic
- PEXC = energy shared among the EC’s users
- PEXP = exported energy to the grid
- PIMP = imported energy from the grid
- RES = Residential user
- TES = thermal energy storage

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Chapter 1 - Introduction

The installation and use of renewable energy generation plants has increased in the last 20 years. This was supported by the EU programs for the decarbonization of the energy generation and carried on by incentives and politics in some of the EU countries. The main targets set by the Community are the reduction of the emissions for the 2030 and 2050, in which the most important goal will be the 55% greenhouse gas emissions reduction respect to the year 1990 levels (as explained in [1]). Anyway, the way to go is the one indicated by the energy outlook in [2]. In recent years, significant progress has made renewable energy sources, particularly photovoltaic, both cheaper and more widely available. However, common citizens still find the investment unattractive. Furthermore, decarbonization does not directly involve the majority of the population due to their lack of information and knowledge on the topic. To incentivize new PV plants installations, the concept of "Energy Communities" is becoming increasingly valuable. Energy communities are defined as "legal entity…based on open/voluntary participation effectively controlled by shareholders members…. the primary purpose is to provide environmental, economic, or social community benefits for shareholders / members and the local area where it operates" [3]. The way in which users' behaviour changed during last years, make Energy Communities currently more newsworthy and promising for the decarbonization. Indeed, normal households with photovoltaic panels are acting as both consumers and producers depending on the amount of energy demanded and produced. In literature they are called "prosumers"[4]. Practically, a consumer self-consumes the energy from its own system and purchase the electricity from the grid. His role changes when the photovoltaic system produces a surplus of energy moving part of the energy from the house to someone else. The consumer is now considered as a producer. A well-executed aggregation of a couple of users with complementary load curves can perfectly match the energy requests. The advantage lies in having surplus of energy produced by one of the two systems when the electrical demand of the second user is too high. This benefit is both economic and environmental. On one hand, users will pay lower bills for the reduced energy purchased from the grid. On the other hand, reduced grid usage translates into fewer losses and less energy usage [5]. Basically, the principle of work of an energy community is simple. All the aggregated users purchase electricity from the grid, meanwhile, the main PV system produces electricity and sell it in the grid. The energy produced and consumed in the same time-step is then considered as virtually self-consumed by the community. This shared energy is calculated as the minimum, in each our, between the energy produced and the energy purchased from the gird by the community and it is rewarded via incentive.

1.2 Literature review

Despite being a relatively recent topic, many articles and studies related to energy communities can be found in literature. To start, in [6] conducts a study discussing the benefits of these new type of communities, stating that “increase the acceptance of renewable energy” and “the most substantial local impacts are associated with indirect project outcomes and investments of project revenues in the local community”. [7] Analysed the positive aspect with respect to EC stating that consumers provide significant value in the energy sector transformation due to their potential to bring about distributed generation. They also mention that “energy communities enable consumers to jointly pursue their individual and collective economic, environmental and social goals while simultaneously contributing to the decarbonization of the energy system". Other authors have discovered that this type of aggregation could be a valuable tool for accrediting vulnerable consumers [8]. Simple consumers role is not to be taken lightly, as [5] demonstrate. They contribute to the self-consumption of the PV by consuming the generation surpluses that otherwise would be “lost”. This leads to an advantage for both prosumers and consumers through higher incentive revenues. Retrofitting buildings alone could lead to faster emissions reduction, considering that the European building stock is old and inefficient, accounting for approximately 40% of EU energy consumption and 36% of emissions [9] . Furthermore, if this initiative is supported by energy communities, the benefits would be even greater.[10] discussed about the energy community as a way to incentivize the shared energy storages among the aggregated users, thereby promoting further aggregations. [11] investigated the profitability of having PV availability in an energy community compared to stand-alone user operation, concluding that “profitability increases when forming EC the more different are the load profiles”. Energy communities are beneficial for exploiting complementarity in load curves when two or more prosumers' generation units complement the corresponding electrical demand profiles [12]. Examples of energy communities’ simulations can be analysed in [13],[14] articles. An interesting case is the Berchidda municipality in Sardinia, as studied in [15], where a smart local energy community was designed to increase energy efficiency by boosting local renewable generation production and consumption, particularly maximizing self-consumption during production hours. The role of active consumers was further enhanced through the implementation of a home automation system, including demand response applications. A similar model was suggested by [16], where the paper introduced a hybrid microgrid model based on DC power sharing generator for residential buildings. In this scenario, the microgrid lead to a benefit for end-users in the form of reduced energy costs, while also benefitting the distributor through increased demand flexibility. [17] analysed the behaviour of a PV sharing system between two offices, each which its own loads, PV system, heat pumps and electric vehicles. The aggregation's results were very highly favourable, leading to increased utilization of the photovoltaic energy, reduced imported energy and lower greenhouse gases emissions. Interestingly, both offices have similar loads. Similar results but with different load curves can be found in paper by[11] which studied a community with heterogeneous loads. In this case the concept of "best aggregation" appears to be conflicting compared to the aggregation of the two offices, where similar loads seem to fit together well.

1.3 Novelty

As seen in the previous chapter, there is no specific and well-defined method or idea for creating energy community. Some communities have aggregated loads that are similar in terms of their load curves shape, while others have aggregations where users' load curves complement each other. The goal of the thesis would be to find a simple criterion that permits the faster identification of the best possible aggregations. For instance, investors or individuals with abundant photovoltaic resources who aim to maximize their profits by selling their solar energy production to community members, while also benefiting from incentives, would greatly benefit from a clear understanding of which users to include in their aggregation. Likewise, potential community members who are contemplating whether to join an energy community or install their own photovoltaic system on their rooftops would appreciate insights into the economic advantages of each choice. Furthermore, the value of the incentive itself warrants critical examination and analysis. Indeed, is not clear if incentive for energy communities is a tool who benefits the whole society. Since all the population is paying for the taxes and so for “support” the incentive, it is not clear if the advantages would directly affect the entire society or only those already benefited. Summing up, the primary objective of this thesis is to establish a criterion for the selection of users to aggregate in an energy community. The key topics to be analyzed include:

1. **Number and type of users:**
    - Investigating the number and types of users that an investor, equipped with photovoltaic panels, should engage to form an energy community. Different user types are considered, distinguished by their "curve shape," representing characteristic load curve distributions throughout a typical day. For instance, residential users exhibit higher loads during midday and evening, while office users experience elevated loads in the afternoon with lower consumption during the night.
2. **User willingness to join:**
    - Assessing whether the users targeted for aggregation in the ECs are inclined to participate in the project. Examining factors such as whether users are more likely to operate independently or if they express interest in joining the community. Additionally, exploring whether users inclined to join are the ones economically disadvantaged or users already financially secure.
3. **Incentive value and structure:**
    - Delving into the significance and structure of the incentive. Evaluating whether the incentive's value is compelling enough to encourage individuals to become part of the community.
4. **Environmental implications:**
    - Determining if there is a necessity to share all the energy produced with community members from an environmental standpoint. Specifically, comparing the operational practices of stand-alone users (those who install their own PV system) with the behavior of an energy community.

By addressing these key aspects, the thesis aims to contribute valuable insights into the strategic considerations and decision-making processes involved in the formation and sustainability of energy communities.

The thesis will be organized into several chapters. In chapter three, all the input data necessary for achieving the final results will be detailed. The fourth chapter, serving as the core of the thesis, will contain all the formulations and a portion of the Python code utilized for analysing the behaviour of these communities. This will be followed by a chapter presenting the most significant results obtained and another dedicated to a sensitivity analysis, wherein certain results will be re-examined with adjustments to specific parameters. Finally, all the results will undergo a comprehensive critical analysis.

Chapter 2 – Evolution of energy sector

The chapter discusses the evolution of energy systems from centralized to decentralized models, emphasizing the shift towards smart grids and sustainable energy production. It highlights the benefits of decentralized systems, such as reduced distribution losses, increased flexibility, improved consumer-producer relationships, and lower energy generation and distribution costs. The concept of prosumers, individuals who can act as both consumers and producers of energy, is introduced as a key element in this transition. The importance of reducing carbon emissions, especially in light of climate change goals, is emphasized. The text then introduces the concept of Energy Communities (ECs) as a response to the changing energy landscape. ECs are described as aggregations of users working towards reducing greenhouse gas emissions by locally exploiting renewable energy sources. The definition of an EC varies, but it generally involves at least one producer and one consumer. The ECs are still connected to the grid, allowing users to sell surplus energy and purchase deficit energy. Overall, the text sets the stage for discussing the economic feasibility of energy communities in the context of evolving energy systems and environmental goals.

2.1 Evolution of energy sector

To begin with, would be correct to speak about how and why “energy” became the most important asset in the recent decades. All the human activities find as their foundation a demand of energy, is not possible to produce something, exchange “information” and simply develop new and better society without any constant and secure energy source. Since the discovery of the fire, going through the use of animals’ force, up to machines motorization, firstly with coal/steam and secondly with the “black gold”, all the society were developed in the same way. At the beginning of the industrial revolution all the system was centralized, i.e., one big producer connected to all the users which had their only option, and at the same time demand, to buy energy. This for some years, it seemed to be the best and easiest way to store fuel, produce energy and distribute it to all the society, which, on average, consists of individuals with little money. The system held up for a long time and today almost all of the modern societies are based on the centralized system. The “infinite” energy amount and the ease of resource extraction blurred the mankind vision for hundreds of years. The sharp increase in demands and comfort it was hiding the dark and dangerous part of this almost infinite source of energy and societal model. Since the past century scientists decided questioning and criticize in a more objectively way the human work and the possible future feedback. But only in recent years these topics became relevant and in plain sight. A new “sustainable” and smart energy production and management idea is needed. The idea of sustainability and smart energy production it is the idea of produce only when it is needed, with only low/zero carbon emissions production facilities (such as nuclear, photovoltaic, wind, hydro, biogas, biomass and other). Smart instead is relative to the way in which the energy produced is then managed, would be better to break down and classify society into small sub-societies with their own characteristics with the aim of managing the grid according to the demand and the structure of these sub-societies. The next natural step would be the transition from the centralized system to the decentralized one.[18] describe in a very simple and fast way which are the positive aspects of the decentralized system respect to the standard system. In a decentralized system includes small production plants that, respect to the actual ones, would be closer to consumers.

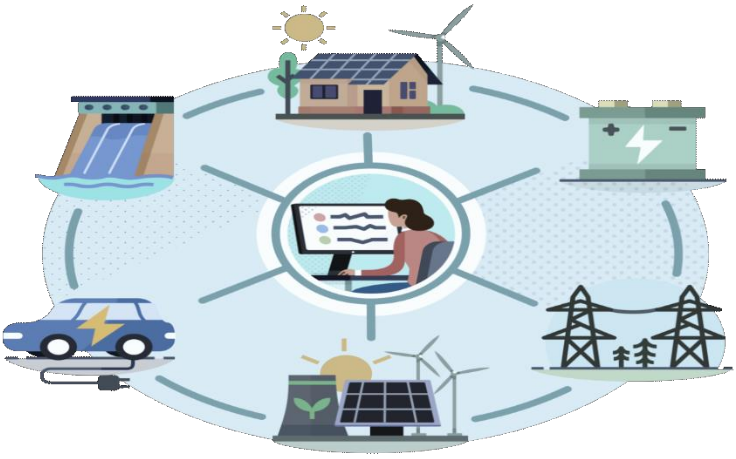


Figure 2.1. *Hive power – decentralized system*

These could be also called as “micro-grid”. The positive aspects, as the [18] suggests are the following:

- Distribution grid losses’ reduction. This is due to the actual long distribution network which limits all grid operators and power producers. A huge part of energy is lost by heat dissipation and is no longer usable, as second principle of thermodynamics teaches.
- Flexibility. As written a few lines above, a smart grid/society corresponds to a community in which each sub-society can manage its own energy production and distribution depending on the demand. Moreover, having more than one production facilities also increase the grid stability and reliability.
- Relation between consumers and producers. In this type of society all the consumers and the producers can exchange data about their production, surpluses and deficits in order to improve their interconnection without any type of second end. Given that in these communities the users are certainly in smaller numbers respect to the actual structure, is easier to check and notice anomalies.
- Energy generation and distribution cost. As it was said before, with decentralized system the energy generation fits the energy demand, moreover the cost for the maintenance of small plants is lower.

So, it can be said that, after the various point reported, the natural evolution of the distribution network will be the smart grid and decentralization of the generation facilities. An important duality is found between energy and the market in general. In the last tens of years, the advent and importance of the internet, it has changed many aspects of daily life, in particular, it changed the market approach. Instead of having producers in one hand and consumers in the other, today everyone can act as both consumer and producer. The same happened also in the energy generation as it was written in the thesis introduction. Nowadays, all the users can act as prosumers, depending on the availability of energy that they or the other have. This is strictly connected to the transition from centralized to decentralized system.

2.2 Energy communities

The advent of prosumers and decentralization goes hand in hand with the emissions reduction goals imposed by the European community. Annual Mondial conferences are held with the aim of discussing and taking actions about climate change, with the hope that, in the coming years, improvements can be seen. These conferences are called "conference of parties" or COP [19]. Getting more than 150 countries to agree is an almost impossible challenge given the totally opposite ideas and ways of operation, as well as degree of technological development. From the recent COPs, what has turned up is something very important and challenging. In the 24th conference, an important IPCC report was presented, it stated that the upper limit of the earth's average temperature increase must be set to +1.5°C respect to the pre-industrial level (1850-1900) in the year 2030 (IPCC, 2022, updated). This is directly correlated to the energy production sector given the direct correlation between the CO2 emissions and the temperature increase. Nobody knows which is the perfect solution, but it seems quite reasonable to use and improve low-impact generation tools and, in a parallel way, a continuous development of new technology. As reported in the introduction chapter, in the last years all the technologies developed for this purpose have seen their cost drop dramatically, making them affordable to small entrepreneurs. In the recent years, due to the coexistence of these important changes in all the aspects such as, reduction of the renewable energy sources cost, internet diffusion, decentralization of the generation facilities, idea of climate changes, prosumers' affirmation, a new way of energy management it began to gain more and more momentum. The name of this type of system is the so-called Energy community ("EC"). The EC functioning it has already been explained in the introduction chapter, but a brief sum is needed. Energy communities are aggregation of users with the declared goal of reducing the greenhouse gas emissions. These aggregations are useful for the decentralization of the energy generation sector, the goal is to exploit locally the higher possible amount of renewable energy sources, reducing the use of fossil fuel and at the same time reducing the grid losses due to the long distances. Moreover, an aggregation like that one would possibly incentives the users to shift their loads to couple their energy demand to the energy production periods, reducing again both the greenhouse gas emission and the cost (in this way the storages will become not so impactful). Nowadays, there is not a single way to define an energy community, but the goal is always the same explained a few lines above. There may be prosumers who decide to aggregate with other prosumers, or one/more prosumers that install and shares photovoltaics with another one or more consumers, or simply a user with great availability of space who install some kW of PV, or other renewable energy generation facilities, and then shares it with one or more consumers or prosumers. The limit is to have at least one producer and one consumer. In most of the cases, the energy community is still connected to the grid and the energy consumption can be seen as a "fictitious" consumption. All the users in the community will self-consume their own PV produced energy, but the surplus of energy is simply sold to the grid. The same happens for the deficit, the user will buy the electricity from the grid, although there is production surpluses from other users, and only with the incentive it will be paid back to him.

3.3 Energy communities legislation

To better understand the energy communities, seem interesting to introduce some of the most important directive introduced locally and in Europe in the last tens of years.

- Directive 2019/944 5 june 2019 [21] – "common rules for the internal market for electricity and amending Directive 2012/27/EU " – The main actor in this directive is the "Active consumer" that is a client (or group of clients) that has the possibility of consuming or selling the electrical energy, that could be both renewable and fossil, with the constraint that this activity of selling and producing electricity is not the main commercial activity.
- D.L. 162 30 December 2019 (milleproroghe) [22] and ARERA 112/2020/R/EEL [23] – Are one of the main articles in the Italian legislation about the energy communities and discusses about the definition of self-consume (that was not defined by the European Directive). The self-consume is defined as the electrical energy consumption where it is produced but do not consider the temporal limit (it is possible to produce the electricity and then to store it) but this is independent on the source that generate electricity. The article 42bis defined the terms and conditions for the activation of collective self-consumption, from renewable sources and the establishment of renewable energy communities, by initiating the testing of rules to enable the final consumers/prosumers to associate for sharing locally the electrical energy produced by

the renewable energy plants (small size plants) [GSE]. The fixe plant limit was fixed to 200 kW and then expanded to 1000 kW

- PNIEC 2018 – National plan for the climate and energy. [24] – Describe the way in which Italy want to reach the community goals for the period 2021-2030 with also a look ahead to 2050. The main goals were to increase the percentage of renewable energy sources in the total final energy consumption, of 30%. decreasing the greenhouse gas emissions in all the sector of the 33% with also a reduction in the primary energy consumption of about the 43%. These respect to the 2005 data. To reach these goals the idea was to increase the investment in the industrial sector and the houses' decarbonization with the introduction of constraint in the house efficiency. As the Clean Energy Package, also this plan recognizes and incentivizes the diffusion of energy communities as a way to reduce the emissions.
- Clean Energy Package [25] – In 2019 the European union released this document about directives focused on energy issues. The field of operation cover not only the energy production and the electrical market but also the energetic efficiency and the building performance. The main aim is to guide the energetic transition making the citizens key actors in achieving the community goals. The directive and regulations are the following ones.
    1. Renewable Energy Directive (EU) 2018/2001;
    2. Governance of the Energy Union and Climate Action Regulation (EU) 2018/1999;
    3. Electricity Regulation (EU) 2019/943;
    4. Regulation on Risk-Preparedness in the Electricity Sector (EU) 2019/941;
    5. Regulation on the European Union Agency for the Cooperation of Energy Regulators (EU) 2019/942.
    6. Electricity Market Directive (EU) 2019/944;
    7. Energy Efficiency Directive (EU) 2018/2002;
    8. Energy Performance of Buildings Directive (EU) 2018/844

The hopes of this Directive, or better, directives, is to help find a pathway such as that the 2030 goals can be achieved. These goals are the reduction of greenhouse gas emissions, the increasing efficiency of all the activities connected to the energy field, the consumption of renewable energy increased up to 32% and finally the very challenging carbon neutrality that would be reached in 2050. To reach the goals the community has to work as a unique entity, giving citizens behaviour the same importance as big industries. The most interesting packet is the RED II i.e., the Renewable energy directive (2018/2001/EU). That is the document which recognizes the role of the prosumer, and also the energy communities, as an important and active stakeholder in both production and consumption of energy from green sources. Moreover, citizens are allowed to sell energy, with no time limit between the production and selling period, through official agreements. The hope of the directive is to incentivize the energy community, the self-consumption, facilitating stakeholders and removing obstacles of any nature.

- NES 2017 [26] – It is the National Electrical Strategy or SEN in Italian – This strategy, written by the Economic Minister, contains the plan for the energetic sector in particular for realizing the objective imposed and described in the roadmap 2050 [27] and it was the foundation basis for the PNIEC described above. It is one of the first documents that introduces the idea and definition of energy community. The goals are different, for example: increasing the competitiveness of the Italian energetic production system through investments on innovations and research. Higher security, in the area of energy supply, by increasing flexibility and resilience of the grid and infrastructures through the investments in differentiation of resources and grid reinforcement. Finally the main important is the goal of reducing the greenhouse gas emissions in all the sectors introducing the idea of higher efficiency and reduced compulsive exploration of resources.

Chapter 3 – Definition of energy community and Input data

In this section, the document introduces various technical and economic aspects related to the analysis of energy communities. It begins by introducing the concept of shared energy within energy communities is introduced, explaining how it is calculated and its relevance for incentives. The text touches upon the definition of energy communities, emphasizing their adaptability and the evolving limits on photovoltaic installations. It notes the primary requirement of a medium to lower voltage cabin among users and discusses the growing trend of larger energy communities with substantial photovoltaic installations. The first section concludes by providing an illustrative figure depicting the shared energy concept. It continuous by categorizing users into residential, commercial, and office types. The text then presents figures illustrating the typical electrical and thermal demands for each user category throughout a day. Following that, the techno-economic data is outlined, including electricity costs, incentives, and avoided grid losses. This data serves as a foundation for evaluating the economic feasibility of energy communities. The section also covers ambient temperatures and solar radiation for different typical days, specifying hourly temperatures. Lastly, the size of the problem, indices, and decision variables are defined, including information on energy conversion and storage systems, investment costs, and other parameters. In summary, this section lays the groundwork for the subsequent analysis of energy communities, covering technical specifications, economic parameters, ambient temperatures, and the definition of key variables and indices.

