UNIVERSITA' DEGLI STUDI DI PADOVA

DIPARTIMENTO DI SCIENZE ECONOMICHE ED AZIENDALI "M. FANNO"

CORSO DI LAUREA MAGISTRALE IN ECONOMICS AND FINANCE

TESI DI LAUREA

"Profitability of participation in an Energy Community."

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MATRICOLA N. 1242490

ANNO ACCADEMICO 2022 – 2023

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Firma dello studente

I thank Prof. Moretto Michele for the professionalism and availability given during the writing of this paper. I thank my friend Riccardo for helping me in data collection and for giving me useful advice. I dedicate this work and this achievement to my family who supported me throughout my course. I also dedicate this achievement to my PSN friends, without whom I would not have reached where I arrived today. I will never forget everything that was done for me.

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ABSTRACT

The notions of smart grids and energy community begin to play a central role in what is the production and sharing of energy. In recent years, the continuous increase in pollution and the increase in energy costs have led energy providers and increasingly households to invest in renewable energy, moreover, these investments are often accompanied by an entry into an energy community, this to optimize any costs and revenues derived from the production and the following sharing of the energy produced. Many previous studies have shown structural differences in the various types of smart grids, at the same time these technical-structural differences involve a different allocation of costs-revenues. In addition to the differences in smart grids we can see evident differences also in the various types of energy communities, these perhaps even more important when you consider the efficiency of such infrastructures and especially the revenues from an investment in them. A first task of this thesis is to provide a general framework of what are smart grids and energy communities, sequentially listing the various characteristics of each of these types, also describing the European directives issued to support the expansion of this type of investment. Once an overall description has been provided, the thesis proposes a model and the resulting investment projects of an energy community and will analyze a dataset to conclude about the profitability of an investment project (or the entry in an energy community) for the final household. The first chapter is composed by two paragraphs, one concerning smart grids and one dedicated to energy communities. The purpose of these two paragraphs is to describe the various types of smart grids with their respective characteristics; also describe the energy communities, listing the different types of communities (each type with its own characteristics) and quoting any laws dedicated to the definition of energy community. The second chapter of this thesis is dedicated to the literature review, this section has been structured in such a way that each of the works considered essential for our thesis has a dedicated paragraph where all the key points of it are extrapolated and explained. This choice has been made because our work will be built on all the assumptions and respective conclusions (demonstrated) made in the papers analyzed. The chapter three of this thesis is dedicated to the creation of the model, explaining the choices of hypotheses, the creation of the functions used and useful to the model. This chapter will explain the choices that have been made in order to create an optimal and not complex system. The fourth chapter is related to data collection, where

we will see data from an energy community and data from the same group of households when they were not yet part of the energy community. We will also see the economic and energetic effects that an energy community's optimization process can have. In this chapter will also explains the chosen method of data collection and the logic followed in using the platforms that allowed us a reliable data collection. Chapter five is dedicated to the elaboration of the data collected in chapter four: at this point will be analyzed data of households not part of the community, will be analyzed data of the energy community and finally will be compared. The aim is to deduce the feasibility of the investment for the household under consideration and the profitability to join the community and stay in the following years. This is why an analysis will be provided on two different scenarios, hypothesized and created based on real data and historical series.

Finally in the conclusions we will resume our work and the results in which led our analysis made.

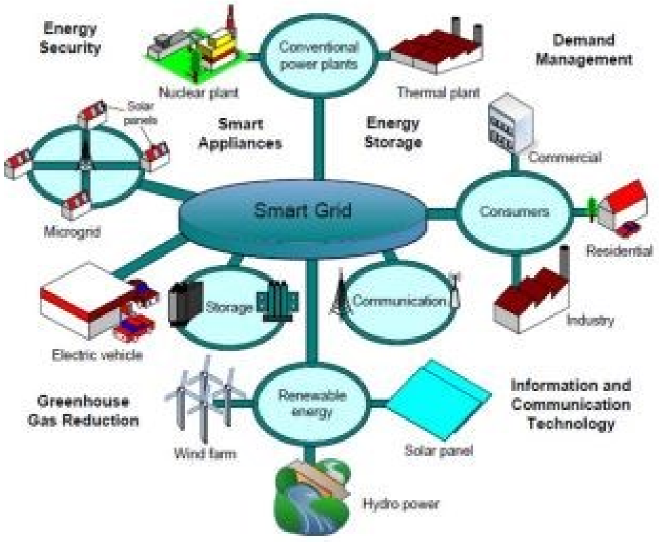
1) INTRODUCTION

1.1) SMART GRIDS

The smart grid is a set of energetical networks and technologies that, due to the mutual exchange of information, manage and monitor the distribution of electricity from all sources of production and meet the different electricity requirements of connected users, producers and consumers in a more efficient, rational and safe way. The adjective "smart" is used because smart grids optimize the distribution of electricity, decentralizes power plants and minimizes overloads and variations in electrical voltage. The smart grids were born in 2006 in conjunction with the evolution of the electricity system and the European energy transition, in fact we see that the use of smart grids greatly stimulates the production and investment in renewable energy, as this dualism turns out to be more efficient for energy providers, for consumer tariffs and for the reduction of negative externalities produced by environmental pollution (considering other forms of energy production, not eco-sustainable). The first definition of smart grids is provided by the Energy Independent and security act of 2007 which lists 10 characteristics that can be considered as intrinsic to the definition of smart grids; these characteristics have in common the use and application of digital and communication technologies to the electricity grid, making data flow and information management central to the smart grid. The adoption of smart grids brings several benefits and advantages, including: reliability and quality of electricity distribution; effectiveness in distribution and flexibility in managing peak demand; environmental protection (strong reduction of negative externalities) and finally to increase the capacity of the existing electricity grid. In addition, smart grids help reduce power outage times.

How are they built from a technical point of view? What do they consist of and how do they differentiate from traditional distribution grids? Usually the distribution of energy (from the power plant to the final consumers) is through medium, low and high voltage lines. Summarizing: the power energy grid that is connected to the power plants, transports high voltage through the transmission grids to medium and low voltage transformer electrical cabins and from there through the distribution lines reach individual end users. The smart grids instead to follow a model of centralized electricity generation, provide for the presence of distributed generation systems, these are systems of production of electricity from renewable sources, in the form of small production units, as can be for example: residential or business photovoltaic systems or small biomass plants. Being these systems not programmable (that is they cannot guarantee a sort of constancy in the production and consequently in the supply of energy, therefore they can present peaks and lack of production) they need a "smart" managing and this is manifested in the local management of any surplus of the overall electricity system by redistributing them in nearby areas, preventing or minimizing a potential production interruption. Another important invention is the bidirectional management, so in addition to the possibility of receiving energy, they can also enter it into the system; if it is in excess redistributing the flow in real time and depending on the actual needs. All this due to technology: smart grids are equipped with automatic and optimal network reconfiguration functions and protections that quickly adapt to the topology of the same. The main distinctions, as can be seen in Figure 1, are outlined: in the use of a two-way system and on the use of intelligent systems and components defined. To provide a complete framework of what they are and how smart grids are formed, we will list the various smart systems and components: integrated communication platform (allows the connection of the components to an open architecture to have information in real time, so as to maximize the efficiency of the system itself; the technology used is usually the best fiber); measurement sensors (such as smart meters, switches and advanced cables); advanced components (high voltage direct current, AC transmission devices, superconducting cables, "smart" appliances).

Figure 1; Smart grid.



Source: X. Yu and Y. Xue, (2016).

Defined the concept of smart grids and described the main features and differences with traditional grids, to complete the overall picture, we provide a real example of smart grids in the market that will be taken as a reference in this elaborate, the Italian market.

Italy is one of the first countries in the world to have adopted the smart grid scheme on a national scale. Italy already makes a discreet use of photovoltaic systems, adopting a smart grid system means therefore increasing the possibilities of storage and control, balancing deficit and surplus over the entire network. A real example of what are the smart grids in Italy, more precisely what are the investment projects in smart grids in Italy, is the PAN: Puglia Active Network. A large-scale project which will lead to the development of a regional smart grid with several advantages: reduction of network losses; the increase in hosting capacity; greater integration of renewable energy sources into the network and the possibility of providing new value-added services. Consisting of about 30.000 km of electricity network to connect 44.000 production plants from renewable sources spread throughout the territory.

1.2) ENERGY COMUNITY

An energy community (from this point will be write as EC) is a group of people which share renewable and clean energy in an equal exchange and represent an innovative model for the production, distribution and consumption of renewable energy. EC reflects a growing desire to find alternative ways of organizing and governing energy systems. Before describing completely the concept of EC and how European and national directives treat ECs, note that these communities arise from the energy evolution that leads distribution networks to become smart grids. The primary objective of creating ECs must be to provide environmental, economic or social benefits to the community itself and the local area in which it operates. This community must therefore not aim at economic profits: collective self-consumption of energy must not be the main source of income for energy suppliers.

The directives describe ECs as a possible type of organized collective citizen actions in the energy system (Frieden et al., 2019). ECs are incorporated as a non-commercial type of market actors that combine non-commercial economic aims with environmental and social community objectives (Roberts et al., 2019).

The concept of collective auto-consumption is described in article 21 of Renewable Energy Directive (which is an European directive[1]). The cited directive describes the specific characteristics of local renewable ECs in terms of size and ownership structure. In the definitions of ECs, we can find a first distinction between Renewable Energy Communities (REC) and Citizens Energy Communities (CEC). The first one type is introduced by RED-II directive issued in 2018, we know that the only type of energy shared is coming from renewable sources, usually in this type of community only households can participate and small local firms. The second type, CEC is detailed in IEMD directive issued in 2019 where the distinction between renewable and non-renewable energy is not important, in fact there is not any specification about the origin of the energy, the key point of the definition of CEC is in the concept of the grid in which entities which composed community are linked. Usually an EC, from the definition, should be connected with public energy networks and not to the local energy network which is managed by a Distribution System Operator, the directive that describes these types of EC allows these communities to connect with a local energy operator, legally this operator will call Closed Distribution System.

Common points of these 2 types of EC are:

- governance that means that the participation is open and voluntary;
- the ownership and control in fact both types describe participation and effective control by citizens, local authorities and smaller businesses;
- the purpose that is to generate social and environmental benefits rather than financial benefits.

REC and CEC have also some differences, we can use them to decide which type of EC we will use in our model of study, these differences are:

- geographical scope: Renewable Energy Directive locates the actors present in the REC in a close area (therefore local) to reference REC project, while the CEC

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[1] Directive (EU) 2018/2001, article 21: Member States shall ensure that renewables self-consumers, individually or through aggregators, are entitled to generate renewable energy, including for their own consumption, store and sell their excess production of renewable electricity, including through renewables power purchase agreements, electricity suppliers and peer-to-peer trading arrangements (...), to receive remuneration (...) for the self-generated renewable electricity that they feed into the grid (...). Member States shall ensure that renewable self-consumers living in the same multiapartment block (...) are permitted to arrange sharing of renewable energy that is produced on their site or sites between themselves.

(with different directive) does not consider important and therefore does not specify the proximity of the actors to the project;

- activities: CEC can operate with renewable energies and also fossil-fuel energy based while REC operates with all forms of renewable energy in the electricity and heating sectors;
- participants: in CEC every actor can participate as member or shareholder who are engaged in large scale activity. While in REC membership is more restricted and only allow natural persons, local authorities and micro, small and medium-sized enterprises whose participation does not constitute their primary economic activity;
- autonomy: REC should be capable to sustain exchange of energy in autonomy (without the intervention of service providers and shareholders) while CEC admits the presence of external bodies, since autonomy is not a characteristic required in the directive defining them;
- effective control: REC could be controlled by micro, small and medium size enterprises that are located near the local area where REC operates; CEC exclude medium size enterprises and allow the control to large size enterprises given them the possibility to exercise an effective control.