3.1 Definition of energy community

Energy communities are not universally defined and are highly adaptable. The primary requirement is the presence of a medium to lower voltage cabin among the users. The smallest possible energy community can be created aggregating a user, that could be a simple consumer, and another one with the availability of renewable energy facility. To be precise, there would be limits on the amount of PV that can be installed but those limits are being expanded more and more over the years (in the 2020 the upper bound was fixed to 200kW of photovoltaic, while in the last years that limit become 1000 kW and probably it will be increased in the following decades[28]). Initially the thesis focused on analysing communities where each user could install a certain capacity of photovoltaic, subjects to limits based on their electricity demand. While that analysis was valuable for understanding energy communities in general, it was less relevant for comparing different energy community's type. Nowadays, the main players in the energy community market are those having great availability of "space" and sources that decide to install huge amount of photovoltaic. Their goal is to exploit as much as possible their production increasing their profit by sharing electricity with some other users, instead of simply selling the electricity. Energy communities will be analysed in the following chapter to find the criteria for the optimal aggregation, i.e., give to the investors some basic ideas on which and how many users is better to aggregate. The goal for the investor is to obtain the best economic advantage. At the same time also the users must obtain something back. They make their load available for absorbing the investor's photovoltaic production instead of simply installing their own system. On the environmental point of view, it is not so useful to compare the different cases given that the amount of photovoltaic installed is always the same. Furthermore, all users have heat pumps instead of boilers, resulting in consistently lower emissions compared to traditional systems. This change was in response to new EU regulations concerning the future fase-out of fossil fuel boilers for household heating. The focus is to compare single user and EC operation in which both use heat pumps instead rather than comparing heat pumps to boiler. The energy shared in the normative is defined as the minimum in each hour between the imported energy from the grid and the energy produced by the photovoltaic system ([29]). This does not exclude the possibility of installing electric or thermal storage tanks.

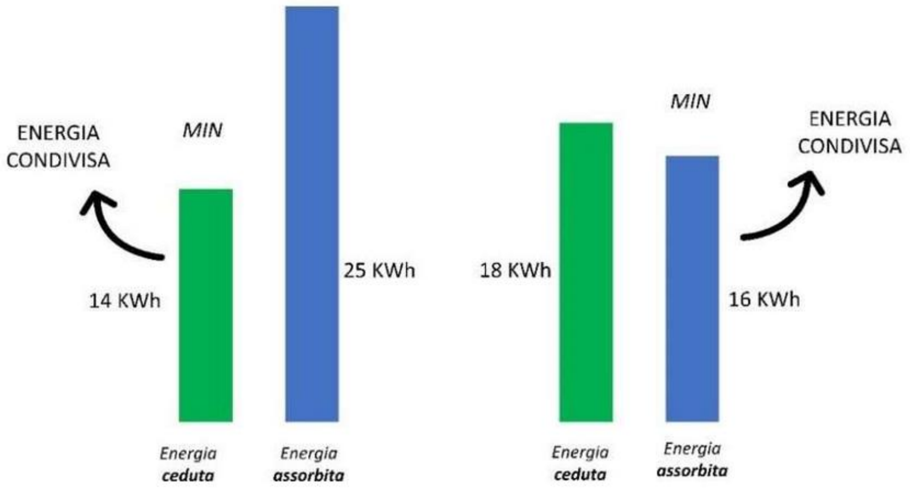


Figure 3.4. *Shared energy calculated as the minimum in each hour between the energy produced and the energy purchased from the grid by the users (from*[29]*)*

Figure 3.4 shows what written before. The shared energy is the minimum in each hour between the sold energy, green column, and the absorbed energy from the grid, blue column. If the community generate 10 kWh in one hour and the users in the community require 8 kWh, it means that all the energy demand is met by the photovoltaic system. However, only 8 kWh are considered shared energy and eligible for incentives. While, if the energy produced is 10 kWh and the users' demand is 20 kWh, all the produced energy can be considered shared thus activating the whole incentive. If the user decided to remain alone and install its own photovoltaic system the operation is different. It buys the electricity from the grid during the non-production hours but self-consumes and sells excess electricity during production hours. If it joins the energy community all the energy derives from the grid and the savings from the incentive.

3.2 Load curves profile

First, three categories of users are selected from literature:

- Residential, that has peak of demand during evening and lower load during the whole day
- Commercial/industrial, that has almost constant and high load during all day except for 4,5 hours during the night
- Office, has constant demand during the late morning and afternoon between 9 and 18 and then the electricity demand decreases sharply.

Residential, commercial/industrial, and office users are mainly analyzed because they represent the demand and behavior of the majority of the population.

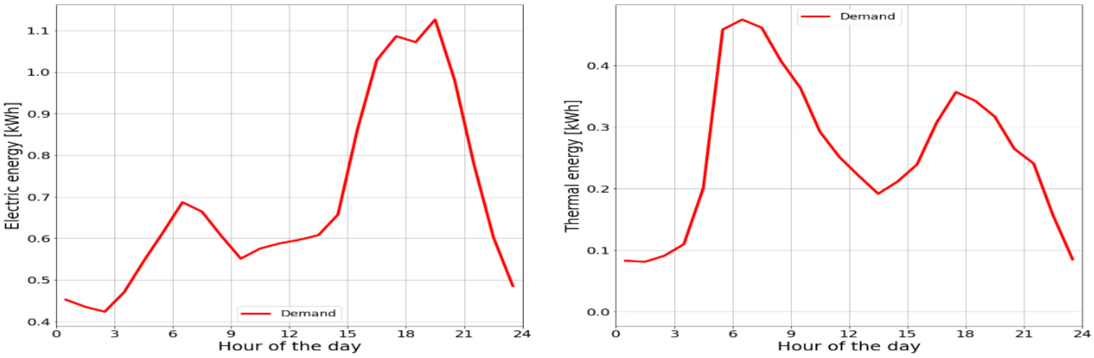


Figure 3.1. *Residential electrical and thermal demand (typical day 1)*

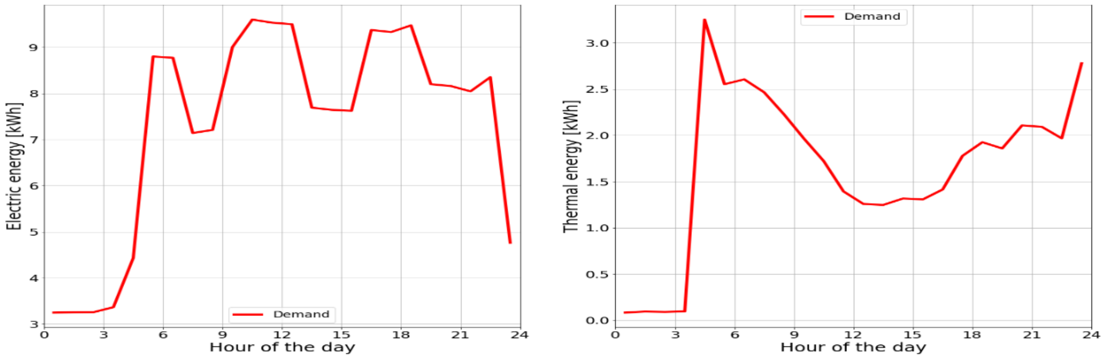


Figure 3.2. *Commercial electrical and thermal demand (typical day 1)*

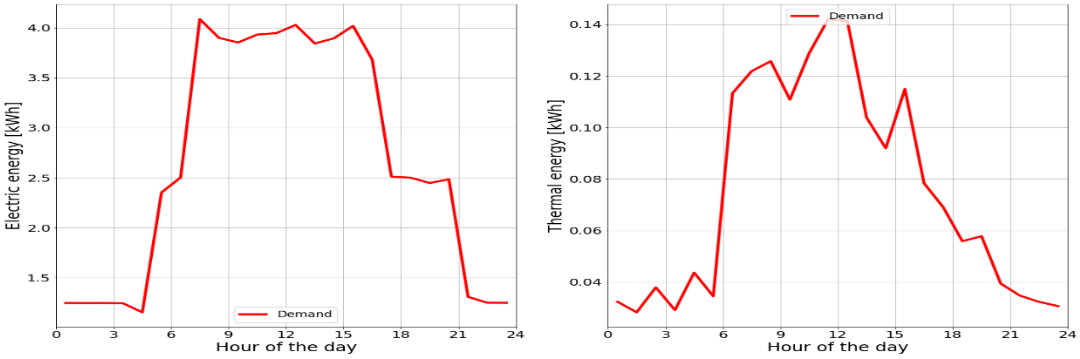


Figure 3.3. *Office electrical and thermal demand (typical day 1)*

The hypotheses are that all the electrical demand can be satisfied by the energy import from the grid or by self-consumption of energy from the photovoltaic system. Thermal demand is always satisfied by the heat pump and thermal energy storage tank.

3.3 Techno-Economic data

All the following data remains fixed during the analyses and will be modified only in the sensitivity analysis chapter.

Table 3.1. *Grid and electricity costs*

Quantity	Unit	Value
Electricity purchasing cost	$\frac{€}{MWh}$	250
Electricity selling price	$\frac{€}{MWh}$	50
CO2 Emissions (imported energy from the grid)	$\frac{kg}{MWh}$	356
Shared energy incentive (Energy community)	$\frac{€}{MWh}$	110
Avoided grid losses incentive (Energy community)	$\frac{€}{MWh}$	9

Electricity purchasing cost and selling price are taken as reference values. The value of electricity purchasing cost is varied during the sensitivity analyses to understand how the EC's behaviour changes when the electricity purchasing cost changes. The CO2 emissions due to the imported energy from the gird is an average value of the emissions emits for each MWh of energy absorbed (is the average value of the emissions generated by the PV, wind turbine, gas turbine, Rankine cycle plants, etc.). The shared energy incentive and the avoided losses inventive are taken from actual legislation. The avoided losses refers to the reduced losses caused by the lower power transported through the grid. The incentive and the avoided grid losses parameters refers only to the energy community operation. In the electricity purchasing cost all the parameters are taken in consideration and are fixed. The network charges due to a different value of available maximum power are not considered.

Table 3.2. *Conversion and storage systems data*

Technology	Quantity	Unit	Value
PV	Investment cost	$\frac{€}{kWp}$	1250
	O&Mcost,fix	%Inv./y	1,1
	Life time	y	20
	Space requirement	$\frac{m^\wedge 2}{kWp}$	5,12
HP	Investment cost	$\frac{€}{kWp}$	1500
	O&Mcost,fix	%Inv./y	2,8
	Life time	y	20
	Minimum load	%MaxLoad	50
	COPid*P(Q)_var	.	1,796076
	COPid*P(Q)_fix	.	2,652666
TES	Investment cost	$\frac{€}{kWp}$	400
	O&Mcost,fix	%Inv./y	4
	Life time	y	20
	RoumdTrip efficiency	.	0,98
	Self Discharge	%SOC/hour	2,1
	Output Capacity	$\frac{kW}{kWh}$	0,7
	Input Capacity	$\frac{kW}{kWh}$	0,7

In table 3.2 all the conversion and storage system data are reported. Values are fixed and they will not be modified during the analyses. “e” and “f” are respectively the COPid*Pvar = 1,79607626416137 and COPid*Pfix = 2,65266648245372 (from the table 2.1). Those are coefficient used for the linearization of the heat pump. In the table is not reported the interest rate (it si fixed to 5%). For the TES is present the value of the self-discharge calculated for each hour.

3.4 Ambient Temperatures and global solar radiation

Table 3.3. *Ambient temperature for each hour and each typical day*

Hour	AmbientTemp[°C] - Typical day (0) - day (45)	AmbientTemp[°C] - Typical day (1) - day (135)	AmbientTemp[°C] - Typical day (2) - day (196)	AmbientTemp[°C] - Typical day (3) - day (319)
0	2,35704141	10,43832288	20,43153763	12,71969773
1	2,27595046	10,15974343	20,08460275	12,53455884
2	2,19261329	9,88321147	19,73978017	12,34829331
3	2,11043395	9,605724313	19,39419235	12,16109827
4	1,97481919	10,02989008	20,16683214	12,12355496
5	1,83796531	10,45280227	20,93933722	12,08497581
6	1,7034559	10,88146625	21,711977	12,04858035
7	2,7262644	12,54691906	23,09203883	13,4765000
8	3,75006432	14,21688023	24,47310305	14,90781989
9	4,77520257	15,8844092	25,85551105	16,33566726
10	5,7106426	16,46371685	26,33288859	16,91555645
11	6,64514881	17,04186649	26,81007646	17,49097372
12	7,58159082	17,62213202	27,28743489	18,06535036
13	7,56363031	17,7260457	27,49712873	18,03915054
14	7,54644265	17,83214427	27,70797909	18,01207855
15	7,52740079	17,94049343	27,91655287	17,98360275
16	6,48809364	16,7223187	27,05367025	16,88109558
17	5,44987679	15,50614427	26,18877927	15,78062425
18	4,40933628	14,28908065	25,32477658	14,68223297
19	3,98659882	13,34852569	24,14337784	14,18451464
20	3,56385529	12,40693907	22,96412067	13,69104749
21	3,14084005	11,46433333	21,7804549	13,19573387
22	2,87991679	11,16151792	21,34292563	12,98787127
23	2,61799859	10,85848656	20,9048632	12,78013351

Table 3.4. *Global solar radiation for each hour and each typical day*

Hour	**Global solar radiation [$\frac{W}{m^2}$] - Typical day (0) - day (45)**	**Global solar radiation [$\frac{W}{m^2}$] - Typical day (1) - day (135)**	**Global solar radiation [$\frac{W}{m^2}$] - Typical day (2) - day (196)**	**Global solar radiation [$\frac{W}{m^2}$] - Typical day (3) - day (319)**
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	4,446075269	15,54167652	0
5	0	51,49833513	111,6400582	3,735787037
6	0	157,0871371	262,0242966	56,5943399
7	30,18579653	293,118193	420,9426478	163,0593734
8	127,1507943	424,0914639	567,3562545	275,5086589
9	209,1859191	536,3084035	674,8240965	359,837201
10	264,4983855	594,3333414	737,1607548	417,620276
11	294,0804576	616,0206995	766,6215899	434,9100242
12	285,6860877	603,5877222	749,2524979	404,0417437
13	241,0434754	543,3920648	676,7005705	345,3401234
14	167,9701546	446,6142309	580,8178599	254,3940355
15	67,37039331	324,8142996	452,3057542	142,432693
16	9,356507616	188,1182616	304,5534633	50,23795998
17	0	63,7119319	157,6222372	5,103092593
18	0	5,305991637	35,80955346	0
19	0	0	0	0
20	0	0	0	0
21	0	0	0	0
22	0	0	0	0
23	0	0	0	0

Table 3.3 and 3.4 report the ambient temperature and global solar radiation for each hour and each typical day. The typical day selected are: one for the winter (45th day), one for the spring (135th day), one for the summer (196th day) and one for the autumn (319th day).

3.5 Structure of the optimization problem, indices and decision variables

Typical days: $k \in K$ = number of typical days/cluster (4).

Time step : $h \in H$ = number of time steps per typical day (24).

Input data:

- Technical specifications of energy conversion units and networks:
    1. Lifetime.
    2. Efficiency.
    3. Load limits.
    4. Gride line capacities.
- Economic parameters:
    1. Investment cost.
    2. Operation and maintenance costs (O&M).
- Energy carriers data:
    1. Emission factor.
    2. Primary-to-final energy ratio.
    3. Purchasing and selling prices of electricity.
- Data series about electricity and heat demand – to define the behaviour of each consumer/prosumer.
- Data series about weather parameters:
    1. Solar radiation.
    2. Ambient temperature.

Decision variables:

- Type, number and size of new energy conversion and storage units to be installed.
- Management over the time of existing and new units to be installed.

Output:

- Size of new energy conversion and storage units.
- Power flows at each hour h of the day k.
- Total costs of the system (subdivided into investment and operation costs).

Facilities:

- Photovoltaic variables:
    1. Capacity Cpv [kWp] only for design problems.
    2. Generated power Ppv [kW] $\forall k \in K, \forall h \in H$.
    3. Solar radiation Isum [WTm^2] $\forall k \in K, \forall h \in H$.
    4. "r" is the interest rate (5%).
    5. "a" is the lifetime in years.
- Heat pump:
    1. Capacity Chp [kW] only for design problems.
    2. Output heat Qhp [kW] $\forall k \in K, \forall h \in H$.
    3. On/off status (binary variable) deltaHP $\forall k \in K, \forall h \in H$.
    4. Auxiliary variable thetaHP $\forall k \in K, \forall h \in H$.
    5. Power consumption Php [kW] $\forall k \in K, \forall h \in H$.
    6. Coefficient of performance COPideal [kW] function of ambient and supply temperature $\forall k \in K, \forall h \in H$.
    7. Ambient temperature Tamb and supply temperature Tsupply.
- Energy storage:
    1. Ces [kWh] only for design problems.
    2. Intra day (daily) state of charge SOCes [kWh] $\forall k \in K, \forall h \in H$.
    3. Charging power/heat Pc [kW] $\forall k \in K, \forall h \in H$.
    4. Discharging power/heat Pd [kW] $\forall k \in K, \forall h \in H$.
    5. Specific input capacity cap$_{in}$ [kW/kWh].
    6. Specific output capacity cap$_{out}$ [kW/kWh].
    7. Rate of self discharge sd.
    8. Round trip efficiency η_{RTE}.
    9. On/off status (binary variable) deltaES $\forall k \in K, \forall h \in H$.
    10. Auxiliary variable thetaES $\forall k \in K, \forall h \in H$.
- Grid variables:
    1. Imported "power" [kW] $\forall k \in K, \forall h \in H$.
    2. Exported "power" [kW] $\forall k \in K, \forall h \in H$.
    3. Shared "power" [kW] $\forall k \in K, \forall h \in H$, power exchanged among the EC's users.