In our analysis we will consider a REC (as type of EC) because want focus our analysis on the profitability of the investment from an households' (and small entities) point of view. Also, because we will admit only renewable forms of energy; implies autonomy in the managing of the energy distribution; lastly because REC has a local area activity, so we can concentrate our analyses in a restricted area with a restricted number of actors.

There is another distinction in the definition and functioning of ECs, we can denote 4 different archetypes of them: cooperative investment, energy sharing, aggregators and microgrid. Cooperative investment is a type of EC where the members join to the community after paying a subscription fee. Energy sharing is like an extension of supplier business, so the energy produced in a community area is sold in the same area. Aggregator instead is a type of activity whose main purpose is to provide flexibility to the EC's actors, this because it allows a very high level of iteration in such a way that market operators are facilitated by the aggregate energy in the EC, this implies the presence of external providers. Microgrids resembles DSO market role, is a coordinated local grid area served by one or more distribution substations and supported by high production and use of local renewables and other distributed energy resources, so this archetype of EC allows the presence of Service Operator.

In Europe there are also several national directives about the regulation of EC. We find out some common points to understand which aspects are considerate more important that other, we simply list what are the characteristics considered important by all the directives issued by the European nations (obviously these directives were issued after the European ones, therefore they deal with many aspects mentioned above).

Central elements of the law include:

- Locality as a necessary condition for the creation of synergies and partnerships for the implementation of energy projects to respond to local needs, using local renewable sources, with the aim of disseminating benefits to ECs' members and generating added value for the greater local communities;
- Insularity, in which special arrangements and privileges are introduced to address issues such as the high cost per kWh as well as the environmental, economic and social issues raised by the use of conventional forms of potential production;
- The activation and enhancement of technological tools to shield vulnerable consumers;
- Financial incentives and support measures in order to exploit domestic potential with the involvement of local communities as defined in national energy targets.

After analyzing the European and national directives, after defining the EC types, our overall analysis shifts to the technical aspect of value energy sharing. In fact, we will see that there will be different methods of value energy sharing and each of these has different characteristics with relative advantages and disadvantages. The different methos of value energy sharing: even share; PV capacity share; Consumption based allocation; Marginal allocation rule; Sharpley rule. With characteristics:

- Even share: this is the most basic method and its weak point is that the households (or members) who participate less in the energy sharing are those with the most marginal advantages because the majority of profits is allocated on participation in the EC and not proportional to the amount of energy produced.
- PV capacity share: this method incentivizes the active prosumers with large generation installed (the value is shared basing on the installed PV power).

- Consumption based allocation: this method is based on momentary consumption of energy; this method prioritizes passive consumers and incentivize energy consumption. In fact, the energy surplus is sold only if the internal consumption is satisfied.
- Marginal allocation (MC) rule: this method allocates the value based on marginal contribution of each member; the marginal contribution is the value added with the participation of another member (in other words represent the change in value in the EC if the member left the community).
- Shapley rule: this is the most complex methos but also the most fair, this rule gives to each member a share of the whole value that is proportional to the average of all personal marginal contribution.

2) LITERATURE REVIEW

Our research aims to create an optimal model of EC. This model assumes so-called optimal characteristics for the creation of an EC, such assumptions are made based on previously research work which demonstrates the efficiency of these aspects. The literature in this field is very wide, we have considered the previous works that will be preparatory to our thesis. This chapter is divided into 6 paragraphs, each paragraph is dedicated to those papers that demonstrate the convenience of a technical aspect compared to others, the works considered more important for the creation of the model have a dedicated paragraph, while all those works that help us complete the framework of the model are inserted in the sixth concluding paragraph (2.6). The analyzed aspects are: the size of the EC, the geographical distance of the members of the EC, the tariff plan and how they modify the choice of users, the consumption preferences of individual members, the optimal revenue sharing method, and the relationship with an aggregator.

2.1) VIABILITY OF AN ENERGY COMMUNITY

The first paper that we analyze is ‘On the viability community’ by Ibrahim Abada, Andreas Ehrenman, Xavier Lambin published in 2020 in The energy Journal. This paper presents the conditions for an optimal coordination of the EC and purpose some solutions to solve stability problem to make the most potential these communities. Is also used a framework of game cooperative theory to test the ability of EC’s actors to share the gains; we would also specify that in our personal analysis we do not consider the theory of cooperative game, but this framework help us to understand possible choices of households. The source of initial cost is the cost of installation, this cost is variable in function of the type of the plant (solar panel, wind power plant, both, etc) and in the particular case of the solar panel plant the cost of installation is in function of the size of the roof. The sources of gains are two: aggregation gains, in the form of decreased network fees and energy gains, as the renewable energy can be consumed at zero marginal cost or sold to third parties and re-injected in the grid. A first takeaway of this paper is that the most basic sharing rules usually fail to provide adequate remunerations to each players. In fact, in this model the household, has the possibility and consider the convenience to exit from energy community; from this statement we can deduce that fair tariffs often cause instability into the EC. A key assumption is that the household have limited number of renewable resources, the utility is exchangeable and household have full public information. The important aspects that we want to analyze in this paper is the construction of the model and the respective assumptions. From a geographical point of view the set of households who participate in EC are located in the same area, closely together. The type of investment in this case is a photovoltaic system, is not considered the possibility of investing in other forms of renewable energy. The time taken into account corresponds to 1 year, the relative consumption is also considered over an annual period it is denoted with fi(t) and it is expressed in kilowatt-hour (Kwh). Then they assume that the electricity tariff has 2 components: energy component and capacity component. Typically, the household with fi(t) consumption profile will pay: $\alpha \max_i f(t) + \delta$ for the capacity (α is variable part of grid tariff expressed in €/Kw while δ is fixed part of grid tariff expressed in €); $\sum_{t=1}^{T} \beta(t) f(t)$for the energy (β(t) is electricity retail price expressed in €/Kwh). They have assumed that the cost of installation has a variable part, being the cost of energy, a cost related to the energy consumed, we will focus on the cost function of the capacity of the plant built. By observing the cost function of capacity, we can denote a fixed component δ (cost to install a meter) and a variable component $\alpha \max_i f(t)$, this part explains how the capacity may vary the investment cost for the construction of the plant. Capacity is an aspect that we will also consider in our elaborate, is set according to the expected annual consumption of the household and the EC itself and according to the size of the roof (this aspect imposes an upper bound on the capacity of the plant we build and therefore also constrains the variable component of the installation cost). An important notion to be specified, is that the positive externalities of the use of EC will not be considered as it does not affect our cost/gain functions and as it would complicate a possible prediction of the choices of the household. Defined the costs and the structure of the EC taken in analysis, the paper moves on the consumption of the energy and therefore also on its distribution, sometimes evidencing the gains of the EC or better the cost reduction (energetic rates). The priority of the EC is to share energy locally, so the excess energy will be sold or distributed locally in this way reduces the energy taxation of the area (which is still composed of the households that make up the EC). If more electricity is produced than used, the excess energy is sold to a Service Provider that pays the electricity γ(t) (electricity wholesale price or feed in tariff, expressed in €/KWh). In the last-mentioned case, the current has an additional benefit for those who are part of the EC. In the model considered, the investment in the photovoltaic system is transformed into an annuity with the corresponding interest rate. Dynamic aspects are also included, such as changing current demand, these changes can be adjusted at the end of the year once the data is collected. The interactions between households depend heavily on the payoff functions of the respective EC coalitions investing in photovoltaic panels. The value of the coalition perceived by the individual household is composed of the difference between gains (including reduction of the energy tariff) and installation costs. So, the value of the coalition is nothing more than the difference between the perceived benefits and all the costs associated with it. The value of the coalition, v(S)[2]:

$$\begin{aligned} v(S) = Max\ \alpha & \left(\sum_{i\in s} Max_t \left(f_i(t)\right) - Max_t \,(\sum_{i\in s} (f_i(t) - \ k_i \left(\mu(s)\right) * g(t))^+ \ \right) \\ & + \ \delta(s-1) \\ & + \sum_{t=1}^{T} \beta(t) \left(\sum_{i\epsilon s} f_i(t) - \ k_i\left(\mu(S)\right) * g(t))\ )^+ \ \right) \\ & + \sum_{t=1}^{T} \gamma(t) * \ (\sum_{i\epsilon S} \left(k_i \left(\mu(s)\right) * g(t) - f_i(t)\right))^+ \\ & - c \ (\textstyle\sum_{i\in S} k_i\left(\mu(s)\right)) \end{aligned}$$

As we can observe the function that expresses the perceived value of the coalition is divided into 4 terms (corresponding to the lines in which the function itself was written), these 4 terms are all depending on the investment decision $\mu(S) = K * \frac{\sum_t g(t)}{\sum_t \sum_{i\epsilon s} f_i(t)}$. Let's see in detail what the 4 items that make up the function: the first term corresponds to the aggregation benefit it explains the fact that households that join to the EC have come together and have aggregated their consumption profiles, we note that the peak demand of the EC is lower than the sum of the peak demand of individual households, however, only the benefits of the EC derived from the energy components and the optimization of energy sharing are considered, any benefits from reduced energy tariff are not included; the second term corresponds to the benefit of a coalition, is the potential benefit to locally

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[2] Indexes not explained in the text:
Ki: contribution of household i to PV capacity (expressed in kW);
μ(S): factor of proportionality linking the investment PV capacity to consumed energy;
g(t): PV production profile (expressed in kWh per kW);

consume energy; the third term is the value of the PV's energy produced and injected in the distribution system; the last term is a cost and correspond to the cost of installation the plant with K capacity. In the theoretical developments of this model, two important assumptions are made that allow to simplify the calculation problem and derive therefore feasible results that allow us to better interpret the stability of the EC. First assumption, assumes that households of the EC have consumption profiles with peaks which occurs outside the range of PV production (for example in the evening) and this assumption is realistic, observing real cases. Second assumption assumes that the maximization program of v(S) has as possible solution $\mu(S) = \bar{\mu}$. This assumption is justified by the fact that the function of investment costs for the PV is concave, so the household group will always be incentivized to invest up to the limit allowed in this area. The weakness of this assumption is that it fails if the costs are too high for the household that make up the EC. The weakness of this assumption is that it fails if the costs are too high for the household that make up the EC. The following paper then provides definitions regarding the structure of the games, the rules of allocation, the structure of the business and about the rules of energy sharing, here are the following definitions[3]:

- Definition 1: There is a set of players (households) I, consuming electricity. A coalition (community) S is a subset of the grand coalition I that generates value exposed in equation *v(S)*. Players can decide to join or not at most one coalition formed of some or all the other households in I, according to the way the payment will be divided among coalition members, called the sharing rule.
- Definition 2: The core of the game *Ker(I)* is the set of all coalitions

  $$x(v) = \left(x_1(v), x_2(v), \dots , x_n(v)\right) \in R^n$$

  Such that: $\forall S \subset I, \sum_{i \in S} x_i(v) \geq v(s)$ it means that the if core and the sharing of the total benefit *v(I)* is done in a way that satisfies all coalitions, the members of any hypothetical coalition receive more than what they get when the grand coalition stands alone; while $\sum_{i=1}^{n} x_i(v) = v(I)$ means that any allocation belonging to the core is Pareto-optimal. In other words, the core is the set of payoff configurations that leave no coalitions in a position to improve the payoffs to all

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[3] We recall "On the viability of Energy Communities" (2020) by Ibrahim Abada, Andreas Ehrenman and Xavier Lambin; for the explanation and demonstration of these definitions to the original paper and in the attached appendix.

of its members. The notion of the core is an essential element for the cooperative game theory, so being this aspect not important for our model, we have given this definition only to give a complete overview of the analysis made in this paper.

- Definition 3: The Shapley value $x^s(v)$ is the unique allocation rule that satisfy symmetry, linearity and Pareto-optimality:

  $\forall i \epsilon \{1,2,\dots,n\}, x_i^s\ (v) = \sum_{i \in S \subset I}(v(s)\ -\ v(S/\{i\})\ *\ \frac{(n-s)!\,(s-1)!}{n!}$.