Chapter 4 - Methods

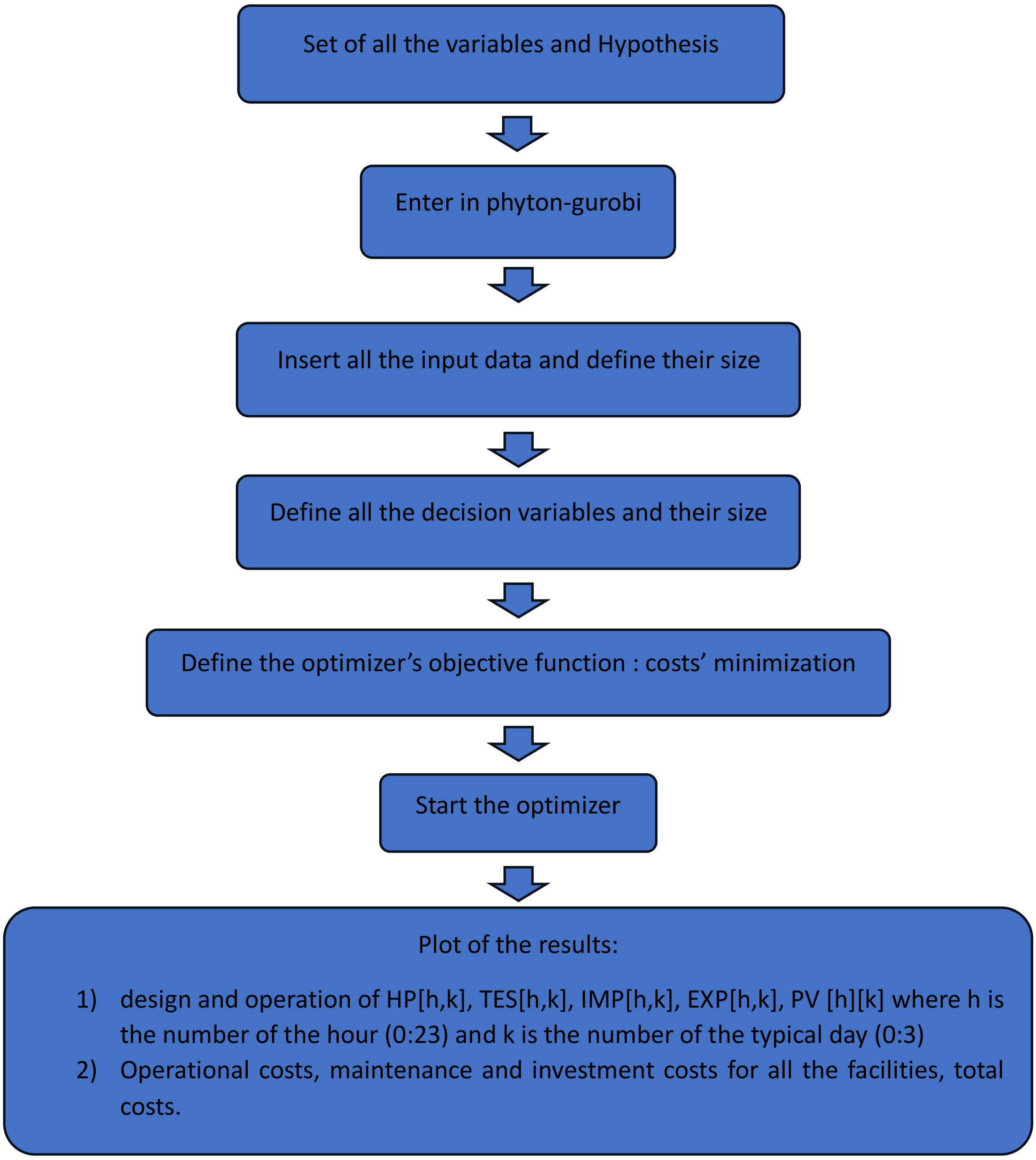
The section delves into the use of Mixed-Integer Linear Programming (MILP) as a prominent method for designing models, due to its simplicity, speed, and adaptability to various problems. The approach involves representing linear characteristic maps for energy conversion units and linearizing those with nonlinear constraints. The procedure description outlines the use of Python, specifically the Gurobi extension, for calculations. The code is designed to simulate both individual user and energy community operations. For individual users, the optimizer determines the optimal combination of heat pump, thermal energy storage, and photovoltaic system to minimize annual operating costs. In the case of aggregated users in an energy community, a cyclic optimization process is employed to assess various combinations of residential, office, and commercial users within specified limits. Formulations are presented, beginning with photovoltaic calculations, ideal coefficient of performance for heat pumps, and thermal energy storage balance equations. Constraints are outlined for heat pumps, thermal energy storage, and photovoltaic systems, including linearization techniques. The section also covers cost calculations for photovoltaic installations, heat pumps, and thermal energy storage, incorporating investment costs, operational costs, and incentives for energy community scenarios. In summary, this section introduces the use of MILP for energy system optimization, describes the procedural aspects of code implementation using Python and Gurobi, and provides detailed formulations and constraints for photovoltaic systems, heat pumps, and thermal energy storage in both individual user and energy community scenarios.

4.1 MILP

The MILP (Mixed-Integer liner Programming) is a well-recognised approach used in most of the design models due to its characteristics that are the simplicity, quickness and adaptability to different problems. This method consists in considering linear characteristic maps of all energy conversion units and in the linearization of the ones that present nonlinear constraints. A very comprehensive analysis of this type of programming approach it is addressed by Rech in [30] in which a CHP plant (combine heat and power plant) it is analysed to show how to build in a correct way the dynamic model and formulate the optimization problem. The final goal of the “MILP” report by Rech, but also the one of all the analysed systems, is to find the best, fast and optimal combination of type, number and way to interconnect the energy conversion units for the optimal exploitation of generation and storage sources used to satisfy the users’ demand in a “smart way”.

4.2 Procedure description

For the calculations Phyton-Gurobi was used. Phyton is [31] a high-level programming language well used and widespread. Due to its simplicity permit allows programming very simple codes/scripts. An extension of phyton, called “Gurobi”, was used for the optimization problems. Also other libraries were added to the code, such as Numpy and Pandas . The main goal is to create a code capable of simulate an individual user operation and an energy community operation. For both the situations, initially there is the need of importing all the input data and assumptions described in chapter 3. In case of single user’s operation, the program calculates which is the amount of heat pump and thermal energy storage to install depending on the shape and size of the thermal demand. In this stand-alone optimization, the optimizer is free to decide when to start and stop the heat pump, with an hourly time-step. Moreover, is free to decide how much photovoltaic capacity to install. All these operations are guided by the cost optimization. It means that the optimizer selects the amount of HP, TES, PV, imported energy and exported energy to reach the minimum annual costs of operation. For example, the users could install a lot of photovoltaic, cover part of its demand and then sell all the energy. However, the investment costs will be higher due to the huge installation of PV system.



1) design and operation of HP[h,k], TES[h,k], IMP[h,k], EXP[h,k], PV [h][k] where h is the number of the hour (0:23) and k is the number of the typical day (0:3)
2) Operational costs, maintenance and investment costs for all the facilities, total costs.

On the other hand, the aggregation operation is a little bit different, but the structure described above is the same. The main difference is the structure of the optimizer part: it is based on a for cycle. For each cycle some users are added to the energy community, starting from the solution with one residential, zero office, zero commercial, up to maximum number of residential, office and commercial. The maximum depends on some limits imposed at the beginning. So, in each cycle the community will be optimized as the stand-alone operation but with some differences. The thermal demand will be satisfied for each user independently on the other users’ operation. Moreover, the amount of photovoltaic is fixed. All the users will satisfy all their electrical demand by the import from the grid, there is no self-consumption. Despite that, they will save money thanks to the incentive applied to the total energy shared. The functioning it is explained at the end of the second chapter. Finally, the optimizer calculates the amount of energy shared and the money from the incentive for each aggregation.

4.3 Mathematical formulations of the energy community model and optimization problem

Starting from the photovoltaic formulations: PPV is the power produced by photovoltaic system that is a simple multiplication between the capacity of PV installed and the Solar radiation. In this case, capacity is constant, while solar radiation is represented as a matrix of size K * H, where K represents the number of the typical day, and H represents 24 hours per day.

$$PPV = \frac{CapPV * SolRad[h,k]}{1000} \tag{4.1}$$

1000 W/m2 is the reference solar radiation for calculating of the peak kW, by which the PV capacity is expressed. The radiation is the global on the tilted plane (30° South [32]). All the radiation calculations refer to the Liu Jordan model (Liu et al., in [[33]) with the simplified assumption of only isotropic radiation [34]. For the heat pumps the ideal coefficient of performance is calculated as follows:

$$COPid = \frac{1}{1 - \frac{Tamb + 273{,}15}{Tsupply + 273{,}15}} \tag{4.2}$$

The ambient temperature is also in this case taken from the input data and it is a matrix 4*24 that contains so the ambient temperature in the 24 hours of all the 4 typical days. The supply temperature is set to 70°C, the reason is the way how the thermal demand it is satisfied. Instead of having a final facility as, for example, radiant floor or fan-coils, the thermal demand is simply satisfied directly by the heat pump and/or thermal energy storage. In other words, it is assumed that the heat provided by the heat pump is used directly to heat the room, as if the heat transfer between heat pump to storage and then from storage to radiant system, for example, has efficiency of 1. This was done in order simplify and not to overload the code. So, 70°C of supply temperature was set instead of 45-50°C for the purpose of considering the simplifications made.

$$PHP = \frac{QHP[h,k] * e + deltaHP[h,k] * f}{COPid[h,k]} \tag{4.3}$$

The formulation for the calculation of the heat pump power is the number 4.3, the heat produced is multiplied by a factor e and summed to the multiplication of the deltaHP and f factors. “e” and “f” are respectively the COPid*Pvar = 1,79607626416137 and COPid*Pfix = 2,65266648245372 (from the table 2.1). Those are coefficient used for the linearization of the heat pump. While the deltaHP is a binary value (0 or 1) used to evaluate the heat pump operation, if it is 1 the heat pump is working, on the other hand if it is set to 0 the heat pump is turned off. Finally, the equation for the thermal energy storage is:

$$\begin{aligned} SocTES[h+1,k] \\ = SocTES[h,k] * (1 - sdTES) + QcTES[h,k] * \sqrt{rteTES} \\ - \frac{QdTES[h,k]}{\sqrt{rteTES}} \end{aligned} \tag{4.4}$$

This is the balance equation for the state of charge. On the left-hand side the state of charge is the one at the time h+1 and this must be equal to the state of charge at time h (right-hand side) and some other parameters. sdTES is the self-discharged parameter that from table 3.2 is set to 2,1. QcTES and QdTES are respectively the charging and discharging heat (also in this case are matrixes 4*24) while rteTES is the round trip efficiency, from the table 3.2 it is equal to 98%.

4.4 Constraints

For the photovoltaic there are not specific constraints, we simply use the constraint to fix the capacity, for example CapPV = 500 kW. For heat pumps and thermal energy storage the things are different.

$$thetaHP[h,k] \le deltaHP[h,k] * M \tag{4.5}$$

$$CapHP - thetaHP[h,k] \le (1 - deltaHP[h,k]) * M \tag{4.6}$$

$$CapHP - thetaHP[h,k] \ge (1 - deltaHP[h,k]) * 0 \tag{4.7}$$

These equations linearize the heat pump behaviour. M is the “big threshold” that corresponds to the maximum capacity. ThetaHP is the parameter used to transform the initial bilinear equation in two linear ones . deltaHP is the binary variable, 0 for the heat pump not in operation and 1 in operation conditions.

$$QHP[h,k] \le thetaHP[h,k] \tag{4.8}$$

$$QHP[h,k] \ge \min\_load\_HP * thetaHP[h,k] \tag{4.9}$$

Formulation (4.8) and (4.9) are heat output upper bound and heat output lower bound. For the thermal energy storage, the constraints are:

$$thetacTES[h,k] \le deltaTES[h,k] * M \tag{4.10}$$

$$CapTES - thetacTES[h,k] \le (1 - deltaTES[h,k]) * M \tag{4.11}$$

$$CapTES - thetacTES[h,k] \ge (1 - deltaTES[h,k]) * 0 \tag{4.12}$$

Formulations (4.10), (4.11) and (4.12) are equations for the charge of thermal energy storage, while

$$thetadTES[h,k] \le (1 - deltaTES[h,k]) * M \tag{4.13}$$

$$CapTES - thetadTES[h,k] \leq deltaTES[h,k] * M \tag{4.14}$$

$$CapTES - thetadTES[h,k] \geq deltaTES[h,k] * 0 \tag{4.15}$$

Formulation (4.13), (4.14) and (4.15) are three auxiliary equations referred to the discharge. The formulation (4.16) instead contains the equation for the State of charge upper bound.

$$SocTES[h,k] \leq CapTES \tag{4.16}$$

In addition to those there are also the equations governing the input and output capacities, the output and input capacity parameters are reported in table 3.2 and are equal to cout=cinp= 0,7 kW/kWh:

$$QcTES[h,k] \leq cinpTES * thetacTES[h,k] \tag{4.17}$$

$$QdTES[h,k] \leq coutTES * thetadTES[h,k] \tag{4.18}$$

The last constraint (formula (4.19)) acts on the limit operation for the daily storage.

$$SocTES[0,k] = SocTES[H,k] \tag{4.19}$$

Finally, the equations for the energy balance are satisfied by formula (4.20) and (4.21).

Electrical energy balance:

$$\begin{aligned} -total_{demand}[h,k] + PIMP[h,k] - PEXP[h,k] + PPV[h][k] - PHPres[h,k] \\ * A - PHPoff[h,k] * C - PHPcomm[h,k] * B = 0 \end{aligned} \tag{4.20}$$

While the thermal demand must be observed individually:

$$-DemTh[h,k] * 1 + QHP[h,k] + QdTES[h,k] - QcTES[h,k] = 0 \tag{4.21}$$

There are as many thermal balances as there are types of users, if one or more type of users do not participate in the community then their thermal demands would be multiplied by zero. After the electrical and thermal balances, the equations for the single or aggregated operations become different. On the optimizer it is possible to distinguish the ones for the calculation of the optimal single house operation (without the energy community so devoid incentives for the energy shared among users) and the ones for the aggregated users. In both cases equations and constraints described above are always valid. Regarding the first case, the limit on the capacity of installed photovoltaic is erased, and in that case the energy exchanged is equal to zero:

$$PEXC[h,k] = 0 \tag{4.22}$$

The electrical demand is satisfied by both the photovoltaic system and the imported energy from the grid (so the energy is not all imported as instead is for the community members). In case of single user operation the photovoltaic system has to be installed by the user itself, so the installation and maintenance costs will be borne by the user's own coffers.

$$CostINVtot = \left(\frac{r * (1+r)^{nPV}}{(1+r)^{nPV} - 1} + OnM_{fix_{PV}}\right) * invPV * CapPV \tag{4.23}$$

The total investment costs for the PV are evaluated as in the formula (4.23).

$$\begin{aligned} CostINV = \Bigg(\left(r * \frac{(1+r)^{nTES}}{(1+r)^{nTES} - 1} + OnM_{fix_{TES}}\right) * invTES * CapTES \\ + \left(r * \frac{(1+r)^{nHP}}{(1+r)^{nHP} - 1} + OnM_{fix_{HP}}\right) * invHP * CapHP \Bigg) \end{aligned} \tag{4.24}$$

r is the interest rate, nPV and nTES are the lifetime, in years, of PV and TES. Formulation (4.24) considers the heat pump and thermal energy storage costs. Each CostINV has to be multiplied by the factor A, B or C (A= number of residential users in the EC, B=number of commercial users in the EC, C=number of office users in the EC).

$$sumCostINVres \ = \ CostINVres * A \tag{4.25}$$

$$sumCostINVoff \ = \ CostINVoff * C \tag{4.26}$$

$$sumCostINVcomm \ = \ CostINVcomm * B \tag{4.27}$$

The operational costs are relative to the energy that the users are importing, multiplied by the cost of purchasing electricity, from which the energy sold (surplus) is then subtracted, also in this case multiplied by the selling price factor.

$$CostOP = \; WTD\left(* \; PIMP[h,k] * cbuy_{el} \; - \; PEXP[h,k] * csell_{el} \right) \tag{4.28}$$

In formula (4.28) WTD is the number of days for that specific typical day (for example 91 days for spring, summer and winter and 92 for the autumn). When all the equations are set, all that remains is to create the objective function:

$$TotalCostToMinimize = CostINV + CostINVtot \; + \; CostOP \tag{4.29}$$

So, finally, the objective function is the minimization of the sum of the investment and maintenance for the photovoltaic installation (CostINV), the investment and maintenance costs for the heat pumps and thermal energy storages (CostINV) and the operational costs (CostOP). This permits to obtain the optimized user with the best photovoltaic/heat pump/thermal energy storage installed capacities. On the other hand, the code for the energy community analysis is a bit different. In the case of energy community, it is possible to exploit the incentive that can be calculated as:

$$PEXC[h,k] = PPV[h][k] - PEXP[h,k] \tag{4.30}$$

So, in formulation (4.30) the energy exchanged is calculated as the difference between the photovoltaic production and the energy exported (that is the surplus of energy). The difference between photovoltaic production and the surplus of energy is the energy really used locally by the users in the community, the one incentivized. In this case the exported energy is “fictitious” because by law, in an energy community all the energy is imported from the grid and all the photovoltaic production is sell to the grid, so the exchanged energy is not real. It is useful to create an equation for the calculation of the imported energy value that is:

$$\begin{aligned} pimp[h,k] = \; & total_{demand}[h,k] + PHPres[h,k] * A + PHPoff[h,k] * C \\ & + PHPcomm[h,k] * B \end{aligned} \tag*{(3 4.31)}$$

Formulation (4.31) is used only for the calculation of the operational costs but is not part of the objective function. In the case of energy community, the investment cost for the photovoltaic falls on the owner.

$$CostOP_{opt} = WTD * (PIMP[h,k] * cbuy_{el} - PEXC[h,k] * cexc) \tag{4.32}$$

Respect to the single owner operation, the operational costs for the optimizer are not the difference between the imported energy and the exported one but between the imported one and the exchanged, in this case multiplied by the value of the incentive “cexc”.

$$\begin{aligned} m.setObjective\big(&sumCostINVres + sumCostINVoff + sumCostINVcomm \\ &+ CostOP_{opt}, grb.GRB.MINIMIZE\big) \end{aligned} \tag{4.33}$$

The formulation (4.33) is like the (4.29) except for the absence of the photovoltaic costs.

Chapter 5 - Results

The objective of this chapter is to present and analyse the results, outputs from the various simulations in phyton. Some comments and suggestions follow the results and table, while critical discussions will be faced in the next chapter. The main analyses carried out are basically two. In both cases the analysed users are the ones presented in chapter 3, namely residential, commercial, office, plotted in figure 3.1, 3.2, 3.3. Each curve is characterized by a value of the load in kWh, i.e., the area under the "curve", and a specific curve's shape, that reflects the typical distribution of the user's load during that typical day. The shape of the curve can be regarded as the distinguish characteristic of different users and it remains fixed in all the analyses, while the value of the load can be varied as desired so as to compare different users but changing energy demand. In the first series of simulations the hypothesis are:

- Electrical and thermal demand are considered as two separate loads, i.e., they must be satisfied separately.
- The thermal load must be satisfied by only heat pumps and thermal energy storage.
- The users' curve shapes are fixed since is this characteristic that distinguishes them form each other.
- The electrical and thermal loads, in terms of total energy request, are not "realistic". in other words, they do not reflect a typical energy demand of these users, but the amount of energy required has been magnified to achieve more comparable results.
- Incentive revenues are distributed without following any particular criteria but simply divided equally among the users. a community consisting of the investor and two users will see its earnings divided into 1/3 for the first user, 1/3 for the second and 1/3 to the investor.

The results of this first analyses were not convincing. The criteria for allocating incentive revenues seem to lead the other way from the initial goals of the energy communities, indeed the users incentivized to join the energy community are the ones that are also more likely and advantaged in the self-installation and consumption of photovoltaic energy. Moreover, the need to have to simulate users' behaviour also from the thermal demand point of view results in little influence in the final analyses, rather slows down the calculation code and not a little. Due to these problems, in the second series of simulations the hypothesis become:

- Electrical and thermal demand are considered as a single electrical demand (heat pumps run on electricity so they can be considered as an electrical load)
- The users' curve shapes are fixed since is this characteristic that distinguishes them form each other.
- The electrical and thermal loads, in terms of total energy request, are now considered as "realistic". They reflect a typical energy demand of these users.
- Incentive revenues are distributed in a different way (it is explained better inside the chapter).

5.1 First series of simulations – equal division of earnings obtained through incentive

Navigating the intricacies of energy community analyses poses a significant challenge, particularly when determining how the incentive earnings should be distributed among participating users and investors. While a straightforward and initial approach involves an equal division of earnings, it becomes evident that such a simplistic strategy may not be the most appropriate.

In the first series of simulations the hypotheses are:

- Electrical and thermal demand are considered as two separate loads, i.e., they must be satisfied separately.
- The thermal load must be satisfied by only heat pumps and thermal energy storage.
- The users' curve shape are fixed since is this characteristic that distinguishes them form each other.
- The electrical and thermal loads, in terms of total energy request, are not "realistic". in other words, they do not reflect a typical energy demand of these users, but the amount of energy required has been magnified to achieve more comparable results.

- Incentive revenues are distributed without following any particular criteria but simply divided equally among the users. a community consisting of the investor and two users will see its earnings divided into 1/3 for the first user, 1/3 for the second and 1/3 to the investor.