  If a game is convex, the core is not empty and the Shapley value belongs to the core. In other words, convexity is a condition that admit an increase in incentives for households (to join the EC) with the increase in the size of the EC.

- Definition 4: Anti-symmetric player are households that have similar profiles but centered at different hours of the day in a way that they support do not intersect: given a reference profile f(t), each individual has a profile:

  $\forall i \in I, \forall t \in \{1,2,\dots,T\}, f_i(t) = f(t - t_1)$, with t_1 , t_2, … , t_n are such that:

  $\forall t \in \{1,2,\dots,T\}, \forall i,j \in I, i \neq j \rightarrow f_i(t).f_j(t) = 0$.

  They will assume in this theoretical part, without any loss of generality, that the standard profile f(t) is the one of a typical household peaking at noon.

- Definition 5: Symmetric households are players that have similar load profiles: given a reference profile f(t), each individual has a profile:

  $\forall i \in I, \forall t \in \{1,2,\dots,T\}, f_i(t) = f(t)$.

This paper has so far considered a convex investment cost of PV function, as explained in the assumptions and definitions below. In fact, as we have said, a convex function increases the incentives for participation by increasing its size. However, the report also provides a case study if the investment cost function is concave. The concavity in the investment cost functions can be due to the presence of economies of scale and fixed costs for the investment in PV. If the investment cost is concave the community benefits from returns to scale as it grows. This aspect can be explained by the first theorem stated in this paper, Theorem 1: when the investment cost is concave and assuming away fixed costs of installation and players are either symmetric or anti-symmetric, the coalition game is convex. We have seen that stability is not guaranteed, but in order for it to be guaranteed, we must make sure that certain conditions are met. Observing real examples and experiments we note that stability is strongly influenced by the conformation of the

EC and the choices made by the individual households that make it up. Brown and Lund (2013) show us that energy rates are inefficient, this could cause instability and therefore spoil the data of the analysis of the paper, is therefore considered exclusively the productivity of the community (setting the rates equal to zero). Two different communities are then built, these communities must both install photovoltaic panels with the same costs, we see that differ in constitution in fact the families that compose them are very different. Basically, we know that the profile of energy consumption for each household is determine from their size, employment status, age, family status; in addition, the values of energy production are set by authentic values collected in the calendar year 2014 and the installation costs of the plants are set equal to the commercial standards present in that year. Since it is possible that the cost functions are concave, we also know that the value of the community increases moderately if even partial stability of the energy coalition is achieved. The two samples taken into analysis are: an EC made up of pensioners, and a mixed EC of students, pensioners, families with different occupations and shopkeepers (are considered households in this model). In other terms the first group is symmetric while the second one is mixed in term of activity and size of households, also for these regions the two groups have different possibilities to access to financial resources. From the results they have obtained from building this model, it emerges that the basic sharing rules fail to enable the community to remain stable; this means that at least one participant in the end, finds it more convenient to exit the EC. Being the core never empty, we can suppose that exist a possible feasible stable allocation, in all cases the Shapley value is an adequate allocation rule. From these results it is clear that reducing the impact of the initial investment can be a driver which improves the stability and profitability of the community, the impact is lower when the EC has many participants and then becomes large, this also makes it easier to optimize the allocation of PV production. However, it is important to highlight that the simple allocation rules are not previous in the core and therefore are not able to stabilize the EC, in fact the Shapley value provides with more stability than other allocation methods, however, does not ensure general and constant stability over time. However, at a time when it is considered a great energy coalition, with numerous interprets, other costs appear, first considered derisory in the analysis made: the coordination costs. When a coalition is created, costs arise that increase with the size of that, these costs are necessary to coordinate the production and energy sharing into the EC. In other words, the cost of coordination can be identified as: $c_{coordination}(S) = c'(s)$; where the first derivative of c(s) is assumed to be strictly convex and smooth function. In Theorem 1[4] we found a first distinction in the community, symmetric EC and anti-symmetric EC; having introduced the costs of coordination, at this point we must explain the two different situations that are created with these two types of EC. The case of anti-symmetric community is explained by Theorem 2[4]: when the coordination cost is taken into account and players are anti-symmetric, the following two propositions are equivalent: the core of the game is not empty and the Shapley value is in the core;

$\alpha Max_t\, f(t) + \delta \geq (n-1) \ * \ c'(n) - nc'(n-1)$.

In other words, when the coordination costs are considered and when the investment cost function (of PV) is linear, the marginal benefit from aggregation of EC has to be sufficient to compensate the increase of the marginal cost due to coordination costs. The case of symmetric EC is explained by Theorem 3[4]: when the coordination cost is taken into account and players are symmetric, the following propositions are equivalent: the core of the game is not empty and the Sharpley value is in the core;

$\delta \geq \ (n-1) * c'(n) \ - \ nc'(n-1)$.

This expression is similar to the case of anti-symmetric community except the fact that capacity fee is not taken into account. With a linear PV function and it aggregation are small, any EC facing convex coordination costs creates positive value that unfortunately cannot be shared in a stable way. So, EC has more possibility to remain stable if its members have anti-symmetric profiles. It is also considered the case that the core is empty, in this situation the paper analyzed proposes a way to stabilize the EC that with an empty core would be unstable. One possible solution may be a simple partition (P) of community members in multiple sub-communities I that do not intersect. The value of P is the sum of all the values of all sub-communities which compose P:

$VP(P) := \sum_{S \in P} v(S)$. From this emerges Definition 6 of the paper: P is an optimal partition of I if it is stable and provides the highest value among stable partitions, P is

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[4] We recall "On the viability of Energy Communities" (2020) by Ibrahim Abada, Andreas Ehrenman and Xavier Lambin; for the explanation and demonstration of these Theorems to the original paper and in the attached appendix.

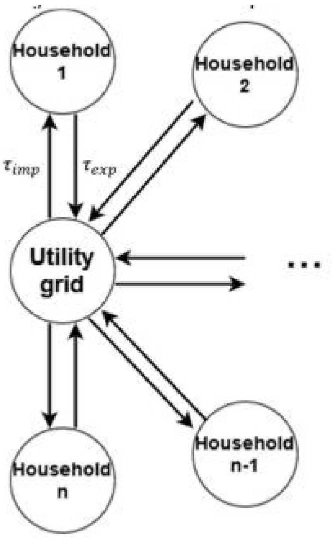
stable; $\forall P' stable\ partition\ of\ I, VP(P') \leq VP(P)$. Where the value of a partition VP(.) is given in the equation: $VP(P) := \sum_{S \in P} v(S)$. An optimal partition will split the community among smaller subgroups with members having sufficiently different consumption profiles, in order to reduce the coordination cost while creating enough aggregation benefits to ensure stability. Dividing the community into multiple parts allows us to reduce coordination costs, sometimes finding the optimal allocation for the consumer and this allows to achieve a stability that would not have been easy before. It has also been noted that consumer behavior changes depending on whether or not it participates in the EC. In addition, we see that incentives to moderate consumption can be reduced by the fact that the perceived benefits of such moderation are then shared with the community and do not remain completely individual. We can therefore define the commitment to energy saving a real good that increases the value of the EC (increasing the benefits). In conclusion, we have seen that this paper does not explain how energy can best be shared in an EC; the main proposal is to develop a benchmark that describes how communities are far from being efficient. This paper finds conditions under which communities can be stable or not, this built benchmark will allow our analysis to have a well-defined framework, built in such a way that the stability of the coalition we are going to consider, will be given as assumed as we will follow all the points that allow a greater stability.

2.2) VALUE CREATION AND SHARING METHODS IN HOUSEHOLD ENERGY COMMUNITY

The second paper analyzed is ‘Value creation and sharing methods in household energy communities’ by Marius Baranauskas, Antti Keski-Koukkari, Poria Hasanpor Divshali, Amir Safdarian, Anna Kulmala published in 2022 in IEEE International Conference on Power Electronics, Smart Grids and Renewable Energy. This paper presents an approach for modelling the value of EC as well as several value sharing methods. We know that EC create values by aggregating the demand and supply profiles of neighboring prosumers. The value should be shared fairly, in this way new members are not discouraged to joining the EC. One of the key factors to create a sustainable and decentralized energy system is the integration of small-scale renewable energy resources

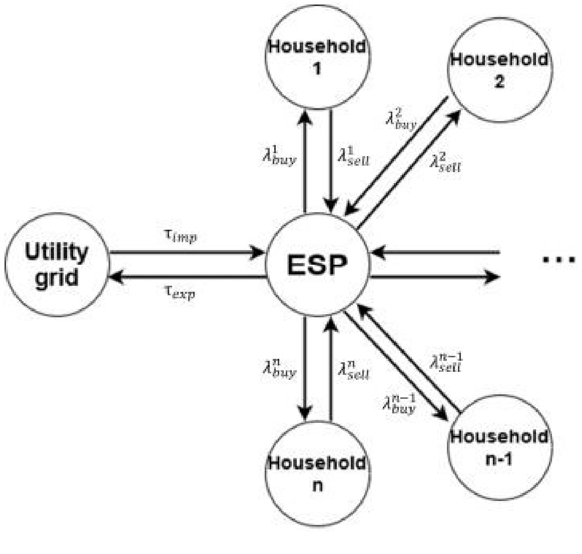
(REC). As we have already mentioned in paragraph 1.2 (in the introduction), two initial distinctions are made on the type of EC: Renewable Energy Community (REC) and Citizens Energy Community (CEC); then the paper exploit 4 different archetypes for energy communities: cooperative investment, energy sharing, aggregator and microgrid (the characteristics of archetypes are described in paragraph 1.2 of introduction). The main topic of this research (which is also the main reason that we take into consideration in our analysis) is comparing different value sharing methods in residential household in EC. To make this, is important to understand what creates value in the EC and to understand the driving factors of forming it. In this paper the value of EC is determined: $v(s) = cost_0(s) - cost_1(s)$, where $cost_0(s)$ is sum of individual households S bills over the first period analyzed (represent a reference point in the model), while $cost_1(s)$ is the modeled EC total bill if the households formed an EC by pooling their consumption and production profiles together. V(s) is the difference between total bill of EC (Figure 2) and a sum of independent households if they had not joined the EC (Figure 3). Where τ represent the import (τ_{imp}) and export (τ_{exp}) prices of the grid, while λ is an internal trading tariff within the EC (available for the households). The ESP (energy sharing provider) is an entity with the task of balancing the EC internally.

Figure 2: Energy Community.



Source: Baranauskas, M., A. Keski-Koukkari, P.H. Divshali, A. Safdarian and A. Kulmala (2022).

Figure 3: independent households.



Source: Baranauskas, M., A. Keski-Koukkari, P.H. Divshali, A. Safdarian and A. Kulmala (2022).

Demand profile of household: $D(i,t) = C(i,t) - P(i,t)$, where C(i,t) is consumption profile of household and P(i,t) is the production profile of household. The generalized cost function for the group of individual households (S is the number of households) is:

$$cost_0(s) = \alpha \sum_{i\epsilon s} max|D(i,t)| + \beta S + \gamma \sum_{i\epsilon s} \sum_{t}^{T} D(i,t)^+$$
$$+ \sum_{i\epsilon s} \sum_{t}^{T} (D(i,t) * (\ \delta(i,t) + \epsilon(i,t)^+)).$$

The price calculation is based on 5 components: α is power based grid tariff; β is a fixed component of grid tariff and retail charge; ϵ is energy-based grid tariff; γ is electricity tax; δ is volumetric energy retail charge.