Electrical and thermal demands are:

1) residential

- Electrical demand = $190578 \, \frac{kWh}{y}$ / Thermal demand = $40578 \, \frac{kWh}{y}$

2) office

- Electrical demand = $188249 \, \frac{kWh}{y}$ / Thermal demand = $40825 \, \frac{kWh}{y}$

3) commercial

- Electrical demand = $182991 \, \frac{kWh}{y}$ / Thermal demand = $40052 \, \frac{kWh}{y}$

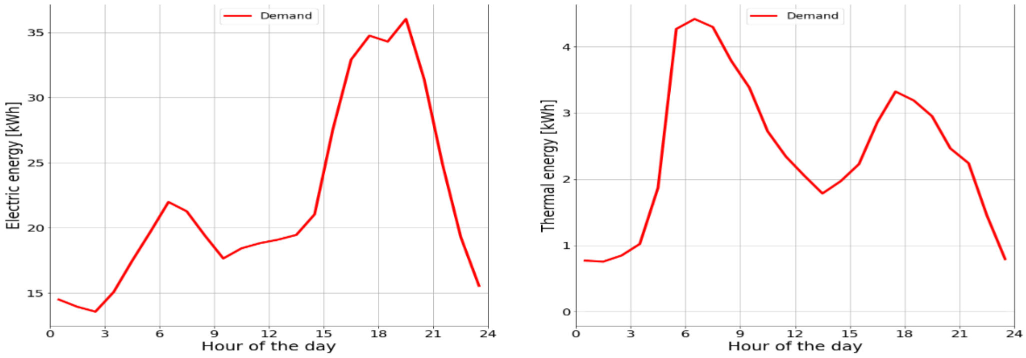


Figure 5.1. *Residential electrical and thermal demand – not realistic users demand but whit realistic load distribution (typical day 1)*

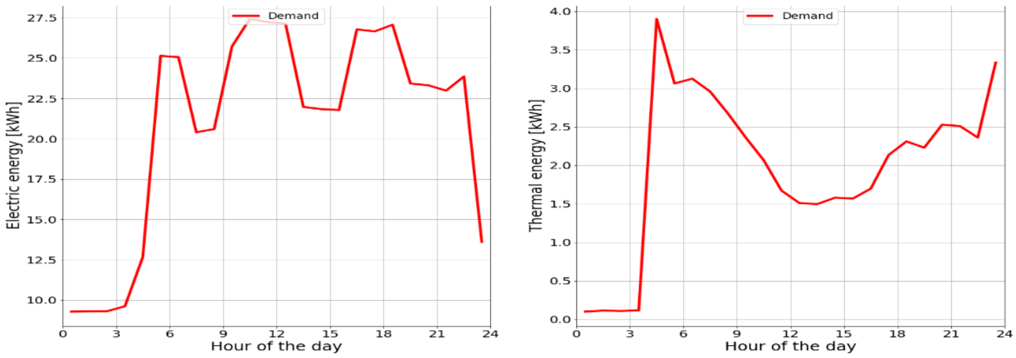


Figure 5.1. *Commercial electrical and thermal demand – not realistic users demand but whit realistic load distribution (typical day 1)*

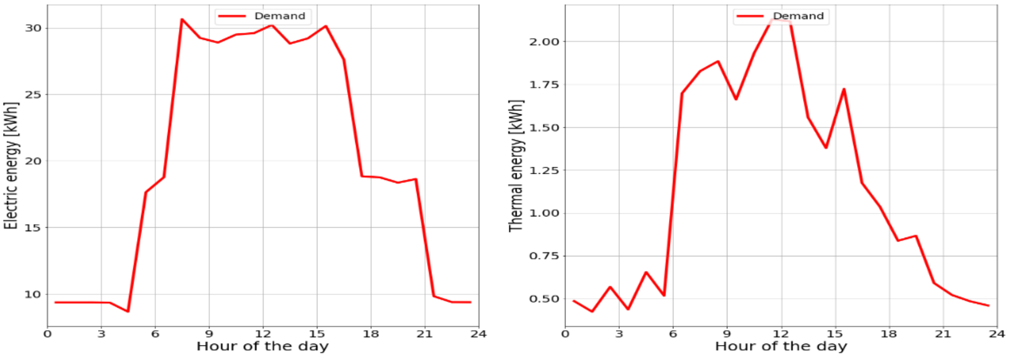


Figure 5.1. *Office electrical and thermal demand – not realistic users demand but whit realistic load distribution (typical day 1)*

As mentioned at the outset of this chapter, the initial simulation focused on the analysis of "non-realistic loads." In this context, the defining characteristic of user behaviour, the shape of its energy consumption curve, remains true to each user, while the absolute values of electrical and thermal demands are artificially scaled for comparative purposes. To begin, let's examine the outcomes of individual user operations, observing how users manage their energy needs without the integration of photovoltaic systems. The cost of purchasing electricity from the grid is set at 250 €/MWh.

Table 5.1. *Electrical and thermal demand, heat pump capacity and thermal energy storage capacity (residential, commercial and office – not realistic curves)*

/	**Electrical demand** $[\frac{kWh}{y}]$	**Thermal demand** $[\frac{kWh}{y}]$	**heat pump [kw]**	**TES [kw]**
Residential	190578	40578	10,3	11,3
Commercial	182990	40052	12,8	9,4
Office	188249	40825	21,7	18,6

The optimizer decides the capacity of thermal energy storage and heat pumps to be installed, including deciding also when to turn them off and on and for how many hours. The criteria is always the cost minimization. Notably, despite the similarity in loads across different users, the capacities of HP and TES vary significantly, likely influenced by the distinctive shapes of the load curves. Table 5.2 provides a comprehensive overview of the associated costs.

Table 5.2. *heat pump and TES costs (investment and maintenance costs divided for the years of operation), operational costs and total costs (residential, commercial and office – not realistic curves)*

/	**HP + TES inv cost $[\frac{€}{y}]$**	**OP cost $[\frac{€}{y}]$**	**TOTAL cost $[\frac{€}{y}]$**
Residential	2.214,00	51.559,00	53.774,00
Commercial	2.527,00	49.583,00	52.110,00
Office	4.462,00	50.877,00	55.382,00

With varying capacities for heat pumps (HP) and thermal energy storage (TES) among the users, the associated investment and maintenance costs differ, with the office user incurring double the costs due to higher installed capacities. Conversely, operational costs remain quite similar since the electrical demands exhibit similar patterns. However, it's acknowledged that the current costs are unrealistically high, given the initial assumptions. The subsequent phase involves introducing an investor into the scenario. This investor has available space for installing photovoltaic panels and aims to establish an energy community. The investor can install 400 kW of photovoltaic capacity. This addition is anticipated to contribute to a more realistic and economically viable outcome.

Table 5.3. *Energy community formed by an investor, with the availability of 400 kW of PV, and 1 single user (residential, commercial and office – not realistic curves)*

Number of residential users	Number of commercial users	Number of office users	Total earnings from the incentive $[\frac{€}{y}]$	Earnings for each user/investor $[\frac{€}{y}]$	Percentage of energy produced that is shared in the EC [%]	PV [kW]
1	0	0	11.757,00	5.897,00	17,0%	400
0	1	0	13.054,00	6.547,00	18,9%	400
0	0	1	15.357,00	7.700,00	22,2%	400

Table 5.3 presents the outcomes of an energy community established by an investor with no electrical or thermal demand and only one user. The energy community incentive of 110 €/MWh allows each aggregation to generate a substantial amount of earnings. The distribution of the funds received, for simplicity, are evenly divided. In reality, this distribution may vary. In the current scenario, with only one user and the investor, the proceeds from the photovoltaic system are split equally between them. For example, with 100 euros gained from the shared energy incentive, 50 are allocated to the investor, and 50 to the

user aggregated. Moving beyond the simplified scenario, where more users are added to the community, the dynamics of fund distribution become more intricate. In the actual distribution, the owner of the photovoltaic system may choose a different allocation strategy. However, for this analysis, an equal split is assumed. From the information in the fifth column of the table 5.3, it is evident that the aggregation involving the office is the most advantageous among the three. This superiority arises from the more efficient utilization of the photovoltaic system. Specifically, the office is able to exploit 22.2% of the total potential incentive (or rather the 22.2% of the energy produced by the photovoltaic panels is shared with the user), as indicated in the sixth column. This percentage is calculated by determining the ratio of the energy shared to the total energy produced by the photovoltaic system. To gain deeper insights into the dynamics, it is crucial to examine the scenario with additional users in the community.

Table 5.4. *Energy community formed by an investor, with the availability of 400 kW of PV, and 2 users (residential, commercial and office – not realistic curves)*

Number of residential users	Number of commercial users	Number of office users	Total earnings from the incentive $[\frac{€}{y}]$	Earnings for each user/investor $[\frac{€}{y}]$	Percentage of energy produced that is shared in the EC [%]	PV [kW]
0	1	1	26.601,00	8.893,00	38,4%	400
1	0	1	25.382,00	8.486,00	36,7%	400
1	1	0	23.001,00	7.690,00	33,2%	400

Table 5.4 presents the outcomes obtained by introducing an additional user to the three distinct aggregations outlined in Table 5.3. Notably, the aggregations that include the office user exhibit the highest percentage of exploited incentives, resulting in greater gains. In these energy communities (ECs), the user count is two, with the investor remaining the same, and the earned money is divided among three entities. Compared to the single-user case, all combinations in the energy communities showcase improvements. This improvement is attributed to the substantial increase in photovoltaic capacity, however not all available photovoltaic capacity is utilized, generating a considerable surplus of energy that, unfortunately, goes unused and is effectively "lost" into the grid.

Table 5.5. *Energy community formed by an investor, with the availability of 400 kW of PV, and 2 users of the same type (residential, commercial and office – not realistic curves)*

Number of residential users	Number of commercial users	Number of office users	Total earnings from the incentive $[\frac{€}{y}]$	Earnings for each user/investor $[\frac{€}{y}]$	Percentage of energy produced that is shared in the EC [%]	PV [kW]
2	0	0	21.620,00	7.229,00	31,2%	400
0	2	0	24.399,00	8.157,00	35,3%	400
0	0	2	28.707,00	9.597,00	41,5%	400

The table 5.5, shows the results of adding two users of the same typology. Comparing table 5.5 and 5.4, is very interesting to underlying how the aggregations with offices are always the best solutions, in particular the one with only two offices. In that case the percentage of incentive is very high, almost the double of the single office case. It is now possible to exclude all the aggregations and continue only adding users to the best one.

Table 5.6. *Energy community formed by an investor, with the availability of 400 kW of PV, and 3 users, 2 offices and an additional one (residential, commercial and office – not realistic curves)*

Number of residential users	Number of commercial users	Number of office users	Total earnings from the incentive $[\frac{€}{y}]$	Earnings for each user/investor $[\frac{€}{y}]$	Percentage of energy produced that is shared in the EC [%]	PV [kW]
0	1	2	38.511,00	9.657,00	55,7%	400
1	0	2	37.253,00	9.341,00	53,8%	400
0	0	3	40.206,00	10.082,00	58,1%	400

In table 5.6 the results confirm the previous discussions about the office user, indeed adding any office seems to be the best solution both for the investor and the users. The percentage of exploiting incentive continues to increase as also the earning for each user.

Table 5.7. *Energy community formed by an investor, with the availability of 400 kW of PV, and 4 users, 3 offices and an additional one (residential, commercial and office – not realistic curves)*

Number of residential users	Number of commercial users	Number of office users	Total earnings from the incentive $[\frac{€}{y}]$	Earnings for each user/investor $[\frac{€}{y}]$	Percentage of energy produced that is shared in the EC [%]	PV [kW]
0	0	4	49.138,00	9.858,00	71%	400
0	1	3	47.797,00	9.589,00	69%	400
1	0	3	46.924,00	9.414,00	68%	400

The community's capacity to aggregate users for optimal economic benefit is not limitless; it is constrained by the fixed installed PV capacity. The percentage of incentive harnessed with four offices surpasses that achieved with only three offices. However, since the total earnings must be divided among five entities, the economically superior energy community remains the one with three offices. It is prudent to compare the costs for an individual user versus those within the energy community in the case of the best aggregation. Referring to Table 5.2, the office's costs amount to 55,238.00 €/y. Subtracting the funds received from the incentive exploitation, the costs decrease to 45,256.87 €/y, resulting in a savings of 18.24%. The results suggest a clear incentive for the investor to aggregate office users due to their superior ability to exploit the incentive. However, it's important to note that the analysis is not exhaustive, as the comparison was conducted with users lacking any installed photovoltaic systems. The outcomes may differ if individual users also have the option to install photovoltaics for self-consumption of electricity.

5.1.1 Difference between single user operation and energy community

The analysis commences by comparing the costs and savings derived from the aggregation within an energy community with the operation of a single user. It is noteworthy that the user's behaviour undergoes a transformation based on whether they are operating alone or as part of an energy community. In the energy community, as elucidated in earlier sections, the energy exchange is essentially a conceptual construct, the energy generated by the photovoltaic system is sold directly to the grid, while users procure all their required energy from the grid. Subsequently, the energy purchased from the grid during photovoltaic production is incentivized, resulting in an economic advantage for the users. Conversely, when a user opts to install their own photovoltaic system, the energy pathway diverges. The energy produced by the PV system is utilized directly by the user, constituting self-consumption. This configuration presents a distinct advantage as a portion of the electrical demand is satisfied by the photovoltaic system, obviating the need to purchase electricity from the grid.

Table 5.8. *Analysis of the final cost for a single office in the best aggregation, with a purchasing cost of 250 €/MWh and a 110 €/MWh incentive*

Number of residential users	Number of commercial users	Number of office users	Total earnings from the incentive $[\frac{€}{y}]$	Earnings for each user/investor $[\frac{€}{y}]$	Percentage of energy produced that is shared in the EC [%]		PV [kW]
0	0	3	40.206,00	10.082,00	58,10 %		400
				hp + tes inv costs [€/y]	**OP costs [€/y]**	**tot cost office [€/y]**	**final cost 1 office [€/y]**
				4.462,00	50.877,00	55.338,00	45.256,87

Table 5.8 shows the best aggregation results in case of investor with the availability of 400 kW of photovoltaic. Heat pump and TES investment and maintenance costs, operational costs and total office costs are the same reported in table 5.2.

Table 5.9. *Analysis of the final cost for a single office that operates alone, with a purchasing cost of 250 €/MWh and a 110 €/MWh incentive*

Number of Residential users	**Number of Commercial users**	**Number of Office users**	**PV [kW]**	**hp + tes inv [€/y]**	**Tot INV costs [€/y]**	**OP costs [€/y]**	**final cost 1 office [€/y]**
0	0	1	135	4.467,00	19.878,00	18.370,00	38.249,03

Table 5.9 shows the single user operation's results, that refers to the case of a single office that decide to install its own photovoltaic system. In this situation the uses must pay for the installation and maintenance of the system but at the same time it benefits from the self-consumption. The investment costs for the heat pump and thermal storage are equal to the

ones in the energy community operation while there is an additional parameter that represents the sum of the investment and maintenance costs of heat pumps, thermal storages and photovoltaic system. However, due to the self-consumption of energy that is not considered in the energy community, the operational costs are always lower than the aggregation operation. Finally, comparing the last column that refers in both table 5.8 and 5.9 to the final costs for a single office user it emerges that the energy community seems to be not a good alternative to the self-installation of the photovoltaic. Office user will save about 30.88% of the money compared to the case without photovoltaic and about 15.50% more than the case of joining the energy community.

5.2 Second series of simulations – energy community with proportional allocation of incentive funds

In the first series of simulations results show that the energy communities seem to be not a promising solution given that the single user prefer to remain alone and install its own system, if the behaviour of the users operating alone is compared to the user behaviour in the best energy community (the best energy community is the EC that lead to the higher incomes both for the investor and users aggregated). The idea is to change completely the way in which earning from the shared energy incentive are distributed. To simplify the code and to compare realistic-load curves, thermal demand is neglected and the total load it is assumed to be similar to real-life users. Table 5.10 contains the electrical demand for the three users. The residential demand amounts to approximately 6000 kWh per year. It is not far from the reality considering an all-electrified house. This figure can be regarded as an average consumption for a typical Italian residential building.

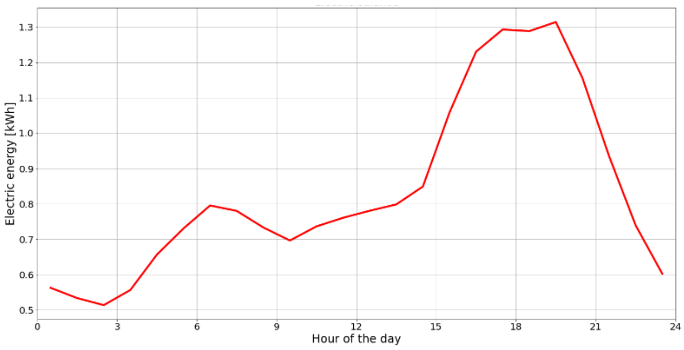


Figure 5.4. *Electrical demand residential user (typical day 2)*

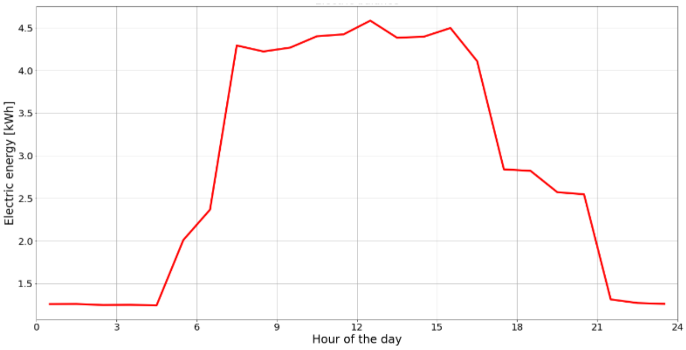


Figure 5.5. *Electrical demand office user (typical day 2)*

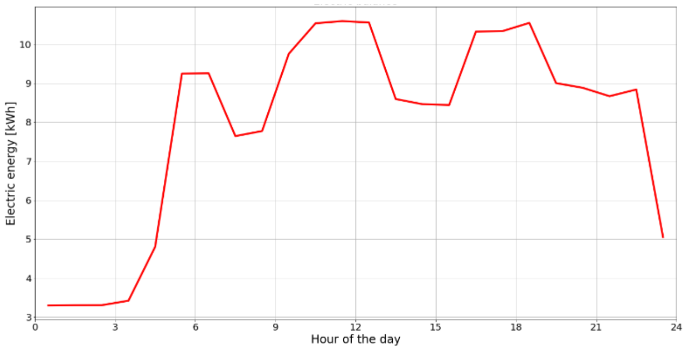


Figure 5.6. *Electrical demand commercial user (typical day 2)*

Table 5.10. *Electrical demand for each user (realistic residential, commercial and office curves)*

N of Residential users	N of Commercial users	Number of Office users	Electrical demand $[\frac{kWh}{y}]$
0	0	1	25.099,81
0	1	0	64.046,65
1	0	0	5.955,556

Now the program calculates as usual the best aggregation for the energy community. The amount of photovoltaic is set to 150 kW. Initially the cost allocation is the same used above.

Table 5.11. *Best possible aggregations in the case of simplified curves, they are ordered from the one with higher incomes to the community with lower allocated incomes (realistic curves)*

Number of residential users	Number of commercial users	Number of office users	Total earnings from the incentive $[\frac{€}{y}]$	Earnings for each user/investor $[\frac{€}{y}]$	Percentage of energy produced that is shared in the EC [%]	PV [kW]
0	4	0	14.498,00	2.908,00	55,9%	150
0	3	0	11.467,00	2.876,00	44,2%	150
0	5	0	17.177,00	2.872,00	66,2%	150
0	6	0	19.445,00	2.787,00	74,9%	150
0	7	0	21.439,00	2.689,00	82,6%	150
0	2	0	8.005,00	2.677,00	30,9%	150
0	4	1	15.862,00	2.652,00	61,1%	150
0	5	1	18.276,00	2.619,00	70,4%	150
0	3	1	12.913,00	2.590,00	49,8%	150
0	8	0	23.043,00	2.569,00	88,8%	150
0	6	1	20.418,00	2.560,00	78,7%	150
1	5	0	17.354,00	2.487,00	66,9%	150
0	7	1	22.223,00	2.477,00	85,6%	150
1	4	0	14.722,00	2.461,00	56,7%	150
1	6	0	19.610,00	2.459,00	75,6%	150
0	9	0	24.397,00	2.448,00	94,0%	150
0	4	2	17.065,00	2.445,00	65,8%	150
0	2	1	9.667,00	2.424,00	37,3%	150
0	5	2	19.321,00	2.423,00	74,5%	150
1	7	0	21.578,00	2.405,00	83,2%	150

In the simulation the allocation criteria were always the same, the money from the incentive are divided in equal parts. This, as demonstrated in the previous simulations, is not the ideal solution. The results are now compared with the ones of the same curves in a stand-alone optimized operation.

Table 5.12. *Optimized users in the case of stand-alone operation. The kW of PV is the optimum one to obtain the lower total costs (realistic curves)*

Number of residential users	Number of commercial users	Number of office users	PV installed [kW]	**Tot INV costs [€/y]**	**OP costs [€/y]**	**final cost 1 user [€/y]**
0	0	1	15.61	1.780,00	2.368,00	4.148,00
0	1	0	34.10	3.889,00	7.566,00	11.455,00
1	0	0	2.65	303,00	854,00	1.156,00

In table 5.12, Tot INV cost is the annual investment + maintenance cost for the photovoltaic installation, while the OP cost is the operational cost, meaning, the annual cost of imported energy in which PV energy's export earnings are subtracted. These are the cost in case of optimized solution on the economic point of view. Next step is to compare the case of optimal aggregation, that means 4 commercial users, with the commercial user alone.