The generalized cost function of EC is defined:

$$cost_1(s) = \alpha' max \sum_{i\epsilon s} |D(i,t)| + \beta' + \sum_{t}^{T} \gamma'(\sum_{i\epsilon s} D(i,t))^+ + \sum_{t}^{T} (\delta'(t)$$
$$+ \epsilon'(t)) \sum_{i\epsilon s} D(i,t).$$

Analyzing the difference between cost$_0$ and cost$_1$, we found that:

- $\sum_{i\epsilon s} max|D(i,t)| \leq max \sum_{i\epsilon s} |D(i,t)|$: represent lower peaks load of the community as the profiles are aggregated in EC.
- $\beta' < \beta S$: with current tariff structure, the EC members can expect tariff discount if the group is treated as single entity.
- $\sum_t^T \gamma'(\sum_{i\epsilon s} D(i,t))^+ \leq \gamma \sum_{i\epsilon s} \sum_t^T D(i,t)^+$: consider the difference in taxing of EC, the tax saving is usually caused by the demand aggregation, as the energy tax is not applied for internal EC consumption.
- $\sum_t^T (\delta'(t) + \epsilon'(t)) \sum_{i\epsilon s} D(i,t) \leq \sum_{i\epsilon s} \sum_t^T (D(i,t) * (\ \delta(i,t) + \epsilon(i,t)^+))$: describes the value created from the aggregation of demand profiles of volumetric charge and energy dependent grid tariff.

The value is created by aggregating prosumers into an EC. The main quantifiable performance indicator is the cost of electrical energy. The value of the EC can be quantified also by other characteristics as self-consumption, self-sufficiency and the strength of the stability of the EC.

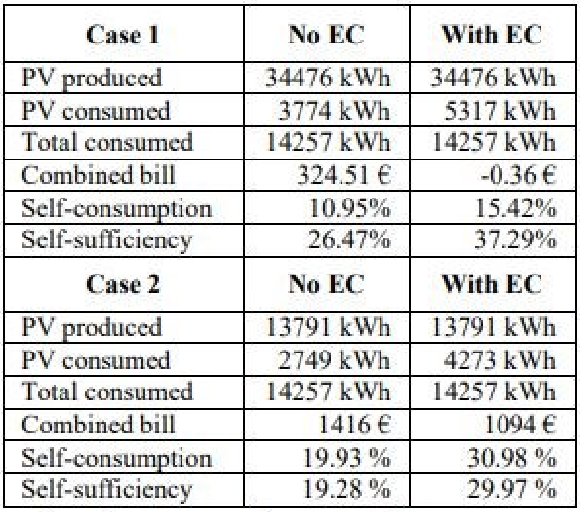
The central topic of this paper is the different methods of sharing value. The model created consider in the calculation the total yearly bill; bill remains the same because they had supposed no flexibility and no storage.

The different value sharing method analyzed are:

- Even share: $v(i) = \frac{v(s)}{s}$ most basic method which favors passive members of EC. A large portion of profits is allocated for joint the EC.
- PV capacity share: the value is shared on the basis of installed PV power, $v(i) = v(S) * \frac{pv(i)}{pv(s)}$ where *pv(i)* is the installed PV capacity of households i and *pv(*s) is total installed capacity of EC. This method incentivizes the active members of the community, ignores entirely passive members.
- Consumption based allocation: this method is based on momentary consumption of electricity, $v(i) = v(S) * \frac{\sum_t^T c(i,t)}{\sum_t^T \sum_{i=1}^S c(i,t)}$. This method prioritized the passive consumers and encourages energy consumption, the surplus of energy is sold on the grid if and only if the internal consumption is satisfied.
- Marginal allocation (MC) rule: simple and basic sharing rules often fail to provide adequate remuneration for all members. This method allocates the value based on marginal contribution of each member, the marginal contribution represents the change in the value of the EC if a member *i* left the community: $MC(i,S) = v(s) - v(S - \{i\})$; while the allocated value is determined: $v(i) = v(S) * \frac{MC(i,S)}{\sum_{i \epsilon S} MC(i,S)}$. Members of EC are unlikely to be penalized by increasing electricity costs, the distribution should be weighted by considering only positive values of MC.
- Shapley value: the Shapley rule is created around the MC rule, this is the most complex method but at the same time also the fairest. Shapley allocation rule gives to each member a share of the entire value that is proportional to the average of all his marginal contributions MC(i,S): $SR(i,S) = \frac{\sum_{i \epsilon S \subset I} MC(i,S)}{\#(i \in S \subset I)}$; while the value is allocated proportionally: $v(i) = v(S) * \frac{SR(i,S)}{\sum_{i \epsilon S} SR(i,S)}$. As MC rule, also Shapley allocation rule does not limit the share to positive values.

This paper tries to illustrate in a more practical way the methods of value sharing described above, offers us a simulation made from a data set collected on a sample of 6 households living in the periphery of Germany, in 15-minute intervals. The households own a unique combination of the following electrical devices: a dishwasher, a washing machine, a freezer, a heat pump, a circulation pump and a refrigerator. The pattern of consumption presents small differences but this is important to create a real based simulation. Another factor that the paper considers is energy tariffs, which can differentiate and sometimes may favors the preference of one method of sharing value over another. For this reason, a sample is built very similar to the German one, with the only difference that the rates and patterns of energy consumption are of a country that has different values, such as Finland. The results are analyzed in two parts, the first part (Table 1) shows us the KPIs in the German sample (case 1) and in the Finnish sample (case 2), adding the distinction regarding participation in the EC.

Table 1: German and Finnish cases – with EC and without



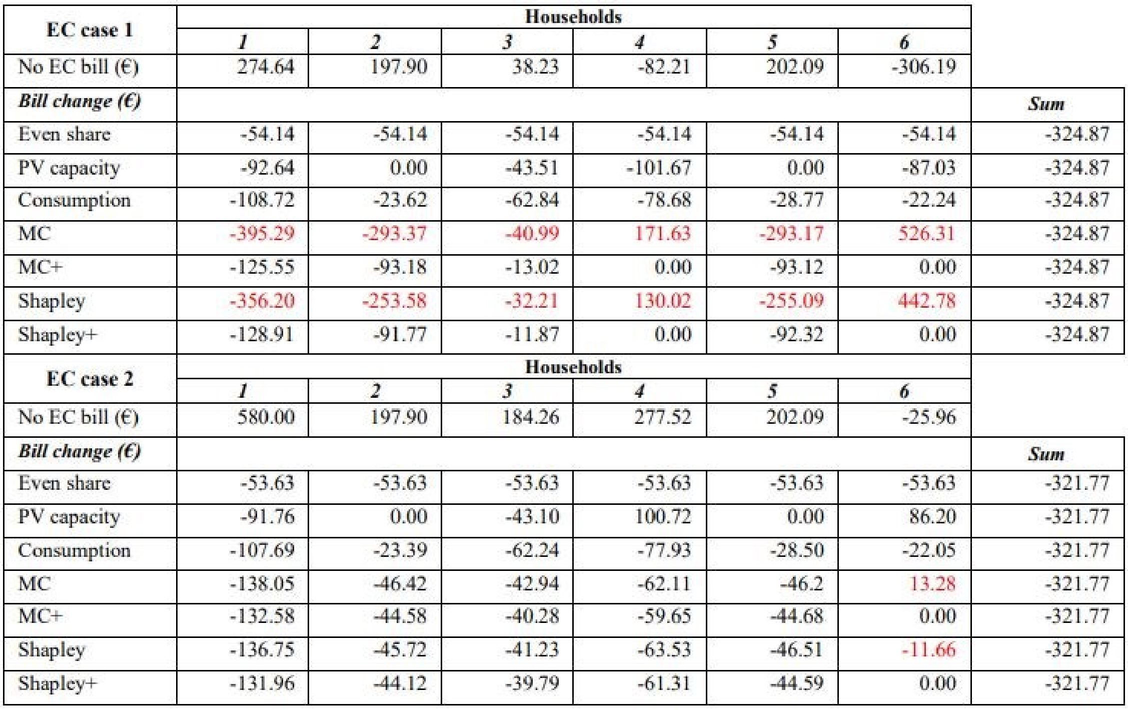
Case 1	No EC	With EC
PV produced	34476 kWh	34476 kWh
PV consumed	3774 kWh	5317 kWh
Total consumed	14257 kWh	14257 kWh
Combined bill	324.51 €	-0.36 €
Self-consumption	10.95%	15.42%
Self-sufficiency	26.47%	37.29%
Case 2	**No EC**	**With EC**
PV produced	13791 kWh	13791 kWh
PV consumed	2749 kWh	4273 kWh
Total consumed	14257 kWh	14257 kWh
Combined bill	1416 €	1094 €
Self-consumption	19.93 %	30.98 %
Self-sufficiency	19.28 %	29.97 %

Source: Baranauskas, M., A. Keski-Koukkari, P.H. Divshali, A. Safdarian and A. Kulmala (2022).

PV produces item means total energy generated by solar panels owned by community members. PV consumed item indicates a fraction of PV production that is consumed locally, individually or by EC's members. Total consumed item represents the aggregated EC's energy consumption. By aggregating household energy load and PV production profiles, local PV consumption increased by over 40% for the EC case 1 and by over 55% for the EC case 2. We can observe that the EC case 1 has higher self-sufficiency but lower self-consumption because has also higher local PV production.

The second analysis was made on the changes of the bills of the individual households according to the different sharing value methods (Table 2). MC and Shapley allocations rules suggest penalties for the passive EC's members and enormous benefits for others (marked in red in Table 2).

Table 2: German and Finnish EC cases – changes of the bills.



EC case 1	**Households**						
	1	***2***	***3***	***4***	***5***	***6***	
No EC bill (€)	274.64	197.90	38.23	-82.21	202.09	-306.19	
Bill change (€)							***Sum***
Even share	-54.14	-54.14	-54.14	-54.14	-54.14	-54.14	-324.87
PV capacity	-92.64	0.00	-43.51	-101.67	0.00	-87.03	-324.87
Consumption	-108.72	-23.62	-62.84	-78.68	-28.77	-22.24	-324.87
MC	-395.29	-293.37	-40.99	171.63	-293.17	526.31	-324.87
MC+	-125.55	-93.18	-13.02	0.00	-93.12	0.00	-324.87
Shapley	-356.20	-253.58	-32.21	130.02	-255.09	442.78	-324.87
Shapley+	-128.91	-91.77	-11.87	0.00	-92.32	0.00	-324.87
EC case 2	**Households**						
	1	***2***	***3***	***4***	***5***	***6***	
No EC bill (€)	580.00	197.90	184.26	277.52	202.09	-25.96	
Bill change (€)							***Sum***
Even share	-53.63	-53.63	-53.63	-53.63	-53.63	-53.63	-321.77
PV capacity	-91.76	0.00	-43.10	100.72	0.00	86.20	-321.77
Consumption	-107.69	-23.39	-62.24	-77.93	-28.50	-22.05	-321.77
MC	-138.05	-46.42	-42.94	-62.11	-46.2	13.28	-321.77
MC+	-132.58	-44.58	-40.28	-59.65	-44.68	0.00	-321.77
Shapley	-136.75	-45.72	-41.23	-63.53	-46.51	-11.66	-321.77
Shapley+	-131.96	-44.12	-39.79	-61.31	-44.59	0.00	-321.77

Source: Baranauskas, M., A. Keski-Koukkari, P.H. Divshali, A. Safdarian and A. Kulmala (2022).

Therefore, they calculated two adjusted methods which are: MC+ and Shapley+, calculated to consider only non-negative values. Looking at the results we see that:

- Even share: assigns value uniformly despite the locally generated energy, this method inadvertently promotes passive consumers because they received benefits only by consuming locally generated energy;
- PV capacity: allocates the value just for active members that produce their energy, in this case passive members receive nothing;
- Consumption based: promotes large consumer which could be beneficial for incentivizing local consumption, this method promotes passive consumption and not incentivize consumption;

- MC: this method is based on the individual value that each member brings to the EC, this marginal value can also consider negative values such as the cost of energy, in this case it is considered as an impracticable method. To solve this problem MC+ was used which considers only the positive components and corresponding positive effects in the EC.
- Shapley: this method reacts like the previous MC; in fact we see that a second Shapley+ is created that considers only the marginal contributions of community members who bring positive values.

The analysis provided by this paper shows that all the most basic sharing methods fail in the fair distribution of value. While we see that the MC and Sharpley offer better results.

2.3) THE SNOWBALL EFFECT OF ENERGY COMMUNITIES

The third paper analyzed is ‘Unintended consequences: the snowball effect of energy community’ by Ibrahim Abada, Andreas Ehrenmann, Xavier Lambin published in 2020 in Elsevier. This paper is interesting because it analyzes the effects of different tariffs on the stability of the EC. It also goes to the explanation of how energy tariffs can cause a snowball effect on members of EC. It observes other aspects mentioned in previous papers, we limit ourselves to the considerations provided by papers ‘On the Viability of Energy Communities’ and ‘Value creation and sharing methods in household energy communities’ because they are more recent. It is also proposed the analysis of the relationship between EC and distribution system operator. After a first distinction between REC and CEC and a legislative definition mentioned in article 21 of Renewable Energy Directive; the analyzed paper lists the two main challenges of the EC’s manager (including also the tariff setting and choice) and offers a list of 3 useful insights to understand the model that you will be evaluating. The first challenge for the manager of the EC is to allocate the benefits of pooling the PV investment (and then joining the community) so that the coalition itself finds a constant stability over time. The sharing of benefits must be done in such a way that all members are satisfied, in other words the manager has to set the configuration of payoffs so that members cannot improve the earnings by leaving the coalition, it must be more profitable to be part of it. The second challenge is in determining the origin of the value, which can be identified in some externalities: not paying the grid component of self-consumed, energy creates value for the community but can lead to a decrease in revenues for network operators, especially the distribution companies. Low contributing consumers will cause an inferior profit for the distribution companies who bear the costs of maintaining the network and who could therefore increase their tariffs; higher tariffs could therefore lead a greater number of consumers to invest in photovoltaics, creating a snowball effect. The three important insights from this paper:

- the formation of EC can lead to the snowball effect through network tariffs. This is because often the formation of an EC implies a reduction in tariff costs, however, the costs of installation and maintenance for the energy operator often remain unchanged, this leads to a subsequent tariff increase and this drives people to enter an EC.
- Per-connection fees are the taxable type that most favors the creation of an EC, while capacity-based or energy-based rates lead to greater inertia among community members. On the contrary, capacity and energy-based tariffs are the most effective ones to promote investments in photovoltaics and batteries.
- The inner stability of an EC is addressed using cooperative game theory but this paper is the first attempt to study the interaction between stable energy communities as mediated throught grid tariff, using an equilibrium formulation also in a non-cooperative game theory framework.

The paper also proposes insights which explain the birth of the snowball effect phenomenon, that is the aspect useful for our analysis. They consider two communities not connected, whose costs must be recovered through a fee levied by a DSO, which charges the installation of the meter a fee $\delta>0$. They define snowball effect a situation such that: given existing grid tariffs, some communities form but not all players join a community; to ensure grid cost recovery following community formation, grid tariffs are modified; following this modification, new communities form or existing communities increase in size. The authors propose a financial analysis aimed at comparing costs and benefits for the construction of the model. It is assumed that there are two buildings n_1 and n_2, household have symmetrical profiles. We then see that the two buildings have different sizes, in fact $n_2>n_1>1$; share the same meter, network costs therefore are unique and correspond to $\delta>0$. Joining a community entails some coordination costs $c(n)$, that increase and, for the sake of illustration, are assumed to be convex in the number of community members (coordination costs are convex). Having set the basis of the model, the first necessary and sufficient condition for an EC composed of n families to form properly is: $u(n_i) \leq \delta$. We know that the function *u(.)* increases by increasing the number of households, this because the households' profiles are symmetric; this means that if $n_1<n_2$ the building 1 is more likely to form a community than building 2. As community form, the grid cost-recovery constraint induces change in δ, the DSO may define tariff parameter δ'such that the revenues are maintaining after building 1 has formed: $(n_1 + n_2)\delta = (1 + n_2)\delta'$ and it means $\delta' > \delta$. So, we will have a snowball effect (as described in definition 1) if and only if: $u(n_1) < \delta < u(n_2) < \delta'$. The first inequality means that the first building forms a community. The second inequality means that the second building would not form a community, given initial tariffs. The last inequality states that the change in grid tariffs, induces the second building to also form a community. The situation becomes more complicated when communities manage themselves without a central authority, they considered the Theorem 3 cited in paper Abada et al (2020) (first paper considered in our literature review): $u(n) + h(n) \leq \delta$; so, the condition for a snowball effect become: $u(n_1) + h(n_1) < \delta < u(n_2) + h(n_2) < \delta'$. We also report the key definitions of this paper which again links to Abada et al. (2020). The first is reported to understand why household join in an EC, they join in an EC in order to share the cost of investment in a photo-voltaic panel with a battery and aggregate their energy consumption. With reference to stability, we see that the stability of a community depends on the existence of an allocation rule that ensures all households the desired benefits, therefore the formation of small ECs is a driver of good stability; also, a community is considered stable if the core is non-empty. One assumption of this paper is that ECs cannot be formed with members who are not part of the same building, this simplifies the calculations and should not affect the key aspects generated by this study. We also see that if households fail to create a community, they will try to create a smaller sub-community so they try to optimize the overall value of the whole building. As already stated, this paper refers to many of the assumptions reported in Abada at al. (2020) in fact we see that in this model the installation cost of the photovoltaic system is based on the capacity of the same. Energy production and consumption profiles of households are also considered equal to those considered in the paper taken as a reference; in fact, the peaks of production occur during the day with the clear sky and the consumption profiles are different and varied in the reference area of the community (there are no consumption profiles equal to each other). The investment decision variable $\mu(S_b)$ is calculated such that the benefits for the set of households is optimized. We know that the benefits derive from the different opportunities offered by participation in the EC; every community can in fact consume the energy produced or can sell the excess energy locally, this reduces energy tariffs, the sale of energy at a price x may represent the tariff reduction that the DSO applies to the EC. This tariff reduction is very important as it is an incentive to the production and consumption of renewable energy. The role of the DSO in this case appears to be key as it is not a profit-maximizer and does not (and should not) impose discriminatory energy tariffs. As already mentioned, there are some externalities between communities of different buildings throught grid tariff. This paper proposes a generalize setting in which these externalities are captured by an equilibrium formulation between communities and DSO; this equilibrium will encompass every possible snowball effect. These externalities, positive or negative, for simplicity are only mentioned in the paper. In fact, non-economic reasons (such as green propensity) are difficult to assess and may complicate the calculation of community value. We, too, in our thesis will limit ourselves to quoting them in such a way as to provide a complete framework of what is the economic model built. It is then assumed that all households participating in the EC, have the same PV and the same technologies in the batteries. The paper departs from the system dynamics approach and directly analyze the equilibrium of the system, without detailing how or how fast the equilibrium is reached. This choice could be explain by two main motivations: firstly it allow to overlook some sensible dynamic aspects of the interaction for which we can have a lack of knowledge, for example: the conversion rates of prosumers, the reaction time of the DSO to the formation of communities (adjustment of tariffs), the availability of financial loans and the evolution of their interest rates; secondly it allows to consider only the long term stability of the coalition without analyzing more complicated dynamic solution concepts. This research already provides come insight regarding the magnitude of snowball effect and how the grid tariff charges can mitigate it. The value of the EC is calculated by calculating the value of coalition of S_b households living in b buildings; given the gird tariff α, δ, φ the objective of this computation is to obtain the optimal investment in PV and battery and also the optimal functioning for the members, this aimed to obtain the optimal payoff for the household. Recall that each consumers pays 2 different types of volumetric charges that are proportional with the consumption, the first is the energy component with tariff *β(t)* and the second is the grid component with tariff φ. The other variables that we can find in the next formula[5] are: $\mu(S_b)$ is the investment decision in PV; $Bat\ (S_b)$ is the investment decision in battery; while $\mathrm{aut}(S_b)_t$, $\mathrm{inj}(S_b)_t$, $\mathrm{st}(S_b)_t$, $\mathrm{with}(S_b)_t$, $\mathrm{l}(S_b)_t$ are their operations. The value of coalition result from an optimization program with several constraints, while the objective function is the payoff sum of: grid tariff savings, PV auto-consumption and injection in the grid, minus the investment and coordination costs.

$$
\begin{aligned}
& v(S_b, \alpha, \phi, \delta) = \\
\text{Max} \quad & \alpha\left(\sum_{i_b \in S_b} \text{Max}_t\left(f_{i_b}(t)\right) - \text{Max}_t\left(\sum_{i_b \in S_b} f_{i_b}(t) - aut(S_b)_t\right)\right) \\
& + \phi \sum_{t=1}^{T} aut(S_b)_t + \delta(s_b - 1) + \sum_{t=1}^{T} \beta(t) aut(S_b)_t \\
& + \sum_{t=1}^{T} \gamma(t) inj(S_b)_t \\
& - c_{PV}\left(\mu(S_b) \frac{\sum_{i_b \in S_b} \sum_{t=1}^{T} f_{i_b}(t)}{\sum_{t=1}^{T} g(t)}\right) - c_{Bat}\left(Bat(S_b)\right) - c_{coo}(S_b) \\
\text{s.t.} \quad & 0 \le \mu(S_b) \le \bar{\mu}_b \\
& 0 \le Bat(S_b) \\
& 0 \le aut(S_b)_t \le \sum_{i_b \in S_b} f_{i_b}(t),\ 0 \le inj(S_b)_t && t = 1, \dots, T \\
& 0 \le st(S_b)_t,\ 0 \le with(S_b)_t,\ 0 \le l(S_b)_t && t = 1, \dots, T \\
& \mu(S_b) \frac{\sum_{i_b \in S_b, t} f_{i_b}(t)}{\sum_{t=1}^{T} g(t)} g(t) + with(S_b)_t - st(S_b)_t \\
& - \left(aut(S_b)_t + inj(S_b)_t\right) = 0 && t = 1, \dots, T \quad \text{(V1)} \\
& l(S_b)_t = l(S_b)_{t-1} + st(S_b)_t - with(S_b)_t && t = 2, \dots, T \quad \text{(V2)} \\
& l(S_b)_t \le Bat(S_b) && t = 1, \dots, T \quad \text{(V3)} \\
& st(S_b)_t \le ch\ Bat(S_b) && t = 1, \dots, T \quad \text{(V4)} \\
& with(S_b)_t \le dch\ Bat(S_b) && t = 1, \dots, T \quad \text{(V5)}
\end{aligned}
$$

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[5] The last 5 constraints (V1, V2, V3, V4, V5) are explained by the authors to clarify the sense of their presence, for completeness we also report them: V1 states that each time period, the PV production should be equal to the amount of energy that is auto-consumed plus the amount that is injected into the grid, plus (or minus) the amount of energy that is charged in (or discharged from) the battery; V2 is the state equation of the battery at each time step, linking the level at time t, to the one at time $t - 1$ plus or minus the amount of energy that is charged in (or discharged from) the battery; V3 bounds the level of the battery by the capacity that is invested; V4 bounds the storage variable by the technical constraint of the battery; V5 bounds the withdrawal variable by the technical constraint of the battery.

They have assumed also that all investment variables are continuous. Investment costs for the PV and for the batteries are largely linear in the range of the capacity that we are considering for a standard building; so, the value for each community is always properly defined.

Relating the stability of the EC this paper report Definition 2 of Abada et al. (2020), the first paper in our literature review. We know that in most cases the community made up of households living in b constructions is not stable. In that case, the paper looks for an optimal portion of the building into smaller stable conditions (as done in the paper Abada et al 2020) that maximize a criterion across the entire building. The agents are driven by economic incentives, they assumed that households would look for the stable partition that maximizes the overall value of the building.