Table 5.13. *Analysis of the final cost for a single commercial user in the best aggregation, with a purchasing cost of 250 €/MWh and a 110 €/MWh incentive*

Number of residential users	Number of commercial users	Number of office users	Total earnings from the incentive $[\frac{€}{y}]$	Earnings for each user/investor $[\frac{€}{y}]$	Percentage of energy produced that is shared in the EC [%]	PV [kW]
0	4	0	14.498,00 €	2.908,00 €	55.9 %	150
				OP costs [€/y]	**tot cost Commercial [€/y]**	**final cost 1 commercial [€/y]**
				16.056,00	16.056,00	13.148,00 €

Comparing the "final cost one commercial" in the best aggregation and the single-user operation the result is always the same, the commercial user prefers to remain alone instead of entering the community. However, in a real situation is the investor that has the power to decide which is the incomes to give to the users. He would rather keep more money than the one with equal subdivision of money. So, the idea is to change the allocation of money.

5.2.1 New money allocation criteria

With this new allocation criteria, the investor has to ensure that users receive at least the amount of money they would save by installing their individual photovoltaic systems. This assurance is calculated using the following formula:

$$\begin{aligned} mmg = \left(res_{agg} - res_{opt}\right) * A + \left(comm_{agg} - comm_{opt}\right) * B \\ + \left(off_{agg} - off_{opt}\right) * C \end{aligned} \tag{5.1}$$

Here, mmgmmg represents the minimum money to be guaranteed, and A, B, and C denote the number of residential, commercial, and office users in the aggregation, respectively. The subscripts opt and agg refer to the single-user optimal solution (stand-alone optimized user) and the aggregation (money spent in the joined energy community), respectively. The disparity between user_agg and user_opt signifies the amount the investor must guarantee to the user to incentivize their participation in the community. In other words, it is the difference between the user expenses in business as usual operation, all imported energy from the grid, and the expenses of the optimized user, imported energy, installation of PV and self-consumption + export.

Table 5.14. *Costs for the optimal solution in the stand-alone operation and the aggregation solution, purchasing cost of 250€/MWh, 110€/MWh incentive (residential, commercial and office)*

/	**User business as usual operation ($User_{agg}$)[$\frac{€}{y}$]**	**User stand-alone optimal operation ($User_{opt}$)[$\frac{€}{y}$]**	$User_{agg} - User_{opt}$ [$\frac{€}{y}$]
Residential	1.493,00	1.156,00	337,00
Commercial	16.056,00	11.455,00	4.601,00
Office	6.291,00	4.148,00	2.143,00

Table 5.15. *minimum money to be guaranteed and investor maximum earnings in the case of aggregation with residential, commercial and office users, purchasing cost of 250 €/MWh, 110 €/MWh incentive (150 kW PV)*

Number of residential users	Number of commercial users	Number of office users	Total earnings from the incentive $[\frac{€}{y}]$	Earnings for each user/investor $[\frac{€}{y}]$	Percentage of energy produced that is shared in the EC [%]	mmg [€/y]	**Investor's gain** $[\frac{€}{y}]$
5	0	0	1.805,00	302,00	7,0%	1.685,00	120,00
4	0	0	1.467,00	294,00	5,7%	1.348,00	119,00
6	0	0	2.140,00	307,00	8,2%	2.022,00	118,00
7	0	0	2.476,00	310,00	9,5%	2.359,00	117,00
8	0	0	2.804,00	313,00	10,8%	2.696,00	108,00
3	0	0	1.114,00	279,00	4,3%	1.011,00	103,00
9	0	0	3.130,00	314,00	12,1%	3.033,00	97,00
2	0	0	758,00	253,00	2,9%	674,00	84,00
10	0	0	3.442,00	314,00	13,3%	3.370,00	72,00
1	0	0	393,00	197,00	1,5%	337,00	56,00
11	0	0	3.750,00	314,00	14,5%	3.707,00	43,00
12	0	0	4.058,00	313,00	15,6%	4.044,00	14,00
13	0	0	4.361,00	313,00	16,8%	4.381,00	-20,00
14	0	0	4.656,00	311,00	17,9%	4.718,00	-62,00
15	0	0	4.950,00	310,00	19,1%	5.055,00	-105,00
2	0	1	2.695,00	676,00	10,4%	2.817,00	-122,00
3	0	1	3.023,00	606,00	11,6%	3.154,00	-131,00
1	0	1	2.348,00	785,00	9,0%	2.480,00	-132,00

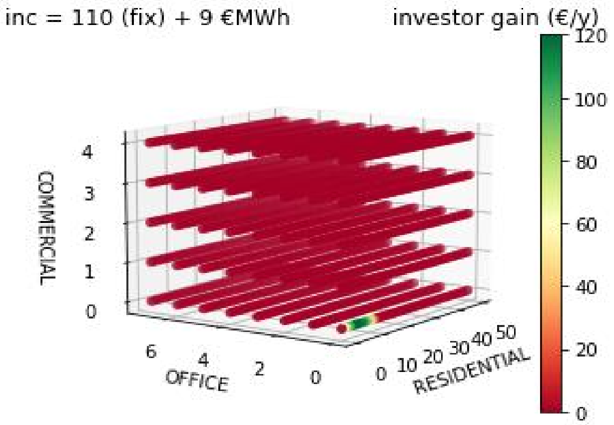


Figure 5.7. *Investor gain for different combination of office, residential and commercial users with an electricity purchasing cost of 250 €/MWh, and an incentive of 110 + 9 €/MWh. The figure is the graphical representation of table 5.15*

Table 5.15 illustrates the outcomes for the most favourable aggregation scenario for the investor. In table are reported the number of type of users in the EC, the total earnings obtained through the inventive for the shared energy (110 + 9 €/MWh), the percentage of energy produced that is effectively shared, the money that the investor has to guarantee to the users to convince them to join the energy community and the final investor gains that are calculated as the difference between total earnings and mmg. At the forefront is the community that ensures the highest gain for the investor. The investor's gain is determined by the formula:

$$\text{Investor's } gain = \frac{€}{y} - mmg \tag{5.2}$$

This is equivalent to the difference between the money received from the incentive and the minimum guaranteed amount. Notably, among the top 20 energy communities, only the last aggregation includes an office user, while all others consist solely of residential users with no commercial users. Although the value of earnings for each user (the parameter used when the allocation criteria was the equal distribution of earnings among the users) is lower compared to the values in tables 5.5 and 5.2, the investor's gain is not significantly high, especially when contrasted with the best aggregation in table 5.2. This suggests that the investor is inclined to form an energy community primarily with residential users, a result that appears contrary to the findings with gain equal splitting. However, the gains are not substantial due to the lower value of the incentive. Users with lower energy demands during daylight hours are more inclined to join the community. The rationale behind this trend could be that commercial and office users, with higher daytime energy demands and financial resources, are more likely to independently install their photovoltaic systems. These users might demand higher compensation from the PV system owner, thereby reducing the maximum potential gain for the investor. Simultaneously, the lower residential electricity demand during the day might not justify the installation of a substantial amount of PV. In this context, energy communities may not be as appealing. Furthermore, the percentage of exploited incentive is almost negligible, falling below 10% of PV exploited in the aggregation for the first five communities.

Chapter 6 – Sensitivity analyses

Sensitivity analyses chapter aims to understand the behaviour of the energy community as certain parameters change. These parameters are:

- Purchasing cost of electricity from the grid.
- Incentive value for the energy shared in the energy community (In Italy is fixed to 110 €/MWh + 9 €/MWh).
- Electrical load.
- Amount of photovoltaic installed by the investor.
- Maximum amount of photovoltaic installable by the user in the stand-alone operation

The analyses in this chapter lead to the conclusion that the incentive should be directly related to the value of the electricity purchasing cost and to the percentage of photovoltaic energy produced that is then consumed by the energy community's members. The analyses continue with the proposal of a new incentive for the energy communities in the chapter 6.4. To convince the investor to exploit a higher amount of photovoltaic energy sharing it with a higher number of users, the incentive should consist of a fixed part and a variable one (both changes depending on the value of the electricity purchasing cost from the grid). The variable part of the incentive would be proportional to the percentage of the energy produced by photovoltaic panels exploited (shared among the energy community's users).

6.1 Variable electricity purchasing cost and shared energy incentive value

The chapter starts with some analysis of the energy community's behaviour if the purchasing cost of electricity change.

Table 6.1. *minimum money to be guaranteed and investor maximum earnings in the case of aggregation with residential, commercial and office users, with a purchasing cost of 300 €/MWh and a 110 €/MWh incentive*

Number of residential users	Number of commercial users	Number of office users	Total earnings from the incentive $[\frac{€}{y}]$	Earnings for each user/investor $[\frac{€}{y}]$	Percentage of energy produced that is shared in the EC [%]	mmg [€/y]	**Investor's gain** $[\frac{€}{y}]$
1	0	0	393,00	197,00	1,5%	450,00	-57,00
2	0	0	758,00	253,00	2,9%	900,00	-142,00
3	0	0	1.114,00	279,00	4,3%	1.350,00	-236,00
4	0	0	1.467,00	294,00	5,7%	1.800,00	-333,00
5	0	0	1.805,00	302,00	7,0%	2.250,00	-445,00
6	0	0	2.140,00	307,00	8,2%	2.700,00	-560,00
7	0	0	2.476,00	310,00	9,5%	3.150,00	-674,00
8	0	0	2.804,00	313,00	10,8%	3.600,00	-796,00
0	0	1	1.999,00	1.002,00	7,7%	2.841,00	-842,00

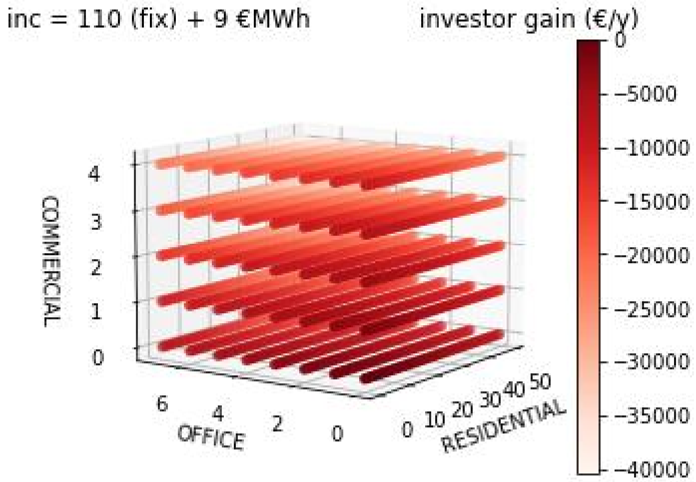


Figure 6.1. *Investor gain for different combination of office, residential and commercial users with an electricity purchasing cost of 300 €/MWh, and an incentive of 110 + 9 €/MWh. The figure is the graphical representation of table 6.1*

In table are reported the number of type of users in the EC, the total earnings obtained through the inventive for the shared energy (110 + 9 €/MWh), the percentage of energy produced that is effectively shared, the money that the investor has to guarantee to the users to convince them to join the energy community and the final investor gains that are calculated as the difference between total earnings and mmg. Table 6.1 (and figure 6.1) presents the optimal aggregations arranged by "maximum investor's gain" with an incentive set at 110 €/MWh and an electricity purchasing cost of 300 €/MWh, 50 €/MWh higher than the standard 250 €/MWh used in the preceding section. Notably, the investor's gain remains consistently negative, and the percentage of exploited incentive is even lower compared to the previous analysis. In this scenario, characterized by a higher electricity purchasing cost and a modest incentive of 110 + 9 €/MWh, the aggregation proves to be impractical for both the investor and the users.

Table 6.2. *Costs for the optimal solution in the stand-alone operation and the aggregation solution, purchasing cost of 300€/MWh, 110€/MWh incentive (residential, commercial and office)*

/	**User business as usual operation ($User_{agg}$)$[\frac{€}{y}]$**	**User stand-alone optimal operation ($User_{opt}$)$[\frac{€}{y}]$**	$User_{agg} - User_{opt}$ $[\frac{€}{y}]$
Residential	1.792,00	1.341,00	451,00
Commercial	19.267,00	13.162,00	6.105,00
Office	7.549,00	4.707,00	2.842,00

Table 6.2 presents the expenses in case of user's business as usual operation (all imported electricity) and optimized solution (import + PV installation). The investor has to leave a higher amount of the incentive incomes to the users given that the incentive is fixed while the electricity price is higher. Table 6.2 shows the difference respect to the case with 250 €/MWh. With a higher purchasing costs users are more likely to install their own photovoltaic. They prefer to install the PV system and self-consume the electricity instead of joining the community and buy all the energy from the grid. The opposite will happen with a decreasing cost of the electricity.

Table 6.3. *minimum money to be guaranteed and investor maximum earnings in the case of aggregation with residential, commercial and office users, with a purchasing cost of 200 €/MWh and a 110+9 €/MWh incentive*

Number of residential users	Number of commercial users	Number of office users	Total earnings from the incentive $[\frac{€}{y}]$	Earnings for each user/investor $[\frac{€}{y}]$	Percentage of energy produced that is shared in the EC [%]	mmg [€/y]	**Investor's gain** $[\frac{€}{y}]$
38	0	0	11.021,00	283,00	42,5%	8.626,00	2.395,00
37	0	0	10.792,00	285,00	41,6%	8.399,00	2.393,00
39	0	0	11.243,00	282,00	43,3%	8.853,00	2.390,00
33	0	1	11.329,00	325,00	43,7%	8.948,00	2.381,00
34	0	1	11.555,00	322,00	44,5%	9.175,00	2.380,00
40	0	0	11.459,00	280,00	44,2%	9.080,00	2.379,00
36	0	0	10.551,00	286,00	40,7%	8.172,00	2.379,00
32	0	1	11.093,00	327,00	42,8%	8.721,00	2.372,00
35	0	1	11.770,00	319,00	45,4%	9.402,00	2.368,00

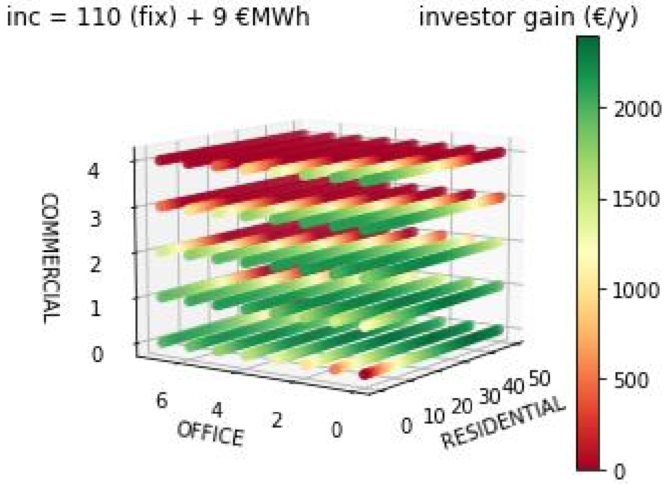


Figure 6.2. *Investor gain for different combination of office, residential and commercial users with an electricity purchasing cost of 200 €/MWh, and an incentive of 110 + 9 €/MWh. The figure is the graphical representation of table 6.3*

Table 6.3 (and table 6.2) demonstrates that ECs are more feasible if the electricity purchasing cost decreases. Higher percentage of incentive exploited means also higher energy produced and used locally where is needed. This reduces a lot the indirect emissions due do grid losses. In figure 6.2 it is graphically shows that there is not a singular best solution but a range of combination of residential, commercial and office users that lead to good investor's gain. The same will probably happen with fixed electricity cost and variable incentive value.

Table 6.4. *minimum money to be guaranteed and investor maximum earnings in the case of aggregation with residential, commercial and office users, with a purchasing cost of 250 €/MWh and a 150+9 €/MWh incentive*

Number of residential users	Number of commercial users	Number of office users	Total earnings from the incentive $[\frac{€}{y}]$	Earnings for each user/investor $[\frac{€}{y}]$	Percentage of energy produced that is shared in the EC [%]	mmg [€/y]	**Investor's gain** $[\frac{€}{y}]$
32	0	0	12.780,00	388,00	36,9%	10.784,00	1.996,00
33	0	0	13.116,00	387,00	37,8%	11.121,00	1.995,00
31	0	0	12.439,00	390,00	35,9%	10.447,00	1.992,00
34	0	0	13.449,00	385,00	38,8%	11.458,00	1.991,00
30	0	0	12098,00	391,00	34,9%	10.110,00	1.988,00
29	0	0	11.756,00	393,00	33,9%	9.773,00	1.983,00
35	0	0	13.774,00	384,00	39,7%	11.795,00	1.979,00
28	0	0	11.415,00	395,00	32,9%	9.436,00	1.979,00
27	0	0	11.067,00	397,00	31,9%	9.099,00	1.968,00

Table 6.4 presents the same type of data of the previous tables (number of users for combination, investor gain, mmg, percentage of exploited energy). The percentage of PV energy produced exploited and maximum gains values are elevated compared to Table 5.15, given a 40 € increase in the incentive to 150 €/MWh. The augmented incentive allows the investor to distribute more energy during production hours, benefiting both the investor and the environment. All examples were examined with a 150 kW PV system. The subsequent exploration involves investigating the outcomes with the same purchasing cost, users, and incentive value but with a reduced amount of photovoltaic.

6.2 Variable loads and PV capacity

Table 6.5. *minimum money to be guaranteed and investor maximum earnings in the case of aggregation with residential, commercial and office users, purchasing cost of 250 €/MWh, 110 €/MWh incentive (100 kW PV)*

Number of residential users	Number of commercial users	Number of office users	Total earnings from the incentive $[\frac{€}{y}]$	Earnings for each user/investor $[\frac{€}{y}]$	Percentage of energy produced that is shared in the EC [%]	mmg [€/y]	**Investor's gain** $[\frac{€}{y}]$
3	0	0	1.091,00	273,00	6,3%	1.011,00	80,00
4	0	0	1.426,00	286,00	8,2%	1.348,00	78,00
5	0	0	1.760,00	294,00	10,2%	1.685,00	75,00
2	0	0	742,00	248,00	4,3%	674,00	68,00
6	0	0	2.086,00	299,00	12,1%	2.022,00	64,00
1	0	0	384,00	192,00	2,2%	337,00	47,00
7	0	0	2.397,00	300,00	13,9%	2.359,00	38,00
8	0	0	2.705,00	301,00	15,6%	2.696,00	9,00
9	0	0	3.005,00	301,00	17,4%	3.033,00	-27,00

Table 6.5 demonstrates the influence of the installed photovoltaic capacity on the outcomes. Utilizing 2/3 of the installed capacity results in a proportional decrease in aggregated users and exploited incentive. Nevertheless, the overall gains diminish due to the reduced amount of shared energy, reflecting a scaled-down version of the scenario with full capacity utilization. Conversely, an increase in photovoltaic capacity attracts more users to the community, maintaining a consistent percentage of incentive exploitation. The gains, however, surge due to the augmented shared energy. The trade-off lies in higher installation costs, contingent upon the investor's objectives. Lastly, exploring a scenario with the same residential curve shape but higher loads could offer additional insights for the analysis.

Table 6.6. *minimum money to be guaranteed and investor maximum earnings in the case of aggregation with residential user (5x load), with a purchasing cost of 250 €/MWh and a 110 €/MWh incentive and 750 kW PV*

Number of residential users	Number of commercial users	Number of office users	Total earnings from the incentive $[\frac{€}{y}]$	Earnings for each user/investor $[\frac{€}{y}]$	Percentage of energy produced that is shared in the EC [%]	mmg [€/y]	**Investor's gain** $[\frac{€}{y}]$
5	0	0	9.025,00	1.509,00	7,0%	8.425,00	600,00
4	0	0	7.337,00	1.472,00	5,7%	6.740,00	59700
6	0	0	10.702,00	1.534,00	8,2%	10.110,00	592,00
7	0	0	12.378,00	1.552,00	9,5%	11.795,00	583,00
8	0	0	14.021,00	1.563,00	10,8%	13.480,00	541,00
3	0	0	5.572,00	1.397,00	4,3%	5.055,00	517,00
9	0	0	15.651,00	1.570,00	12,1%	15.165,00	486,00
2	0	0	3.790,00	1.267,00	2,9%	3.370,00	420,00
10	0	0	17.212,00	1.570,00	13,3%	16.850,00	362,00

In the scenario with a fivefold increase in residential user loads, the aggregation yields higher incomes for both users and the investor. However, this comes with the caveat that the investor needs to install a substantial amount of photovoltaic capacity, and only a small percentage of the incentive is exploited. It's worth noting that increasing the number of photovoltaic units doesn't alter the percentage of exploited incentive as long as the load and curve shape remain fixed. This underscores the importance of carefully considering the balance between increased energy production and the associated costs in the context of higher user loads.