In this paper is introduced also the concept of equilibrium, and from this are defined 3 further important concepts: when communities corresponding to a whole building fail to materialize, we look for the optimal partitioning, this consists in the splitting of buildings in several communities such that the total value of them is maximized; they assumed that the DSO has a grid cost recovery constraint, this means that DSO can dynamically updates its tariff; finally a consideration relating equilibrium is that the system has reached an equilibrium if and only if all buildings are partitioned optimally and the DSO recover its cost. In other words, given the grid tariff in equilibrium the EC have no incentive to change their structure.

This paper highlighted that grid tariffs are a strong determinant of community formation, and of the sequent installation of PV or technologies in the batteries. A grid cost recoveries constraint implies that there may be substantial spillovers between communities and snowball effect. Depending on policymakers' motivations, the snowball effect may be deemed beneficial especially if the policy goal is to increase PV or battery installations. However, if communities form too large a share of the consumer-base, investments in new technologies may be excessive and may prompt policymakers to favorable tariff structures that induce weaker spillovers. If EC are seen as a vector to promote investment in PV and battery solutions then capacity-based or energy-based tariffs are suitable: a strong incentive to reduce peak demand or withdrawals from the grid leads households to invest in these new technologies. Furthermore, this paper shows that this effect is magnified by a potential snowball effect, with the risk of triggering some over-investments in PV, that incur strong costs to the system which may outweigh the benefits of green energy. A policymaker that is keener on increasing the welfare of communities while reducing their cost of coordination should design the grid tariff as a function this cost: when this cost is small, setting a fixed tariff is still the best option. A comprehensive picture should take account of the benefits in terms of environmental conservation which would then increase the appeal of a higher α or ϕ. If a policymaker is primarily motivated by the sense of community that may be created by such coalitions, per-connection fees are most suitable as it forms the largest communities.

2.4) A BI-LEVEL FORMULATION TO HELP AGGREGATOR SIZE ENERGY COMMUNITIES

The fourth paper analyzed is 'Bi-level formulation to help aggregator size Energy Communities: a proposal for virtual and physical Closed Distribution Systems' by Davide Fioriti, Davide Poli, Antonio Frangioni published in 2021 in IEEE. In this study authors propose a business model and a sizing methodology to help aggregators size where users are aggregated behind a single point of delivery (PoD); this problem is formulated as non-linear bi-level optimization method and compared to the equivalent case with no EC. We know that typically the ECs commercially aggregate multiple users, each one with own private PoD with respect to the public grid. The policy framework can allow selected users to aggregate behind single PoD creating a Closed Distribution System. To date, the laws relating to renewable energy and the formation of ECs are not present in many states; there are legislative proposals that aim to provide economic incentives to those who join the EC. In these terms we know that by forming an EC, an user can provide support to the power system and prosumers may be incentivized by supplying their surplus power; in this way social, environmental and economic benefits can be fostered. This paper also makes a distinction between CEC and REC, a distinction already mentioned in paragraph 1.2. One of the main problems of this model arises in the optimal design and mechanisms of profit sharing. In fact, the benefits are put in terms of cost reduction (due to public incentives). So, the EC first defines the gratification mechanism, then they specify the operating mechanism and finally they create the optimal design for the EC itself. The aggregators have the goal of maximizing the users' social welfare. A distinction was made between competitive and non-competitive systems: in competitive systems each users aim to maximize its own benefits while in non-competitive systems the aggregator which is coordinated to provide network services is focused on power-heating application. In this paper authors create a model of a CEC operated by an aggregator, where the aggregator is treated as operator with specific remuneration. The model is created with the aim of maximizing the sharing of the energy. So, the EC shall be a no-profit legal entity whose members are allowed to share energy to reach social, environmental and economic benefits. Relating the aggregator, we know that it is a for-profit company, and so it shall be remunerated with the specific legal agreements. This business model proposes eight main key features which are:

1) Each user signs the membership contract to be part of the EC;
2) Assets installed in the property of the users are their full responsibility;
3) The aggregate behaves as a single user whose energy flows are equivalent to the net energy balance between all users (a private network with a single external PoD connects different internal users);
4) Each user of the community buys or sell the electricity from the local market of the EC;
5) Electricity price of the EC is regulated by the aggregator so as to be always no worse than the price of public market;
6) The total costs due to the peak power are distributed according to the peak power of each users;
7) The aggregator guarantees a total costs discount to each user, with respect to the total costs without the EC;
8) The aggregator is remunerated as a proportion of the energy sharing between users and a fraction of the reduced costs related to the peak power usage with respect to the public electricity markets.

A further analysis of the useful energy market is provided to complete the framework of the constructed model. The aggregators operate in the internal market with the aim to reduces the tariff (with respect to the market's tariff), it also has the aim to maximizes profits for the members of the EC (total benefits are share proportionally). The EC in the model is composed from 3 members: A who is supplying power member, while B and C are absorbing power members. In fact, we see that if B and C were not to be part of the community, A will go to sell its energy in the market at a net rate higher than that used to buy energy. We can therefore understand how the surplus generated by A can be absorbed by B and C. In any case we see that the gains will be divided into A, while B and C will gain by reducing the tariff plan because they used energy produced in the EC. The optimization problem[6] is described by:

$$max\ AP^A$$
$$s.t. [aggregator\ costraints]$$
$$max\ SW^U = \sum_{i \in I} AP_i^U$$
$$s.t. [user\ costraints]$$

While the mathematical representation of the annual revenues for the aggregator are describe:

$max\ AP^A = \sum_{t=1}^{N^T} m_t^T R_t^{A,M} + \sum_{w \in W} m_w R_w^{A,PP}$ [7]. The idea is that in the proposed business model, the revenues of the EC and the aggregator agreed to be proportional to the energy sharing occurring among the users. When A shares energy to neighbor, B and C avoid to paying the public market energy at the respective tariff; the difference of the prices is the revenue for A and the aggregator retains a fraction σ of this surplus. The revenues related to the peak power management are proportional to the reduced costs enabled by the aggregator for the EC. The aggregator guarantees that each user is better off with the EC that without with constraint, which specified that the annualized profits of each user should be higher by a constant factor. The lower problem of the aggregator is maximizing the social welfare of the users (that is the sum of each user annualized profits). In order to incentivize the energy sharing the peak cost is calculated only on the energy flows that are not shared within the users. So, in the user problem the energy sharing between suppliers and buyers is guaranteed by:

$\sum_{i \in I} P_{i,t}^{U,M+} = \sum_{i \in I} P_{i,t}^{U,M-}, \forall t \in T$[8].

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[6] AP^A: aggregator's profitability;
AP^U: users' profitability;
SW^U: social wealth (sum of each user wealth).

[7] $R_t^{A,M}$: represents the revenues related to the energy that is shared between the users,
$R_w^{A,PP}$: represents the fraction of revenues related to the peak power reduction.

[8] $P_{i,t}^{U,M+}$: energy shared by user *i* in each time step;
$P_{i,t}^{U,M-}$: shared energy absorbed by user *i*.

To solve the optimization problem, it is transformed in a single level formulation using KKT reformulation. Using this reformulation, they can transform the single level problem adding the upper problem additional constraints related to the feasibility of the lower problem. To speed up the optimization process while guaranteeing adequate optimally conditions, we used a two-step procedure to solve the problem: reformulate the bi-level problem with the product method and then solve the single level problem (using Ipopt); reformulate the bi-level problem with the Fortuny-Amat-McCarl method and solve the problem using Gurobi.

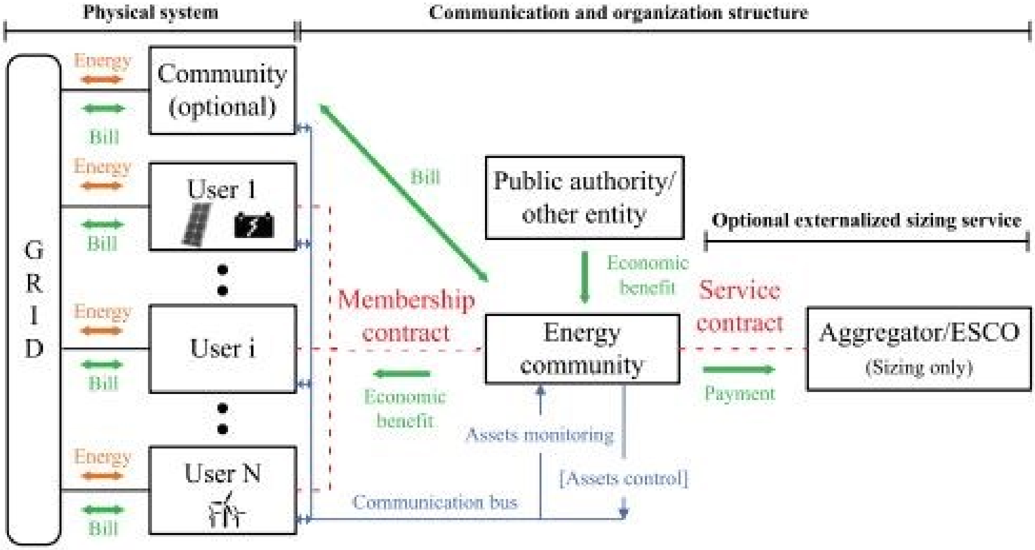
To interpret the model the analyzed paper creates a case study of an EC composed by 4 commercial users clustered in a local area. Each user installs a pre specified PV with a power of 100kW at the cost of 1400€/kW (the lifetime of the PV system is 25 years), this case study is created in Italian area so it could be useful in our paper (because the model that we are creating is geographically set in an Italian territory). The market prices are assumed 16c€/kWh when energy is withdrawn from the public grid and 5c€/kWh when energy is injected to the public grid (the peak power tariff is 36€/kW). The bi-level model is proposed on the case study and the solution is compared to the scenario where no EC is in place and each user optimizes its own system independently to the other users. Looking at the results we note that the majority of annualized profits of users is negative (for simplicity is in fact considered the absolute value). The total design of the battery systems decreases, and the capacity of user decrease; in EC configuration the energy excess of a user is met by the load of other users. Thanks to this energy sharing, the need for batteries is reduced which is the reason why the total investment in batteries is reduced. These results suggest that ECs can be suitable in promoting investments in renewable assets and promote synergies between different users that may turn out in reducing the need for battery storage, depending on the load profiles, the generation profile and cost parameters.

Summarizing what has been proposed so far, the paper creates a business model for an EC and the corresponding methodology to facilitate the aggregation of current to the aggregator. EC allow for an increase in the amount of renewable assets and are also reduced in battery storage design. The latter, however, needs to be reduced according to the correlation between demand and renewable energy production. In conclusion, the proposed bi-level approach has suggested the potential benefits of this methodology.