Table 6.7 *minimum money to be guaranteed and investor maximum earnings in the case of aggregation with residential user (5x load), with a purchasing cost of 250 €/MWh and a 110 €/MWh incentive and 1500 kW PV*

Number of residential users	Number of commercial users	Number of office users	Total earnings from the incentive $[\frac{€}{y}]$	Earnings for each user/investor $[\frac{€}{y}]$	Percentage of energy produced that is shared in the EC [%]	mmg [€/y]	**Investor's gain $[\frac{€}{y}]$**
9	0	0	16.374,00	1.643,00	6,3%	15.165,00	1.209,00
10	0	0	18.051,00	1.646,00	7,0%	16.850,00	1.201,00
8	0	0	14.675,00	1.636,00	5,7%	13.480,00	1.195,00
11	0	0	19.727,00	1.649,00	7,6%	18.535,00	1.192,00
12	0	0	21.403,00	1.652,00	8,2%	20.220,00	1.183,00
13	0	0	23.080,00	1.654,00	8,9%	21.905,00	1.175,00
14	0	0	24.756,00	1.656,00	9,5%	23.590,00	1.166,00
7	0	0	12.925,00	1.621,00	5,0%	11.795,00	1.130,00
15	0	0	26.401,00	1.655,00	10,2%	25.275,00	1.126,00

Table 6.7 demonstrates what just said. The percentage incentive is still lower than 10% although more photovoltaic is installed. The gains are higher but there are not other benefits.

Table 6.8. *minimum money to be guaranteed and investor maximum earnings in the case of aggregation with residential user (10x load), with a purchasing cost of 250 €/MWh and 110 €/MWh incentive and 1500 kW PV*

Number of residential users	Number of commercial users	Number of office users	Total earnings from the incentive $[\frac{€}{y}]$	Earnings for each user/investor $[\frac{€}{y}]$	Percentage of energy produced that is shared in the EC [%]	mmg [€/y]	**Investor's gain $[\frac{€}{y}]$**
5	0	0	18.051,00	3.018,00	7,0%	16.850,00	1.201,00
4	0	0	14.675,00	2.944,00	5,7%	13.480,00	1.195,00
6	0	0	21.403,00	3.067,00	8,2%	20.220,00	1.183,00
7	0	0	24.756,00	3.104,00	9,5%	23.590,00	1.166,00
8	0	0	28.043,00	3.126,00	10,8%	26.960,00	1.083,00
3	0	0	11.143,00	2.794,00	4,3%	10.110,00	1.033,00
9	0	0	31.302,00	3.140,00	12,1%	30.330,00	972,00
2	0	0	7.580,00	2.535,00	2,9%	6.740,00	840,00
10	0	0	34.424,00	3.139,00	13,3%	33.700,00	724,00

As the residential user load increases further, the scenario becomes less favorable. With a tenfold increase in load, the investor needs to install 1.5 MW of photovoltaic capacity to achieve significant gains. However, this appears to be environmentally and economically questionable. The system owner would incur substantial installation costs but would only be able to activate the incentive for a fraction, again lower than 10%, of the produced energy. This trend holds true for office and commercial users as well, although the advantages obtained in these cases are consistently lower and not comparable to those achieved with residential users only.

6.3 Not optimized users

In all the previous analyses, users were compared in the context of aggregation and stand-alone operation. However, in these final analyses, a new assumption is introduced: users are situated in a condominium with restricted rooftop space, limiting the available area for photovoltaic installations. Consequently, the photovoltaic capacity is constrained to 2/3 of the optimal solution for each user type. For instance, consider an apartment complex with 5 residential units and 2 offices, where limited rooftop space allows only 38.15 kW of PV installation. In contrast, optimized users would require a minimum of 58 kW of photovoltaic capacity to function optimally (as shown in table 5.12).

Table 6.9. *No-optimized users in the case of stand-alone operation. The kW of PV is 2/3 respect to the optimum one to obtain the lower total costs (realistic curves)*

Number of Residential users	Number of Commercial users	Number of office users	PV installed [kW]	**Tot INV costs [€/y]**	**OP costs [€/y]**	**final cost 1 user [€/y]**
0	0	1	10	1.141,00	3.166,00	4.306,00
0	1	0	23	2.623,00	9.071,00	11.694,00
1	0	0	1.75	200,00	974,00	1.173,00

The first case is the analysis of the system in the situation with maximum 2/3 of the best photovoltaic installable capacity. The best stand-alone operation results are shown in table 5.12.

Table 6.10. *minimum money to be guaranteed and investor maximum earnings in the case of aggregation with not optimized users (2/3 of the best photovoltaic capacity), with a purchasing cost of 250 €/MWh and 110 €/MWh incentive and 150 kW PV*

Number of residential users	Number of commercial users	Number of office users	Total earnings from the incentive $[\frac{€}{y}]$	Earnings for each user/investor $[\frac{€}{y}]$	Percentage of energy produced that is shared in the EC [%]	mmg [€/y]	**Investor's gain** $[\frac{€}{y}]$
9	0	0	3.130,00	314,00	12,1%	2.880,00	250,00
8	0	0	2.804,00	313,00	10,8%	2.560,00	244,00
10	0	0	3.442,00	314,00	13,3%	3.200,00	242,00
7	0	0	2.476,00	310,00	9,5%	2.240,00	236,00
11	0	0	3.750,00	314,00	14,5%	3.520,00	230,00
6	0	0	2.140,00	307,00	8,2%	1.920,00	220,00
12	0	0	4.058,00	313,00	15,6%	3.840,00	218,00
5	0	0	1.805,00	302,00	7,0%	1.600,00	205,00
13	0	0	3.130,00	313,00	16,8%	2.880,00	250,00

A comparison between this table and Table 5.15, which illustrates the maximum gain in the case of aggregation with the same investor having 150 kW of PV, along with identical incentive and purchasing cost values, reveals that when space availability for individual users is constrained, their inclination to participate in an energy community increases. This is evident in the higher maximum gain for the investor. Additionally, from an environmental standpoint, the outcomes are favorable, as a greater percentage of the incentive is exploited. Thus, with the same PV capacity installed, more energy is utilized locally. Further improvements can be expected if the limit on photovoltaic installation is reduced from 2/3 to 1/2 of the optimal solution.

Table 6.11. *No-optimized users in the case of stand-alone operation. The kW of PV is 1/2 respect to the optimum one to obtain the lower total costs (realistic curves)*

Number of Residential users	Number of Commercial users	Number of office users	PV installed [kW]	**Tot INV costs [€/y]**	**OP costs [€/y]**	**final cost 1 user [€/y]**
0	0	1	7.5	856,00	3.686,00	4.541,00
0	1	0	17	1.939,00	10.192,00	12.131,00
1	0	0	1.3	148,00	1.055,00	1.204,00

Table 6.11 shows the final cost for the single user solution but with only half of the photovoltaic capacity that would be available in the optimal solution.

Table 6.12. *minimum money to be guaranteed and investor maximum earnings in the case of aggregation with not optimized users (1/2 of the best photovoltaic capacity), with a purchasing cost of 250 €/MWh and 110 €/MWh incentive and 150 kW PV*

Number of residential users	Number of commercial users	Number of office users	Total earnings from the incentive $[\frac{€}{y}]$	Earnings for each user/investor $[\frac{€}{y}]$	Percentage of energy produced that is shared in the EC [%]	mmg [€/y]	**Investor's gain** $[\frac{€}{y}]$
18	0	0	5.832,00	308,00	22,5%	5.202,00	630,00
19	0	0	6.116,00	307,00	23,6%	5.491,00	625,00
17	0	0	5.538,00	309,00	21,3%	4.913,00	625,00
16	0	0	5.244,00	309,00	20,2%	4.624,00	620,00
15	0	0	4.950,00	310,00	19,1%	4.335,00	615,00
20	0	0	6.394,00	305,00	24,6%	5.780,00	614,00
14	0	0	4.656,00	311,00	17,9%	4.046,00	610,00
13	0	0	4.361,00	313,00	16,8%	3.757,00	604,00
21	0	0	6.668,00	304,00	25,7%	6.069,00	599,00

Results are more interesting in table 6.12, the percentage incentive exploited is greater than the one in table 6.11 where 2/3 of the maximum capacity was used. The gains are higher than both the case of 2/3 optimal PV but also respect to the optimized users.

Table 6.12. *minimum money to be guaranteed and investor maximum earnings in the case of aggregation with not optimized users (1/2 of the best photovoltaic capacity), with a purchasing cost of 250 €/MWh and 130 €/MWh incentive and 150 kW PV*

Number of residential users	Number of commercial users	Number of office users	Total earnings from the incentive $[\frac{€}{y}]$	Earnings for each user/investor $[\frac{€}{y}]$	Percentage of energy produced that is shared in the EC [%]	mmg [€/y]	**Investor's gain** $[\frac{€}{y}]$
9	0	5	13.442,00	899,00	44,3%	11.346,00	2.096,00
6	0	6	14.323,00	1.105,00	47,3%	12.228,00	2.095,00
10	0	5	13.726,00	861,00	45,3%	11.635,00	2.091,00
5	0	6	14.024,00	1.172,00	46,3%	11.939,00	2.085,00
7	0	6	14.601,00	1.046,00	48,2%	12.517,00	2.084,00
8	0	5	13.141,00	941,00	43,4%	11.057,00	2.084,00
13	0	4	12.836,00	715,00	42,3%	10.753,00	2.083,00
14	0	4	13.121,00	693,00	43,3%	11.042,00	2.079,00
11	0	5	14.002,00	826,00	46,2%	11.924,00	2.078,00

Elevating the incentive value results in an automatic increase in gains and shared energy, fostering greater local utilization of the generated photovoltaic energy. In contrast to the analysis with a 110 + 9 €/MWh incentive, the inclusion of office users in the first ten energy communities becomes apparent. This inclusion guarantees higher energy consumption during daylight hours, consequently contributing to a higher percentage of incentive exploitation.

6.4 comparison between the single optimized user and the aggregations with the introduction of a new incentive

The aim of this section is to assess the utilization of locally produced photovoltaic energy. Specifically, the goal is to evaluate the actual exploitation of photovoltaic energy at its source. During production hours, some of the generated energy may not be utilized locally but is shared among other users. As indicated in table 5.15, only a portion of the produced energy, less than 10%, is genuinely used locally. An interesting concept is to introduce an incentive that varies based on the percentage of energy exploited from the photovoltaic source.

6.4.1 Incentive with a fixed part and a variable part

Initially, it is appropriate to create a plot similar to table 5.15. In this scenario, the photovoltaic capacity remains constant at 150 kW. However, as demonstrated in Chapter 6, varying the amount of photovoltaic capacity does not alter the investor's behaviour. The preference for residential users persists, and the percentage incentive remains unchanged.

Table 6.13. *minimum money to be guaranteed and investor maximum earnings in the case of aggregation with residential, commercial and office users, purchasing cost of 250 €/MWh, 110+9 €/MWh incentive (150 kWPV)*

Number of residential users	Number of commercial users	Number of office users	Total earnings from the incentive $[\frac{€}{y}]$	Earnings for each user/investor $[\frac{€}{y}]$	Percentage of energy produced that is shared in the EC [%]	mmg [€/y]	**Investor's gain $[\frac{€}{y}]$**
5	0	0	1.805,00	302,00	7,0%	1.685,00	120,00
4	0	0	1.467,00	294,00	5,7%	1.348,00	119,00
6	0	0	2.140,00	307,00	8,2%	2.022,00	118,00
7	0	0	2.476,00	310,00	9,5%	2.359,00	117,00
8	0	0	2.804,00	313,00	10,8%	2.696,00	108,00
3	0	0	1.114,00	279,00	4,3%	1.011,00	103,00
9	0	0	3.130,00	314,00	12,1%	3.033,00	97,00
2	0	0	758,00	253,00	2,9%	674,00	84,00
10	0	0	3.442,00	314,00	13,3%	3.370,00	72,00

The number of users participating in the aggregation is minimal, and the utilization of photovoltaic energy is extremely limited, with only 7% of the incentive being employed. In this scenario, a mere 7% of the produced energy is utilized locally, while the remaining 93% is distributed among other users on the grid. This situation hinders the achievement of the energy community's goals. One potential solution is to introduce an incentive tied to the amount of shared energy, thereby depending on the percentage of produced energy that is shared (referred to as the percentage incentive in the table). The new incentive model is structured as follows:

- Fixed incentive
- Variable incentive

It is not feasible to maintain a fixed incentive perpetually. Therefore, it would be more effective to implement an incentive that varies based on the electricity purchasing cost. Commencing with a 250 €/MWh electricity purchasing cost, the incentive is calculated using the following formula:

- Fixed_incentive = 110 €/MWh
- Variable_incentive = 70 €/MWh
- Losses avoided = 9 €/MWh

The incentive values is calculated as follows:

- Incentive_value = fixed_incentive + variable_incentive * percentage_PPV_shared + avoided losses

The percentage of PPV shared is the energy produced by the photovoltaic that is effectively shared. So the total amount of money earned thanks to the incentive are:

- Inc = incentive_values/1000 * PEXC[h,k] fo h in range H and k in range K (*WTD to obtain the entire year)

In this way, the incentive increases if the aggregated users increase. The investor is now more interested in an aggregation that permit him to exploit as much as possible the energy produced.

Table 6.14. *minimum money to be guaranteed and investor maximum earnings in the case of aggregation with residential, commercial and office users, purchasing cost of 250 €/MWh, variable incentive (150 kW PV)*

Number of residential users	Number of commercial users	Number of office users	Total earnings from the incentive $[\frac{€}{y}]$	Earnings for each user/investor $[\frac{€}{y}]$	Percentage of energy produced that is shared in the EC [%]	mmg [€/y]	**Investor's gain $[\frac{€}{y}]$**
29	0	6	23.901,00	664,00	66,3%	22.631,00	1.270,00
28	0	6	23.552,00	673,00	65,5%	22.294,00	1.258,00
30	0	6	24.221,00	655,00	67,0%	22.968,00	1.253,00
23	1	5	24.318,00	811,00	67,2%	23.066,00	1.252,00
24	1	5	24.652,00	795,00	67,9%	23.403,00	1.249,00
23	0	7	23.997,00	774,00	66,5%	22.752,00	1.245,00
35	0	5	23.753,00	579,00	66,0%	22.510,00	1.243,00
34	0	5	23.413,00	585,00	65,2%	22.173,00	1.240,00
22	0	7	23.652,00	788,00	65,7%	22.415,00	1.237,00
24	0	7	24.326,00	760,00	67,2%	23.089,00	1.237,00
22	1	5	23.965,00	826,00	66,4%	22.729,00	1.236,00
31	0	6	24.539,00	646,00	67,6%	23.305,00	1.234,00
27	0	6	23.190,00	682,00	64,7%	21.957,00	1.233,00
36	0	5	24.078,00	573,00	66,7%	22.847,00	1.231,00
33	0	5	23.065,00	591,00	64,5%	21.836,00	1.229,00
29	1	4	24.171,00	691,00	66,9%	22.945,00	1.226,00
21	0	7	23.304,00	804,00	65,0%	22.078,00	1.226,00
25	1	5	24.962,00	780,00	68,6%	23.740,00	1.222,00
28	1	4	23.830,00	701,00	66,1%	22.608,00	1.222,00
21	1	5	23.610,00	843,00	65,6%	22.392,00	1.218,00

Table 6.15. *minimum money to be guaranteed and investor maximum earnings in the case of aggregation with residential users, purchasing cost of 250 €/MWh, variable incentive (150 kW PV)*

Number of residential users	Number of commercial users	Number of office users	Total earnings from the incentive $[\frac{€}{y}]$	Earnings for each user/investor $[\frac{€}{y}]$	Percentage of energy produced that is shared in the EC [%]	mmg [€/y]	**Investor's gain** $[\frac{€}{y}]$
56	0	0	19.848,00	348,00	57,2%	18.872,00	976,00
57	0	0	20.181,00	348,00	58,0%	19.209,00	972,00
38	0	0	13.774,00	353,00	42,5%	12.806,00	968,00
55	0	0	19.503,00	348,00	56,4%	18.535,00	968,00
39	0	0	14.109,00	353,00	43,3%	13.143,00	966,00
37	0	0	13.433,00	353,00	41,6%	12.469,00	964,00
54	0	0	19.159,00	348,00	55,6%	18.198,00	961,00
58	0	0	20.506,00	348,00	58,7%	19.546,00	960,00
53	0	0	18.818,00	348,00	54,8%	17.861,00	957,00
50	0	0	17.806,00	349,00	52,4%	16.850,00	956,00
40	0	0	14.436,00	352,00	44,2%	13.480,00	956,00
52	0	0	18.479,00	349,00	54,0%	17.524,00	955,00
51	0	0	18.142,00	349,00	53,2%	17.187,00	955,00
49	0	0	17.467,00	349,00	51,6%	16.513,00	954,00
59	0	0	20.832,00	347,00	59,5%	19.883,00	949,00
41	0	0	14.765,00	352,00	45,0%	13.817,00	948,00
48	0	0	17.122,00	349,00	50,8%	16.176,00	946,00
36	0	0	13.074,00	353,00	40,7%	12.132,00	942,00
42	0	0	15.095,00	351,00	45,8%	14.154,00	941,00
60	0	0	21.160,00	347,00	60,2%	20.220,00	940,00

Table 6.14 and 6.15 presents: number and type of users aggregated in an EC (table 6.14 take into account both residential, commercial and office while table 6.15 only residential users to compare the results with the results in chapter 5), total earnings from the shared energy incentive, mmg, percentage of energy produced by PV that is used by the community members (shared energy) and the investor gain. The variable incentive model exhibits promising outcomes for promoting the expansion of energy communities. The utilization of shared energy significantly increases, and even offices and commercial users are incorporated, although residential users remain the primary option (refer to table 6.15 for the case with only

residential users to facilitate comparison with the previous incentive). The gains are higher, and the percentage of photovoltaic energy exploited in the energy community, comparing the total shared energy to the produced energy, is notably elevated. Although it does not reach 100%, this is not necessarily a drawback. From an environmental standpoint, exploiting 100% of the incentive with these load curves might not be the optimal solution, as it could result in lower energy availability for each user. This would lead to higher energy purchases from the grid, subsequently increasing emissions. Therefore, it would be insightful to compare emissions in the case of single-user operation with those of the energy community. The assumed average indirect emissions from using energy from the grid and from using photovoltaic energy (considering the entire life cycle) are:

- Emissions from energy imported from the grid = 356 kgCO2/MWh
- Emissions from energy produced by PV = 50 kgCO2/MWh

In the case of energy communities (ECs), to calculate emissions accurately, the imported energy is determined as fictitious. In this context, only the energy not imported during photovoltaic non-production hours is considered as imported. Conversely, all the energy produced by the PV is factored into the calculation. Thus, whether there is one user or a hundred, the energy produced is the output from the 150 kW of photovoltaic panels.

Table 6.16. *Emissions in case of single user operation for each user (realistic residential, commercial and office curves)*

Number of Residential users	Number of Commercial users	Number of Office users	**Ghg Emissions [kgCO2]**
0	0	1	5.140,00
0	1	0	14.666,00
1	0	0	1.526,00

Table 6.16 shows the emissions in kgCO2 for each user. This is the case of optimal operation, so the calculations are made considering the results in chapters 5 and 6 (table 5.12).