2.5) OPTIMAL SIZING OF ENERGY COMMUNITIES WITH FAIR REVENUE SHARING AND EXIT CLAUSES

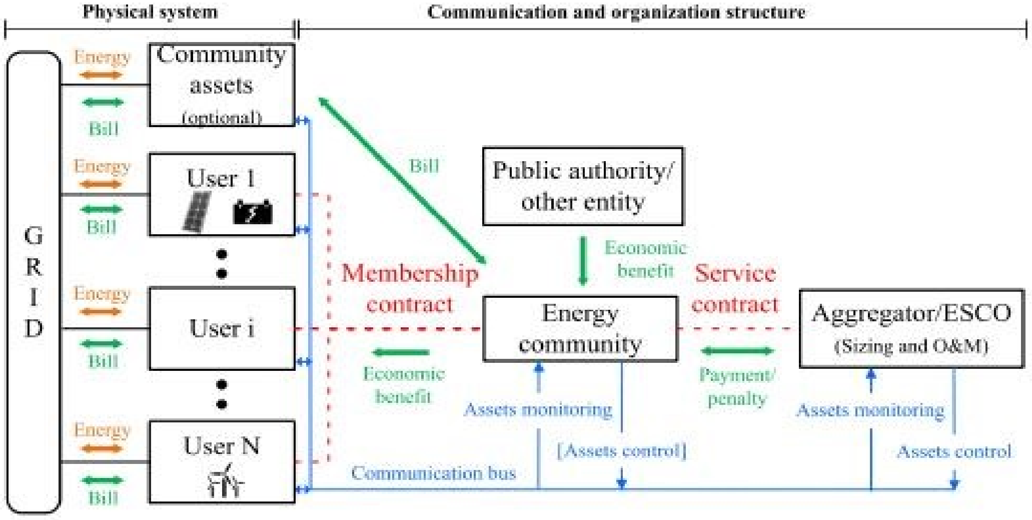
The fifth paper analyzed is ‘Optimal sizing of energy communities with fair revenue sharing and exit clauses: value, role and business model of aggregators and users’ by Davide Fioriti, Davide Poli, Antonio Frangioni published in 2021 in Elsevier. This study proposes a business model for aggregator of an EC, and relative optimization problem, considering some crucial aspects which are: alleviating the risks of agency problem; fairly distributing the reward awarded to the EC; estimating the fair payment for the aggregator’s services; defining appropriate exit clauses ruling what happens when a user leaves the EC. A mathematical model is developed which quantifies and evaluates the effect of the aggregator, which causes a reduction in costs and a development in the consumption of renewable energies. Furthermore, the model aims to provide an optimal sizing methodology that maximizes the utilities present in the model. This sizing methodology is based on a custom business model for ECs that is aimed to stimulate the cooperation among users and the optimal operation of the EC by the community manager, or aggregator, also including exit clauses to rule how users leave the community. Aggregators traditionally are private operators acting on the energy market to provide benefits by offering or covering the market reaching a low level of pricing through storage systems implementing demand or introducing policies on the question. Previous studies have been based on optimal aggregation techniques, sometimes using economic indicators. Other studies have focused on maximizing social welfare; finally, others propose theories on cooperative and non-operational games. In non-cooperative approaches users do not cooperate for achieving maximum social welfare; this approach is proposed to provide additional flexibility in a local energy network and market. In any case of a typical EC, players are usual to be not interested in direct trading and would like to delegate this role; as a consequence, this paper denotes that a cooperative approach is regarded as more appropriate, especially considering the social focus of EC policies. In the cooperative formulation the users cooperate with the goal of achieving the cheapest solution, however, is important that the coalition stay stable and the total reward shall also be fairly distributed among users. As we already cited in the first paper analyzed the stability of a coalition depends on the cost/profit allocation, that should satisfy 2 principles: efficiency and rationality. Rationality guarantees that no subset of users benefits from leaving the community. Efficiency specifies that all benefits given by the aggregate shall be completely distributed among all components of the aggregate. All solutions are efficient and rational belong the concept of the core, its definition is embedded in the nucleolus concept adopted for the coordination of multiple microgrids in a distribution system. In relation to sharing methods, this paper refers to several methods, including the Shapley value, which is most likely to entail community stability. We therefore consider it appropriate not to mention the other sharing methods analyzed by the authors. Nucleolus and core are concepts useful to lead the efficiency and rationality in the profit allocation but does not guarantee the uniqueness and fairness of the community; while we see that Shapley value ensures fairness and uniqueness but does not guarantee rationality. Many studies cited in the literature focus on user aggregation but leave out related aspects of the business model, such as optimal management, remuneration of aggregation services, and long-term stability of the community. The present paper provide a comprehensive treatment of all these aspects, the main contributions are: proposal and discussion of a business model to alleviate the agency problem in the management of the EC; proposal of exit clauses that clearly state at which conditions a user can leave the community; evaluation of the fair benefit generated by the aggregator, considered as a player contrary to standard approaches; development of several new reward allocation mechanism and comparison to existing methodologies to reach efficient, rational and fair distribution of the reward received by the EC; extensive comparison of different fair game theoretic mechanism to allocate the collective profits; development of a mathematical optimization model to properly size the EC. According to the EU directives the EC created is a non-profit entity whose participants take collective actions with the aim of involving all energy consumers as much as possible in the energy field and promoting social innovation. The incentive to form an EC is usually based on granting economic benefits when energy is produced and consumed by EC users. The current trend in the adoption of EC indicates that the creation of committees requires skills that are unlikely to possess a local group of citizens whose major activity is not related to energy production. In fact, the need and necessity of these skills are translated into the figure of the aggregator, which as we see in the figure 4 and in the figure 5, provides fundamental support to the EC by coordinating the objectives with those of the EC itself. A further challenge for community creation poses responsibility and ownership of the assets used in the EC. The new asset installation implies incurring costs and some users could be unable to sustain. However, all contributions made by users are accounted and then taken into account when distributing the benefits derived from the EC. The assets can be installed at a consumer property, but property can be owned by the consumer himself, the EC or a third company lending the goods for a fee. When the consumer is not the owner of the assets, the clauses to address the cost bearing are shared.

Figure 4, Business model of energy community with no externalized activity of system operation.



Source: Fioriti, D., D. Poli and A. Frangioni (2021).

Figure 5, Business model of energy community with externalized design and operation.



Source: Fioriti, D., D. Poli and A. Frangioni (2021).

This paper primary considered the case when the assets are owned by the users and then the case when assets are owned by the EC. Regarding the non-externalized operational decisions, in the business model shown in figure 4 the EC can ask a support for the initial design of the system. Subsequent decisions and subsequent monitoring are assigned to a consultancy company, this involves the stipulation of a contract remunerated with a fee, the lack of experience in the sector and professionalism within the EC could make users make decisions that are not efficient for final profits and this reduces their benefits. In figure 5 instead we see the case where the decisions are completely externalized to a consultancy company, in this case the aggregator, in addition to proposing an initial optimal system, assume responsibility of monitoring the progress of the EC and subsequently of making decisions that maximize EC benefits. The aggregator always makes decisions respecting the terms agreed in the contract (with the members of the EC) but having the adequate technical knowledge is able to make the right choices. For these reasons, in our thesis we will consider the case where the decisions are granted to an expert (therefore outsourced), in order to maximizes the benefits of the EC.

The key features considering externalized business model are:

- users join EC by mean of membership contracts;
- EC may economically support users in funding new installations;
- in the contracts exit clauses specify that any users leaving the aggregate shall reimburse the EC up a given economic amount;
- membership contract enables the EC and its technical advisors to access the real time consumption data to control some of user’s devices;
- EC delegates the optimal design, maintenance and operation to an aggregator by means of a service contract with clauses that reduces the risk of agency problem;
- each user buys on the public market electricity absorbed from the grid and is paid from the public market for his extra production injected into the grid;
- the benefits of the aggregate are rewarded to the EC that distributes them between the aggregator and the user according to fair schemes.

The contract that must be stipulated must aim to eliminate agency problems; the best sizing of the system is the one that solves the following maximization system:
max $\{NP\ V^{A}$ s.t. Agg./Users constraints, $SW^{U,CO} \geq SW^{U,NC}\}$[9]
The combined optimization in the following maximization problem implies that the output of the individual user can prevent other users from achieving the set goals. For this reason, it is planned to include economic exit clauses that pay the decrease in benefits due to the user's exit.

In this paper are reported some aspects relating to game theory which influence the presented model. The first concept analyzed is the Core that is defined as a key concept of game theory, which provides a theoretical framework to enhance the conditions of stable distribution of divisible collective goods among users of a given coalition. It is a set of what are the various conditions that can meet the principles of stability and efficiency. A second consideration is the Shapley value, that proposes an axiomatic definition of equity that through efficiency includes symmetry, additivity and fictional players. The symmetry specifies that players who make the same contribution should be rewarded with the same amount; additivity specifies that when two games are added on the same players, their profit distribution is also added; the 'dummy player' property specifies that a player who participates without creating any value for the aggregate is rewarded without any profit. Shapley unlike Core does not require the property of rationality. The next concept is Nucleolus which has been proposed to strengthen the stability of a coalition by distributing profits to iteratively increase the total utility of a sub coalition with the smallest surplus. As the Shapley value aims to offer a solution to several optimization problems that grows exponentially with the magnitude of the community. Nucleolus does not necessarily meet the axioms of equity postulated by Shapley and therefore it is questionable whether it provides an equitable distribution of profits.

The authors then develop a mathematical model aimed at optimizing: the sizing and user system in both cooperative configurations (with and without cooperation); the fair allocation of the premium among users; the setting of exit clauses. To correctly estimate operating costs, the model represents seasonality in load profile, renewable energy

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[9] Constraints for users are imposed in such a way that the benefits with the presence of the aggregator are greater than the benefits without the presence of the aggregator: $SW^{U,CO} \geq SW^{U,NC}$.

production and their variability over the year. In particular, annual simulations are approximated using representative days to ensure a good compromise between accurate results and low computational cost.

In conclusion we see that this elaborate successfully proposes: a business model and an optimization methodology for EC; measures to alleviate agency problems (through game theory); fair sharing policies; payments to aggregators and exit clauses to avoid losses of EC users. This is demonstrated by a case study and the respective analysis of the results, which indicates: Nucleolus as less convenient method for the aggregator but more convenient for users; we see that Shapley and Core are more in favor of the aggregator. For the choice of these methods, the authors recommend implementing it according to the type of model we want to propose, our work will be based on the user side and for this reason we would take into account the evaluations made about the Nucleolus and the respective methods used.

2.6) OTHER RESEARCH

In this paragraph we will list other research included into the previous literature analyzed. Previous works are subdivided in different thematic areas, in this way it is clearer how they contributed to the formation of the model present in our thesis.

The first thematic area is related with cooperative game theory, although not considered the game theory in our thesis, we consider very important to mention all the previous work that has allowed the conception of optimal characteristics of the proposed EC models. Shapley, 1953; Young 1994 developed a game theoretical approach to analyze the stability of EC sharing a PV panel with respect to grid tariffs. Young 1994; Moulin 2002 explain clearly how cooperative theory could be applied to costs and surplus sharing. Hagspiel (2016) found that Shapley value could be used to allocate generator's contributions, then Abada et al. (2020) demonstrates the efficiency of the method. Lastly, Kellner (2016); Pierru (2007); Duphine (2016); Contreras et al. (2009); Kattuman et al. (2004); Junqueira et al. (2007); Voropai and Ivanova (2006) analyzed cooperative games theory in other types of aspects for example externalities connected to CO_2's emission; allocation of network costs and optimal system planning. Cooperative game theory is useful to understand the concept of stability of the EC and to propose appropriate allocation rules which give us a stability during a long period of time.

The second thematic area is focuses on decentralized energy literature. Olivares et al. (2014); Lopes et al. (2016); Hyams et al. (2011); Comodi et al. (2015) have limited the analysis to the technically attainable benefits obtained by decentralized communities. Lo Prete et al. (2012) and Wouters (2015) discuss how ECs or micro-grids may be integrated in the existing system but, likewise, do not address whether these coalitions hold in practice. Also, Olivares et al. (2014); Basak (2012); Steinheimer et al. (2012); Matenli et al. (2016) have been done operational research on ECs and micro-grids, showing an increased interest in the business model focusing on the benefits and analyzing them in a theoretical and empirical way. Lo Prete et al. (2016) and Lee et al. (2014) also focus on the allocation of gains between ECs and other players of the energy system, rather than between agents acting within the EC.

The third thematic area is related on the business model and on the presence of an aggregator. Cornélusse, Savelli, Paoletti, Giannitrapani, Vicino (2019) assume that the aggregator could behave with the goal of maximizing the users' social welfare. While Monesecchi, Meneghello, Merlo (2020) assume the opposite, that is that the aggregator does not have the same objective of the users, aiming therefore to maximize the own benefit. For this reason, Fioriti, Poli, Frangioni (2021) build a model of accurate analysis, on the advantage that can involve the presence of an aggregator.