Table 6.17. *Emissions comparison in the case of single user operation and aggregation with residential, commercial and office users, purchasing cost of 250 €/MWh, variable incentive (150 kW PV)*

Number of Residential users	Number of Commercial users	Number of Office users	Percentage of energy produced that is shared in the EC [%]	Single user operation emissions [kgCO2/y]	EC operation emissions [kgCO2/y]	Increase in emissions respect to the single user optimized case [kgCO2/y]	Increase in emissions respect to the single user optimized case [%]
29	0	6	66,3%	75.094,00	74.760,00	334,00	0,45%
28	0	6	65,5%	73.568,00	73.223,00	345,00	0,47%
30	0	6	67,0%	76.620,00	76.348,00	272,00	0,36%
23	1	5	67,2%	75.464,00	75.207,00	257,00	0,34%
24	1	5	67,9%	76.990,00	76.774,00	216,00	0,28%
23	0	7	66,5%	71.078,00	70.802,00	276,00	0,39%
35	0	5	66,0%	79.110,00	78.806,00	304,00	0,39%
34	0	5	65,2%	77.584,00	77.255,00	329,00	0,43%
22	0	7	65,7%	69.552,00	69.257,00	295,00	0,43%
24	0	7	67,2%	72.604,00	72.376,00	228,00	0,32%
22	1	5	66,4%	73.938,00	73.673,00	265,00	0,36%
31	0	6	67,6%	78.146,00	77.942,00	204,00	0,26%
27	0	6	64,7%	72.042,00	71.712,00	330,00	0,46%
36	0	5	66,7%	80.636,00	80.384,00	252,00	0,31%
33	0	5	64,5%	76.058,00	75.722,00	336,00	0,44%
29	1	4	66,9%	79.480,00	79.248,00	232,00	0,29%
21	0	7	65,0%	68.026,00	67.723,00	303,00	0,45%
25	1	5	68,6%	78.516,00	78.383,00	133,00	0,17%
28	1	4	66,1%	77.954,00	77.697,00	257,00	0,33%
21	1	5	65,6%	72.412,00	72.147,00	265,00	0,37%

Table 6.17 illustrates the environmental benefits of the identified optimal energy communities, which not only maximize investor gains but also contribute to lower emissions compared to single-user operations where the photovoltaic capacity is optimized. While the percentage of photovoltaic exploitation does not reach 100%, the subsequent table will shed light on why it may not be environmentally advantageous to compel the complete local utilization of all photovoltaic energy within the energy community.

Table 6.18. *Emissions comparison in the case of single user operation and aggregation with residential, commercial and office users, purchasing cost of 250 €/MWh, variable incentive (150 kW PV)*

Number of Residential users	Number of Commercial users	Number of Office users	Percentage of energy produced that is shared in the EC [%]	Single user operation emissions [kgCO2/y]	EC operation emissions [kgCO2/y]	Increase in emissions respect to the single user optimized case [kgCO2/y]	Increase in emissions respect to the single user optimized case [%]
26	3	8	91,9%	124.794,00	134.966,00	-10.172,00	-7,54%
18	6	3	92,6%	130.884,00	141.190,00	-10.306,00	-7,30%
39	4	4	92,6%	138.738,00	149.041,00	-10.303,00	-6,91%
19	4	7	92,0%	123.638,00	133.878,00	-10.240,00	-7,65%
11	7	2	92,7%	129.728,00	140.101,00	-10.373,00	-7,40%
32	5	3	92,8%	137.582,00	147.952,00	-10.370,00	-7,01%
12	5	6	92,2%	122.482,00	132.789,00	-10.307,00	-7,76%
33	3	7	92,2%	130.336,00	140.640,00	-10.304,00	-7,33%
4	8	1	92,9%	128.572,00	139.013,00	-10.441,00	-7,51%
25	6	2	92,9%	136.426,00	146.863,00	-10.437,00	-7,11%
5	6	5	92,3%	121.326,00	131.700,00	-10.374,00	-7,88%
26	4	6	92,3%	129.180,00	139.551,00	-10.371,00	-7,43%
39	5	2	93,1%	143.124,00	153.626,00	-10.502,00	-6,84%
18	7	1	93,0%	135.270,00	145.775,00	-10.505,00	-7,21%
6	4	9	91,7%	114.080,00	124.388,00	-10.308,00	-8,29%
19	5	5	92,5%	128.024,00	138.462,00	-10.438,00	-7,54%
32	6	1	93,2%	141.968,00	152.537,00	-10.569,00	-6,93%
11	8	0	93,2%	134.114,00	144.686,00	-10.572,00	-7,31%

Table 6.18 highlights a counterintuitive outcome: despite the increased percentage of shared energy in energy communities, the emissions tend to be higher compared to single-user operations. This can be attributed to the distribution of photovoltaic energy production, where a larger number of users may lead to insufficient coverage of the same portion of the load that optimized single-user operations with the ideal amount of photovoltaic would achieve. Consequently, the energy community relies more on grid imports, resulting in higher emissions.

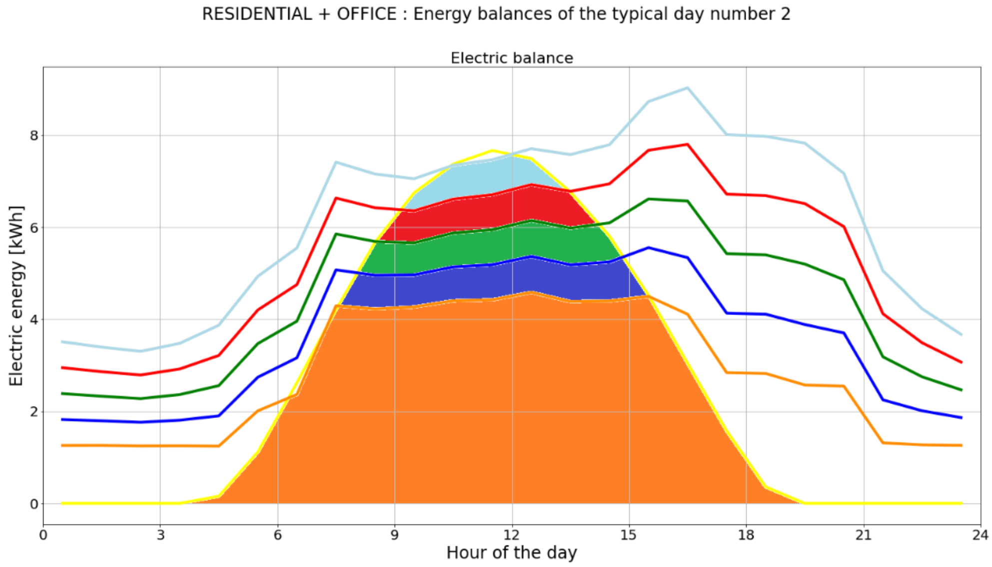


Figure 6.3. *Energy shared (1 office, some residential users and the investor)*

Figure 10.1 provides a visual representation of the described scenario. The orange line represents the office load, and the orange area signifies the energy demanded during photovoltaic production hours. Other curves and areas correspond to residential users. As more residential users are added, the area for each user (and thus the shared energy for each user) decreases until it becomes unsustainable, even with full incentive exploitation. In such situations, individual users might find it more beneficial to install their own systems. This observation is also applicable to the investor, as a higher income is counteracted by a very high number of users, leading to lower marginal gains. As discussed in Chapter 6, decreasing electricity purchasing costs pose no problems, and the investor gain is substantial, with exploited PV energy exceeding 40% at a purchasing cost of 200 €/MWh. However, with increasing electricity purchasing costs, the Energy Community (EC) appears less attractive to users. To address this, an incentive that varies based on electricity prices is proposed to encourage users to participate in the community under less favorable conditions. Initial analyses revealed a linear equation correlating total incentive:

```
total_inc = 1.38*cbuy_el - 165
```

where `cbuy_el` is the electricity purchasing cost in €/MWh. The case with:

- Electricity purchasing cost = 250 €/MWh
- Fixed incentive part = 110 €/MWh
- Variable incentive part = 70 €/MWh

- Reference incentive = fixed part + variable part = 180 €/MWh

Is taking as reference. The new value of fixed and variable part are calculated as follows:

```
diff_inc = total_inc - reference_incentive

new_fixed_inc = reference_fix_inc + diff_inc/2

new_var_inc = reference_var_inc + diff_inc/2

new_inc = new_fix_inc + new_var_inc * percentage_PPV_shared +
avoided_losses
```

in this way the value of the incentive increases if the electricity purchasing cost increases.

Table 6.19. *minimum money to be guaranteed and investor maximum earnings in the case of aggregation with residential, commercial and office users, purchasing cost of 300 €/MWh, variable incentive (150 kW PV)*

Number of residential users	Number of commercial users	Number of office users	Total earnings from the incentive $[\frac{€}{y}]$	Earnings for each user/investor $[\frac{€}{y}]$	Percentage of energy produced that is shared in the EC [%]	mmg [€/y]	**Investor's gain $[\frac{€}{y}]$**
24	1	5	33.226,00	1.072,00	67,9%	31.110,00	2.116,00
23	1	5	32.765,00	1.092,00	67,2%	30.660,00	2.105,00
19	1	6	33.800,00	1.252,00	68,8%	31.701,00	2.099,00
20	1	6	34.247,00	1.223,00	69,5%	32.151,00	2.096,00
25	1	5	33.655,00	1.052,00	68,6%	31.560,00	2.095,00
29	0	6	32.191,00	894,00	66,3%	30.096,00	2.095,00
24	0	7	32.777,00	1.024,00	67,2%	30.687,00	2.090,00
18	1	6	33.338,00	1.282,00	68,1%	31.251,00	2.087,00
23	0	7	32.323,00	1.043,00	66,5%	30.237,00	2.086,00
30	0	6	32.632,00	882,00	67,0%	30.546,00	2.086,00
31	0	6	33.070,00	870,00	67,6%	30.996,00	2.074,00
22	1	5	32.279,00	1.113,00	66,4%	30.210,00	2.069,00
17	1	6	32.869,00	1.315,00	67,3%	30.801,00	2.068,00
25	0	7	33.204,00	1.006,00	67,9%	31.137,00	2.067,00
28	0	6	31.710,00	906,00	65,5%	29.646,00	2.064,00
22	0	7	31.848,00	1.062,00	65,7%	29.787,00	2.061,00
21	1	6	34.659,00	1.195,00	70,1%	32.601,00	2.058,00
32	0	6	33.501,00	859,00	68,3%	31.446,00	2.055,00
26	1	5	34.064,00	1.032,00	69,2%	32.010,00	2.054,00
26	0	7	33.633,00	989,00	68,5%	31.587,00	2.046,00

Respect to the values in table 6.1 the energy community is now feasible with also good gains for the investor that can share energy with the users, give them part of the earnings and keep part of them. The same example could be done also for other cases. The value of the incentive is “imaginary” so were not taken into account factors such as tasses and other economic things that will obviously affect the value of the incentive.

Chapter 7 – Discussion of findings

7.1 Number and type of users to aggregate into the energy communities. Dependency of the incentive on the value of the electricity price

The thesis aims to determine the optimal user profile for an investor looking to form an energy community, seeking the best economic advantage. The key aspect of this calculation revolves around devising a strategy for distributing the funds obtained from the state shared energy's incentive. While it might be assumed that the allocation of earnings is solely at the discretion of the investor, a standardized approach is crucial for meaningful comparisons across different energy community scenarios. To address this, two distinct approaches have been considered. Initially, the straightforward method involved an equal subdivision of the earnings derived from the incentive. This approach provides a baseline for comparison and facilitates a clearer evaluation of the economic implications across various analysed cases. In simpler terms, within an energy community consisting of three users and one investor, with a total of 100 € earned from the shared energy incentive, the earnings are evenly distributed among the members. For instance, in a community with 3 users and 1 investor, each participant receives 25 € (100 € divided equally among the 3 users and 1 investor). To study the behaviour of energy communities, realistic user profiles are employed, grouped into three prevalent types for the sake of simplicity and code efficiency in Python. These predominant user types include residential users, characterized by a consistent load pattern during the afternoon and night with peaks in the morning and early evening; commercial users, exhibiting near-constant load during the day with variations during the night; and office users, distinguished by a peak load between 10 AM and 5 PM. The load curves for these user types are depicted in figures 3.1, 3.2, and 3.3. These users are examined with comparable electrical and thermal demands, roughly around 187,000 kWh/y and 40,000 kW/y, respectively. It's important to note that these numbers are not reflective of realistic consumption for these user types; rather, the electrical and thermal demands are scaled up for the sake of facilitating a straightforward comparison. By inputting all the relevant data into the code, it becomes a straightforward process to calculate, utilizing a for loop, all conceivable combinations of users, representing all potential energy communities. The underlying assumptions include considering the investor as a user with no specific load but with available space capable of accommodating 400 kW of photovoltaic capacity, an incentive of 110+9 €/MWh, and an electricity purchasing cost from the grid set at 250 €/MWh. The outcomes of these calculations are visualized in tables 5.4 to 5.7. In comparing the results, the optimal energy community, using equal division of earnings as a reference, comprises 3 office users and the investor, yielding a total of 40200 €/y from the energy-sharing incentive. When earnings are distributed into 4 parts, each user/investor gains approximately 10000 €/y, with 58% of the total energy produced by the photovoltaic system effectively utilized by the community members. Assessing the annual costs for an office in single-user operation (with all energy imported from the grid, totalling 55382 €/y) against the cost incurred when aggregated into the community (subtracting the earnings from the incentive, resulting in 45256 €/y), it is evident that savings amount to about 18% for each office user opting to join this specific energy community. To conduct a more comprehensive analysis, it is essential to compare the behaviour of an office in energy community operation against its performance in single optimized operation, specifically with the installation of photovoltaic panels for self-consumption. This comparative assessment can be facilitated by another Python code designed to analyse the optimal solutions for single-user operations, including the installation and self-consumption of photovoltaic panels. For an optimized office (optimized from an economic standpoint), the code indicates the installation of 135 kW of PV, incurring a total expenditure of 38249 €/y. In single-user operation, the office achieves an annual savings of about 30% compared to exclusive reliance on imported energy, and approximately 15% savings when compared to participation in the best energy community. This approach suggests that the current method of dividing earnings may be counterproductive, as it deems the best community to be one that aggregates the fewest users but with the highest utilization of PV. However, this "best" aggregation is almost impractical, as the earnings for each user are insufficient to persuade them to join the community rather than installing their own photovoltaic panels. A second criterion for allocating incentive gains is analysed, aiming to calculate the amount of money required to persuade each type of user to join the community. This can be determined by comparing users' expenses in the scenarios of solely imported energy and single-user optimized operation. There are some variations in the hypotheses compared to previous analyses. The user types remain the same, but in this case, the thermal load is incorporated into the electrical demand. Since heat pumps, which operate electrically, satisfy the thermal load, it is convenient to view the heat pump loads as an additional electrical demand. Furthermore, in contrast to the previous case, the electrical demands are smaller and varied among users to better reflect real-life user behaviour: residential users have an electrical demand of 5955 kWh/y, office users of 25100 kWh/y, and commercial users of 64000 kWh/y. The analyses are conducted with 150 kW PV installed by the investor, but the capacity can be adjusted as needed since all results will be easily scaled. Finally, the electricity purchasing cost remains at 250 €/MWh, and the incentive is set at 110+9 €/MWh. With these assumptions, it is possible to calculate the Minimum Money to Guarantee (MMG) for users to convince them to join the community. As mentioned earlier, MMG is calculated as the difference between the user's expenses in the energy community (fully imported) and the user's expenses in the stand-alone solution. The results are presented in Table 5.14. For residential users, the MMG is equal to 337 €/y (in EC operation = 1493 €/y, in optimal stand-alone operation = 1156 €/y), for office users it is 2143 €/y (in EC operation = 6291 €/y, in optimal stand-alone operation = 4148 €/y), and for commercial users, it is 4601 €/y (in EC operation = 16056 €/y, in optimal stand-alone operation = 11455 €/y). After running the program, the results for the best energy communities are displayed in Table 5.15, ordered from the highest "investor's gain" to the lowest. This value is calculated as the difference between the amount of money that the investor receives through the sharing of the photovoltaic energy produced and the MMG (the guaranteed money multiplied by the number of users in the community). In the top 20 communities, almost exclusively residential users are added. This can be explained by the fact that residential users' loads do not have a high peak during midday hours when photovoltaic panels operate most efficiently. Consequently, the appeal of installing their own PV system is not as significant as it is for office and commercial users. In the case of single-user optimal operation (users installing the optimal amount of PV for economic efficiency), residential users can achieve 22% savings compared to the normal "all import" solution, while office users save about 34%, and commercial users save 29% (Table 5.12 and 5.14). It is evident that, for offices and commercial entities, it is more cost-effective to operate independently and install a certain number of photovoltaic panels compared to residential users. However, this dynamic could shift if the incentive value changes, as the appeal of aggregating in a community might become more attractive for offices/commercial entities. Referring back to Table 5.15, which showcases the best energy communities with a 110+9 €/MWh incentive and 250 €/MWh electricity purchasing cost, it's clear that investor gains are very low. Even in the case of the best energy community with 5 residential users aggregated, the investor gains are only 120 €/y. With such minimal potential gains, the viability of energy communities diminishes. These modest earnings result from the incentive's dependence on the cost of electricity from the grid. If, for instance, the electricity purchasing cost is increased to 300 €/MWh, maintaining a fixed incentive, energy communities become unfeasible, as demonstrated in Table 6.1, where all community configurations lead to a loss for the investor. In this scenario, investor gains are consistently negative across all combinations, signifying that the money guaranteed to users is higher than the money earned from the incentive. In simpler terms, both residential, office, and commercial users prefer to operate independently in such conditions. On the contrary, if the electricity purchasing cost decreases to 200 €/MWh, the most favourable aggregations involve numerous residential users and some offices. Taking the best-performing one as an example (refer to Table 6.3, comprising 38 residential users), the investor's gain is approximately 2400 €/y. Similar outcomes can be achieved by maintaining an electricity purchasing cost of 250 €/MWh and adjusting the incentive value. For instance, using an incentive of 150+9 €/MWh (Table 6.4), the best energy communities closely resemble the results in Table 6.3 (200 €/MWh purchasing cost and 110+9 €/MWh incentive). The optimal one in this case comprises 32 residential users, contributing 2000 €/y to the investor. In summary, due to variables such as incentive value, electricity purchasing cost, allocation of gains from the incentive, and users' electricity demand curves, which can vary based on user type and geographic location, the identification of a universally perfect criterion for the optimal aggregation of users is somewhat "utopian." The thesis demonstrates that residential users are more inclined to join an energy community, primarily due to their lower requirement for installing a higher amount of photovoltaic panels. For an investor lacking information about nearby users' consumption patterns, the most sensible solution would be to aggregate residential users. However, the number of users to aggregate ultimately depends on the values of the incentive, electricity purchasing costs and the way in which users and investor decides how do distribute the earning from the incentive. Regardless, it is recommended for any investor interested in creating an energy community to utilize simple calculation tools for identifying the most favourable aggregation. In Appendix B, a simple calculation code is presented, illustrating how one can evaluate the best energy communities by knowing only the amount of installed photovoltaic capacity and the users' electricity demands. A notable aspect is that users such as offices and commercial entities are generally financially advantaged and have the economic potential to install their own systems, whereas typical residential users may be economically weaker. Energy communities could offer support to users who are not typically involved in emission reduction projects, creating advantages for the entire population. To maximize benefits, residential users or those with higher loads during late afternoons and mornings should consider shifting their loads below the sun's energy production curve. Modern technologies enable users to schedule the start times of appliances like washing machines and dishwashers, and studies demonstrate that load shifting can lead to savings for users. Encouraging normal residential users to adjust their load profiles to align with photovoltaic production curves is a viable strategy. However, this "load shifting" approach may not be suitable for everyone, as changing habits is challenging and not easily replicated on a large scale. While having all users generate and consume electricity according to their needs is the ideal solution, not all users are willing to adopt such changes or install their own photovoltaic systems. In such cases, energy communities emerge as a promising solution to introduce these consumers to renewable and local energy production.

7.2 Value of the incentive – proposal of a new type of incentive to reach the greenhouse gas emissions value of a single optimized user.

From an environmental perspective, the most effective strategy for decarbonization involves promoting the self-consumption of photovoltaic energy through the installation of an optimal amount of photovoltaic capacity on each roof. This optimal quantity can be readily calculated using a straightforward Python code. However, under the current fixed incentive structure outlined in legislation, the rationale behind energy communities becomes somewhat undermined. For instance, with an electricity purchasing cost of 250 €/MWh, 150 kW of installed photovoltaic capacity, and a fixed incentive of 110+9 €/MWh, the most economically viable energy community, one that satisfies the economic demands of users and maximizes returns for the investor, can only harness 7% of the total energy produced by the photovoltaic system. In this scenario, the optimal solution involves five residential users, resulting in 93% of the energy generated being distributed to the grid rather than utilized locally. It is feasible to compute and compare greenhouse gas emissions in both the single-user scenario and the energy community operation, accounting for indirect emissions from energy purchased from the grid (356 kgCO2/MWh) and life cycle emissions for photovoltaic panels (50 kgCO2/MWh). In the case of the optimized residential user, emissions amount to 1526 kgCO2/y. This figure is comprised of emissions resulting from the import of energy from the grid (3671 kWh/y imported = 1307 kgCO2/y emitted) and emissions associated with the self-consumption of energy generated by the photovoltaic system (4425 kWh/y produced by PV = 221 kgCO2 emitted). Simultaneously, the "best" energy community, consisting of only 5 residential users exploiting the 150 kW of photovoltaic capacity installed by the investors, emits 16148 kgCO2/y. This total comprises 10932 kgCO2 indirectly generated by the 150 kW of photovoltaic installed, while the remaining 5216 kgCO2 is emitted due to the electricity purchased from the grid (14649 kWh/y), driven by the early morning and late evening/night loads. Comparing this with the emissions of 5 residential users operating independently, emitting 1526 kgCO2/y * 5 = 7630 kgCO2/y, it becomes evident that there is a substantial energy waste in the energy community scenario. In reality, the notion of waste is nuanced because the surplus energy is fed back into the grid. However, given that the primary goal of energy communities is to curtail emissions by utilizing energy locally, installing 150 kW of capacity but utilizing only a small fraction, 7%, contradicts the fundamental purpose for their creation. In such a scenario, the approach of self-installation and consumption appears to be more effective. One potential solution is to introduce an incentive comprising a fixed component and a variable component tied to the amount of energy produced by the photovoltaic system that is consumed locally by users in the community. For instance, with an incentive structure of 110+9 €/MWh as the fixed part and an additional 70 €/MWh as the variable part, an adaptable incentive is created. This variable component increases with higher utilization of the energy produced and decreases if the opposite occurs, following the formula (110 + 9 + 70 * percentage exploited PV energy produced). This approach aligns more closely with the objective of promoting local energy consumption within the community. Utilizing this type of incentive, the optimal energy community, specifically considering residential users, is illustrated in Table 10.3. This configuration, consisting of 56 users and representing the best aggregation when factoring in the variable incentive, 150 kW of installed photovoltaic capacity, and a 250 €/MWh electricity purchasing cost, results in emissions of 85436 kgCO2/y. Remarkably, 57% of the energy produced by the 150 kW of photovoltaic capacity is used locally, shared among the users. In contrast, the emissions for a scenario with 56 residential users installing and using their individual photovoltaic systems amount to 85456 kgCO2/y (1526 * 56). The discrepancy between the two cases is negligible. This example underscores that an incentive structure that adapts based on the utilization of photovoltaic energy is more effective than a standard fixed incentive.

7.3 Incentive for night users – brief discussion about the users that contribute to support the incentive but cannot join energy communities due to their almost zero daytime load

A brief discussion on the value of the incentive is warranted, particularly regarding its sustainability and ethical implications. While the appropriateness of the incentive value compared to electricity purchasing costs has been explored, there is a need to assess whether the government-imposed value is both sustainable and morally justifiable. One argument posits that, since all users contribute to the incentive through taxes, everyone should reap its benefits to prevent an exclusive advantage for the wealthy. However, it has been acknowledged that users with available space and financial means may prefer installing their independent systems, creating a semblance of balance. Yet, this balance does not extend to users whose activities primarily occur during nighttime hours, precluding them from capitalizing on shared solar energy. Although electrical energy storage systems could address this, the environmental impact of the necessary large-scale batteries currently challenges the emission reduction goals associated with solar energy utilization. Night users, who cannot fully benefit from energy community aggregation, still contribute to the incentive through taxes. A potential solution involves offering small incentives to these users if they can shift some activities to daylight hours. For instance, Thermo-active building systems (TABS) could be employed in heating or cooling applications to harness solar energy during daylight and utilize stored thermal energy during the night. While this approach may not fully substitute conventional energy sources, it allows night users to leverage the incentive and incorporate renewable energy into their consumption patterns. It is essential to note that this example, involving TABS, is one among various possibilities, and it is not as impactful as harnessing all solar energy to meet electrical demand. Additionally, alternative solutions like biogas engines were not explored in this thesis. Nevertheless, the core idea remains, to devise strategies that enable users with specific constraints to participate in and benefit from the incentive system, promoting a more inclusive and equitable renewable energy framework.

Chapter 8 – Conclusions

The criterion for the optimal aggregation is not unique. It can be said that all the analyses and results are useful to understand better how an energy community works elongating its strengths but also emphasizing the negative ones. The energy communities' goal is to support the energy transition attempting to exhort those people/activities that are not trying to road to a sustainable future as the directive "imposes". From findings what turns out is that the optimal solution in terms of photovoltaic installation would be the total self-consumption. In other words, with the availability of only photovoltaic systems the less impactful solution would be installation of the optimal number of photovoltaic panels for each user. In addition, moving the electrical demand during sunlight hours (load shifting) is another step to exploit the energy produced by the photovoltaic system in a better way. In the real world this is nearly impossible and that is why the introduction of energy communities could help reaching faster the decarbonisation goals. Not all the users have the economic and space necessary to install the optimal amount of photovoltaic, particularly weaker users that normally appear to be residential users or more in general users who share the same roof. The consumers just mentioned are not interested in installing and maintaining some capacity of photovoltaic knowing that it would not bring great economic benefits. The advantage of the share-energy incentive lies in the fact that it makes these users attractive to those with energy availability who are less interested in aggregating more economically advantaged users. They would demand more compensation for energy consumption aware of their "position" and economic/space availability. The main obstacle encountered during the analyses is the selection of the method with which users and investor distribute the earnings from the shared energy incentive. Initially was set as base case an equal subdivision of the earnings, it means, with 100 € eared and an EC formed by three users plus the investor, each would be entitled to 25 €. However, with this money allocation the energy communities appear to be not interesting. Indeed, the best EC found form the phyton code is the one aggregating 3 offices but comparing the savings of each office in case of aggregation and the one in case of single user optimized operation, the best solution is the photovoltaic self-installation and consumption that lead to 15% more savings respect to the case of aggregation into an energy community. The method for distributing earnings was revised. In this second approach, the investor returns to each user an amount equivalent to what they would have earned with an optimal amount of photovoltaic installation based on their load. The best-performing energy community focused on residential users, specifically aggregating 5 residential users for optimal gains with 150 kW installed by the investor. However, the actual utilization of photovoltaic energy in these communities was only 7%, and even the top ten communities remained below 10%. Additionally, investor gains were lower than expected, totalling only €120 per year. The sensitivity analyses chapter introduced a new incentive structure, showing notable improvements. This approach, with a fixed and variable portion, tied the variable part to the percentage of photovoltaic energy truly shared among users. This resulted in increased local photovoltaic exploitation, making energy communities appealing economically and environmentally. With this new incentive, considering a fixed photovoltaic amount of 150 kW, the number of users and the percentage of exploited photovoltaic energy increased. The best community, comprising 56 residential users, achieved 58% local photovoltaic exploitation, providing the investor with about €1000 per year. This enables residential users to access renewable energy without installation costs or maintenance hassles. In summary, it is evident that energy communities could offer a promising solution for achieving decarbonization goals. A well-designed incentive has the potential to engage a significant portion of residential users, who may not typically participate in decarbonization programs. This participation allows them to contribute actively to the project without incurring costs, simply by making their energy load available to investors. Therefore, with a well-designed incentive, users who are typically economically advantaged and choose to install their own photovoltaic (PV) systems for self-consumption could, additionally, utilize any extra space to install more PV. This would enable them to generate more energy and share it with other users, particularly those who are economically weaker, in fact residential users. In the thesis the systems analysed only make use of photovoltaic and energy imported from the grid, which is seen as big inexhaustible storage. Instead, a complete analysis should include other utilities as wind farms, biogas engine, geothermal, etc. Future works would include a cumulative analysis based on the study of more detailed communities introducing also the concept of demand responds and load shifting.

Chapter 9 – Bibliography

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Chapter 10 - Appendix

Section dedicated to additional elements used in for the thesis.

10.1 APPENDIX A - Phyton code

The code is divided in 5 sections:

- import of the required packages.
- import of the input data.
- "For-loop cycle" for the calculations.
- optimizer.
- data plotting.

10.1.1 Import of the required packages

The 3 main imported packages are:

- Gurobi: is a library used for the optimization operation.
- Numpy: is a library for mathematics.
- Pandas: is a library used for the data analysis

In addition to those also "*matplotlib*" was used, it is a library for the plots, graphs and diagrams.

10.1.2 Import of input data

First of all, two indices were created: H = 24 and K = 4, they respectively represent the number of hours and the number of typical days. From the excel file *Typical days*, all the data relative to electrical demand, thermal demand, solar radiation and ambient temperature were exported by pandas. As a result, all the excel data became matrixes [H, K]. In the case analysed all the electrical and thermal demands were scaled up/down to reach comparable/similar values. This is an example on how the data are imported:

```
TimeSeries = pd.read_excel('TypicalDays.xlsx',        # excel file
                           sheet_name='TimeSeries',   # excel sheet
                           index_col=[0,1])                 # columns with indeces
```

```
# Solar radiation in [W/m2]
SolRad = np.zeros((H,K))            # initialization as a zero matrix with Numpy
cname = "SolarRad_glob[W/m2]"    # column name in the excel file
for k in range(K):               # iterate for each typical day
    SolRad[:,k] = TimeSeries[cname].loc[k].to_numpy()
    # the .loc[k] function allows the selection of the desired typical day (k)
```

Also, the Weights were imported as WTD. Weights is a matrix with 1 column and 4 rows, each row corresponds to a single typical day. They were simply used to obtain, with only 4 typical days, all the days of the year, in particular 91 days for the winter, summer and autumn and 92 days of spring. Finally, also all the techno-economic parameters were imported in the same way. These values are the same of the table 2.1 and 2.2.

10.1.3 Optimization cycle

The main part of the code is the for cycle used for the optimization. For cycle was used for the calculation of all the possible energy communities' combinations. To begin with, the number of users should be specified by modifying the parameters: RES, COMM and OFF that correspond to residential, commercial and offices users. Given the 3 types of users, there are 3 for cycles in sequence:

```
for A in range (RES):
        for B in range (COM):
               for C in range (OFF):
```

The parameters A, B and C are very important for the following calculations, they represent the number of users for a specific typical curve. After the initialization of the code with grb.Model() and the set of termination criteria Params.MIPGap = 1e-2, Params.TimeLimit = 30, the code really begin. First, for each iteration the total demand has to be updated:

```
total_demand = (C * DemEloff) + (A * DemElres) + (B * DemElcomm)
```

the total demand corresponds to the sum of the 3 electrical demands multiplied by their factor A, B and C. In this way for each cycle the total electrical demand changes depending on the number of users in the energy community. Secondly all the design variables must be set, they could be continuous or binary. Each variable is defined in this way:

```
CapPV = m.addVar(lb = 0, ub = grb.GRB.INFINITY, vtype = grb.GRB.CONTINUOUS,name = "CapPV")
```

This is the example with the photovoltaic capacity. With the two bounds, lower and upper one, the variable type, that as we said can be normally continuous or binary, and finally the name of the variable. Similarly, the other variables are defined.

```
CapHPres = m.addVar(vtype=grb.GRB.CONTINUOUS, name="CapHPres")

QHPres = m.addVars(H, K, vtype=grb.GRB.CONTINUOUS, name="QHPres")

deltaHPres = m.addVars(H, K, vtype=grb.GRB.BINARY, name="deltaHPres")

thetaHPres = m.addVars(H, K, vtype=grb.GRB.CONTINUOUS, name="thetaHPres")
```

This is the example for the heat pump variable. In the heat pump case, the variables are relative to the capacity, the output heat, the deltaHP that it is the parameter used to govern the on/off status and in the end the thetaHP that is the auxiliary variable for the heat pump linearization. One can note the addition of the H,K parameters, necessary for understand the hourly operation of the different facilities. Moreover, each variable has an additional name “RES”. Indeed, each typical user has its own variables. This is because all the users have to satisfy their own thermal demand, so the capacity and the operation of the different heat pump installed are different. The same was done for the thermal energy storages:

```
CapTESres = m.addVar(vtype=grb.GRB.CONTINUOUS, name="CapTESres")

SocTESres = m.addVars(H+1, K, vtype=grb.GRB.CONTINUOUS, name="SocTESres")

QcTESres = m.addVars(H, K, vtype=grb.GRB.CONTINUOUS, name="QcTESres")

QdTESres = m.addVars(H, K, vtype=grb.GRB.CONTINUOUS, name="QdTESres")

deltaTESres = m.addVars(H, K, vtype=grb.GRB.BINARY, name="deltaTESres")

thetacTESres =m.addVars(H, K, vtype=grb.GRB.CONTINUOUS,
name="thetacTESres")

thetadTESres= m.addVars(H, K, vtype=grb.GRB.CONTINUOUS,
name="thetadTESres")
```

Thermal energy storage variables are very similar to the Heat pump ones. The variables must be defined for each type of users because of the different optimized operations. Other parameters are the ones connected to the grid operations.

```
PIMP = m.addVars(H, K, vtype=grb.GRB.CONTINUOUS, name="PIMP")

PEXP = m.addVars(H, K, vtype=grb.GRB.CONTINUOUS, name="PEXP")

PEXC = m.addVars(H, K, vtype=grb.GRB.CONTINUOUS, name="PEXC")

pimp = m.addVars(H, K, vtype=grb.GRB.CONTINUOUS, name="pimp")
```

The “PIMP” is the imported energy that is calculated in the formula (electrical balance). The imported energy is not the one that users will pay because the legislation said that users in energy community have to buy all the electricity from the grid, this total imported energy is represented by “pimp”. “PEXP” is used only for electrical balance calculations but as reported at the beginning of this chapter, all the exported energy, the surplus, is sold to the grid but the earnings must be allocated to the owner. All the parameters are so defined.

10.1.4 Optimizer

In the same for cycle, at the end of all the parameters definitions, there is the optimizer section. The optimizer calculates for each cycle, so for each EC, the best “operation” and the formulas are the same described in the section 2.2. The Optimizer minimizes both the operational costs, that corresponds to a minimization of the imported energy and maximization of the exchanged one, so the one shared, and investment costs. In the case of investment costs, is not possible to reduce the costs because there is the need to satisfy the thermal demand, in that case the optimizer is used only to calculate the best design and operation of the heat pumps and thermal energy storages.

10.1.5 Plot of the results

The final part involves generating results plots. Python simplifies this process with a single command to directly print the results into an Excel file. The Excel file includes a table detailing, for each community type, the number of users, the specific user types, thermal and electrical demand in kWh/y, the installed kW of HP and TES for each user type, the total gains from the incentive (as well as individual gains for each user and the investor), and all the yearly expenses for HP and TES maintenance, investment, and electrical energy import for a single user. Additionally, various parameters are plotted, with significance in EC analysis. One key parameter is the "percentage incentive," calculated as the ratio of total energy shared to the total energy produced by the photovoltaic system. This parameter is crucial for achieving the final goal of finding the optimal aggregation. A high percentage of incentive signifies the potential for substantial earnings from the incentive. If such a community is not very large, meaning it has a limited number of users, the earnings per user are correspondingly higher.

10.2 APPENDIX B – Fast code for the earnings from the incentive for the EC shared energy calculation

The code used for the optimization cycle in case of both thermal and electrical demand optimization presents different problems as the slowness due to the large quantities of variables and number of possible aggregations. For an investor that has to decide which users to aggregate would be better to have an immediate idea about the energy that can shared with the users, knowing the maximum number of photovoltaic panels installable. In the code used in the previous simulation the design and operation of each facility were calculated. However, in real application the users involved have already installed their heat pump and thermal energy storages, this involves and electrical demand that already takes into account the thermal demand. The idea is to develop a code in phyton that permit the investor to faster calculate the amount of energy shared for each type of aggregation. Knowing the curve of the sun production and the users' curves, by clustering, statistics and bills, it is easy to evaluate faster the amount of money that can be obtained by each type of aggregation.

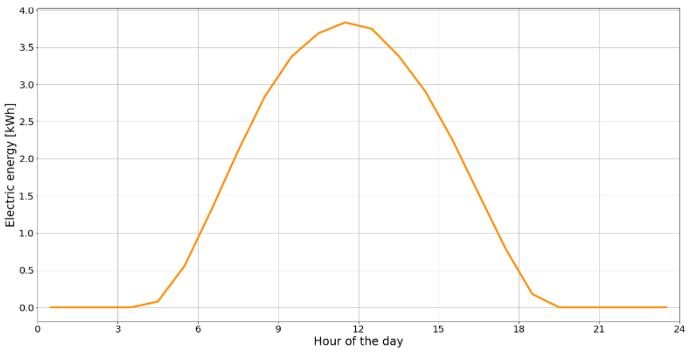

Figure 9.1. *Sun energy production*

Figure 9.1 shows the curve of the sun in case of 15 kW of installed capacity, the energy produced is proportional to the solar radiation so changes day by day and in particular it changes seasonally. Knowing the amount of photovoltaic to be installed and the irradiation during the year in a certain area, the photovoltaic energy production curve is easy to be print. Knowing the bills and the clustering/statistic also the users' load curves can be printed in an easy way.

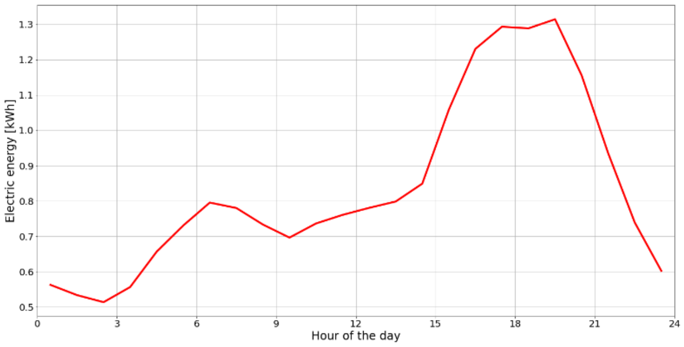

Figure 9.2. *Electrical demand residential user*

By combining figure 9.1 and 9.2 it is possible to calculate in an easy way the incentivized energy, so the shared one. For each time step the shared energy is the minimum between the two curves.

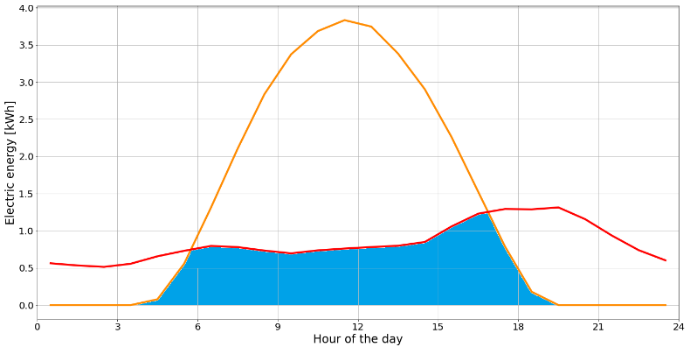

Figure 9.3. *Energy shared (1 user and the investor)*

Figure 9.3 shows the amount of energy shared in case of one user and the investor, but the path is the same adding other users or increasing the amount of energy produced by the photovoltaic system. Knowing also the value of the incentive is then very easy to calculate the amount of money that the investor will gain.

10.2.1 Code composition

The initial part of the code that is the one including the input of all the data is equal to the codes used in the fourth/fifth chapter. The code starts with the selection of the total number of users that would be better to cluster and divide in different groups. To simplify the code the 3 groups are always the same residential, commercial and office.

```
res = 5

com = 5

off = 5
```

Given that the code is used for the final calculation, the capacity of installed photovoltaic is already known, so there is a slot for the insertion of the capacity installed.

```
SUN = np.zeros((H,K))

for k in range(K):

    SUN[:,k] = SolRad[:,k] * CapPV / 1000
```

`SUN` is initialized as a matrix with only zeros and then it is filled by the photovoltaic production,i.e., the product of solar radiation matrix and capacity installed.

```
for A in range(res):

    for B in range(com):

        for C in range(off):
```

The "for" cycle is the sum of different "for" cycles and the number of cycles depends on the different type of users analysed. Given the simplicity of the calculation there are no limitation on the number of users. The values of A, B and C are dependent on the number of users for each type. The total demand is also calculated in the same way as it was done before in the chapter 2.

```
Inc[A,B,C] = np.sum(np.minimum(SUN,total_demand))
```

`Inc[A,B,C]` represents the matrix of the energy incentivized in which for each position of the matrix, that corresponds to a specific combination of A,B and C, is initially calculated the minimum between the matrix of the photovoltaic production and the total demand and finally all the elements of the matrix are summed in order to obtain the total energy shared during the year for that specific combination. At the end, to obtain the total gain in "€" simply multiply that value by the incentive. The code is very simple and permit the owner of the PV field to have an idea on which will be the best aggregation. Is then the owner that will decide which is the percentage will he want to keep and what percentage will be given to users.