Fourth thematic area is focused on grid tariff, the most relevant aspect is the interaction between decentralized generation and grid tariff. The capacity components of the grid tariff may induce excessive efforts to reduce grid payments, Borenstein (2016) suggests that a combination of fixed charges and volumetric prices may result in a reasonable balance between efficiency and equity. Schittekatte et al. (2017) provide for different pricing structures and examine how individual decisions affect them and in turn, the decisions of other individuals. They also show that capacity-based charges can lead to excessive investment in new technologies. In the case of EC, these considerations are essentials.

The engineering's work and analysis are several, we have concentrated in the consideration in those works which have allowed us to create an optimal model and secondly, we have considered those works that have put the bases and the technical data to arrive at the proposed conditions of efficiency. At the economic level there is no literature useful in our proposal of thesis.

3) MODEL

The configuration chosen for our EC refers to the results and conclusions of previous works described in Chapter 2. Our model aims to create a stable EC that maximizes user's utility, in fact our analysis aims the feasibility of the investment by the family unit and not from the point of view of a possible service provider. The subparagraphs will describe each choice made and each aspect considered, explaining any possible alternatives and justifying the choices.

3.1) CONFIGURATION OF ENERGY COMMUNITY

In this section we analyze the configuration and characteristics of our EC. This paragraph will consist of 5 sub-paragraphs that will describe the choices regarding: type of EC; composition of households; size of the EC; owner of the investment made in the photovoltaic system and an explanation regarding the decision to not consider externalities in the model. Topics covered in this paragraph will give an identity to users[10] in the EC; then we shall be able to create an appropriate cost/revenue functions and to hypothesize a possible advantage in participating in the EC. In addition, it is important to specify that in our model, the households (the users who form our EC) have all the information available in the market, in this way we would eliminate all possible agency problems that could be created with a local service provider.

3.1.1) Type of Energy Community

First, we have to create the sample of households that will make up the EC. The chosen EC will not be a CEC (Citizen Energy Community) but rather a REC (Renewable Energy Community) because, as we have already described in Chapter 2, our EC will consist entirely of a renewable energy production system (and therefore this characteristic refers to a REC, as the CEC also admits traditional methods of energy production). Once determined the type of EC we define which will be the main source of energy production, for simplicity our model admit only the photovoltaic as source of renewable energy. At this point we must set the type of buildings that compose it, or rather describe the

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[10] Users in the EC are rational because their decisions are guided exclusively by the desire to complete their own goals (it is assumed they are the maximization of their NPV). Users are also considered intelligent, so it is assumed that each player is aware of the rules of the game and can think consistent assumptions to make decisions.

composition in terms of real estate: only residential, commercial or hybrid. By the logic used to create the model, we will stabilize a hybrid EC which contains both commercial and residential buildings. Then we analyze the data collected on a geographical area, being that our goal is the realistic analysis about the feasibility of the investment, we can admit (unlike other research previously done) the presence of both types of properties. This distinction is made because energy consumption profiles are very important for the calculation of tariff costs and especially for establishing methods of energy sharing.

3.1.2) Composition of households

As described in [1], the composition of households is more efficient if asymmetric. This means that the individuals within should have different consumption functions and the time habits could be considered complementary. An EC with symmetrical composition will present households who consume a similar amount of energy at the same times of the day, this could lead to energy gaps or high quantities of energy accumulations. As shown by [1] an EC of retired people only, for example, will have peaks of production that will be offset by high daily consumption as personal habits will push such individuals to consume a high amount of energy. By differentiating the families that constitutes our EC, we would admit in it the presence of retired people, families with children, childless couples, singles, full-time workers, night workers, etc. In this way the peaks of production are not affected by the peaks of consumption that can occur in the case of a symmetrical company. Concluding the assumptions regarding the conformation of households, when it comes to an EC with different energy consumption profiles it is important to specify the fact that there will be individuals who will consume more energy than produced (consumer) and there will be individuals who produce more energy than consumed (producer), in [4] an analysis was made relating how these two types of users can gain from participating in a EC; this aspect helps us to understand that the economic advantages deriving from the entry in a EC are not based only on the mere monetary gain but the increment in the utility of the household derives from other aspects like the tariff decrease; the reduction of costs and the benefits that a EC entails.

3.1.3) Dimension of Energy Community

According to [1] a large coalition allows more efficient energy sharing but compromises its stability. A large coalition is unlikely to be located in a restricted geographical area, this increases the costs for energy sharing and requires the construction of adequate plants which allow sharing. As explained above, our goal is to ensure the stability of the EC itself, so we cannot consider a large EC. For efficiency we therefore analyze a small EC where users are located in a restricted geographical area. In this way there will be no need to invest in infrastructure for sharing, but we could focus on a possible presence of local aggregator that allows the managing of energy (obviously taking for granted the investment that will be made in the various photovoltaic systems). The investment in infrastructure does not burden the user indirectly, but would imply the presence of a service provider, which investing a large sum could reduce the tariff advantage perceived by users who join the EC. We therefore see that a small EC is not affected by the costs of coordination that weighs on its stability, avoiding these costs we can focus more on the economic advantage.

3.1.4) Owner of photovoltaic plants

As explained in [5] for the user, the first major cost to be sustained is the one to install photovoltaic system. In our EC we cannot know if the users analyzed have the necessary economic resources to invest in photovoltaic systems. Also, for privacy reasons we are not able to obtain data related to the actual ownership of the photovoltaic system taken into analysis. In [5] are considered cases where the property (and consequently the asset) is owned by the user and where it is owned by a third party (in this case the financing of the installation will be supported by the third party). In our model we have not chosen as energy producers (therefore who has a photovoltaic system) the individual families, to have a greater probability that the plants are the property of the users. However, we have set up data collection and analysis such that this is completely irrelevant. In fact, we have considered the investment cost as a variable that the entire EC must support, this because the calculation of profitability is done on the entire EC and not on the single user.

3.1.5) Consideration of externalities

In our thesis we take from [1] the considerations of positive externalities in the model. We are aware that positive externalities are relevant for households in a given geographical area, both in terms of pollution and in terms of quality of life. In our data collection, we analyze also positive externalities: we calculate the benefit received by society as a result of the reduction in CO_2 emissions, due to the use of energy from renewable sources. As we will explain in Chapter 4, this analysis is not complete as it is not net of any negative externalities (which involves the installation and disposal of a photovoltaic system) and above all the adaptation to the 20-year horizon is not adequate as it is difficult to estimate. However, our model aims at an economic analysis, the choice of inserting this calculation is dictated by the desire to communicate how important an EC can be for society.

3.2) ENERGY SHARING METHODS

In this section we will explain the chosen method of energy sharing. Will be analyzed the various methods considered to be the most efficient in previous works. Finally, will be chosen the most efficient method, which maximizes the efficiency of the EC and does not compromise its stability. As explained in [1] the simplest sharing methods as: per-capita, pro-rata of consumption or peak of demand; fail to provide an adequate remuneration to users of EC. This would create discontent in the EC and some users may find more useful to leave it, thus could compromise stability[11]. We see that in [2] other methods of energy sharing are analyzed: even share; PV capacity share; consumption-based allocation; marginal allocation rule (MC)[12]; Shapley rule. As explained in [2], the first three methods

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[11] Two concepts that reinforce the definition of stability using game theory are covered in the paper [5] and [39]: the Core and the Nucleolus. These concepts can help us to outline which Shapley and MC is the most effective energy sharing method. The core is a key concept that allows us to enhance the conditions for the stability of EC and for a stable distribution among the users who compose it. From its concept we assume that a division is considered efficient if all the collective benefits are somehow distributed among all the community's users. Nucleolus is a concept that refers to efficiency in the distribution of economic profits in such a way which improves the stability of the EC. The goal according to the Nucleolus concept is that profits are distributed consistently in all sub-units that are created in the EC (each sub-unit with the similar utility function).

[12] Recall the theory the MC rule is one of the most efficient sharing methods but usually fails to reward properly users in the EC as simple energy sharing methods. This method allocates the value based on the marginal contribution of each member, as a marginal contribution we mean the additional value received by the EC with its participation (in other words it can be seen as the negative value change if the user leaves

are also considered basic and have some aspects that could damage the stability of the EC. According to [1] the Shapley value is the rule of allocation and energy sharing that involves more efficiency and stability in the EC; if compared with MC rule, Shapley is considered more complex and efficient. This method, explains [2], allocates the value basing on the marginal contribution of each user of the EC, according to this formula[13]:

$$Shapley\ allocation = \frac{1}{number\ of\ users} * \sum \frac{marginal\ contribution\ into\ coalition}{number\ of\ coalition}$$

The concept of coalitions is based on the fact that energy sharing in large EC occurs mainly between users of similar size within a restricted geographical area. Being our model an EC with reduced dimensions (small number of users) and restricted in a same area, the concept of coalition is not important; is sufficient to know that the allocation is made based on the marginal contribution of each user. In [5] we see that the concept of Shapley is combined with additional characteristics already indicated in [1] (efficiency) and already indicated in [2] (fairness); these characteristics[14] are: symmetry, additivity and dummy player. We therefore see that Shapley value does not penalize those who do not bring value but is limited to not remunerate them economically, going therefore to favor them, guaranteeing them the lowest costs related to the energy produced and guaranteeing cheaper rates. For privacy reasons, we cannot verify the sharing method chosen in the analyzed EC; however, looking at the data we can deduce that Shapley allocation is the chosen allocation method. We limit ourselves to observing the characteristics explained by the theory in this paragraph and verifying that they have actually been respected.

3.3) INVESTMENT COSTS AND ENERGY TARIFFS

In this section we will analyze the various costs that the user of the EC may have to incur. We divide the analysis into investment costs necessary for the installation of the plant and in tariff costs for the purchase of energy from an external energy service provider. Being

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the EC). In this model, however, not only positive variables are considered, sometimes providing an incorrect allocation of benefits in relation to the contributions of individual users.

[13] We recall [2] for the explanation of the formula.

[14] Symmetry means that two users making the same contribution must be remunerated equally; additivity means that every single additional activity linked to a user, which creates benefits to the EC, must be subsequently remunerated to the user; the property "dummy player" specifies that users who do not create any additional value for the EC should not be remunerated with any profit.

the costs are the first difficulty to which our users face, we have to set the investment and the successive rates so that income and savings for participation in the EC are attractive to them. We took hint from [1] to create the function to enhance the EC and created our own formula:

$$EC\ value\ =\ Total\ savings\ in\ 20\ years\ -\ investment\ costs$$

The choice of the investment function of the user has an important role for the sustainability of the investment and for the stability of the EC. Unfortunately for privacy reasons we have not been able to collect information about the investment functions of the users of the EC analyzed. However, we estimated the costs reliably from the capacity of the installed plants. For our calculation it was not relevant to have the precise price and the respective investment function because the calculation was made on an economic value and not on a function which had to be maximized. Analyzing the EC as a single entity we go to define its value analyzing the difference of the costs, therefore seeing the costs borne by the aggregation of users if they are not part of the EC and the costs if they are part of it. We use the function[13] reported by [2]:

$$\Delta costs =\ costs\ with\ out\ EC\ -\ costs\ with\ EC$$

Having analyzed the structure of the investment functions and how the difference in costs (between the non-EC members and the members of it) can represent for us the value of the EC, let's see how in [1] the cost of installing a photovoltaic system and the subsequent tariff costs are charged. First of all, we assume that the cost for the installation of the plant is strongly connected to the capacity of the plant itself, in fact we see that a large roof (and therefore able to accommodate a high-capacity plant) will possibly cost more than a small roof. Subsequently [1] considers the real economic tariffs as a cost borne by the user: the energy tariffs for those who are part of the EC are marginally lower than those who do not participate; however, as efficient as the energy production of our EC is, our users still need to buy energy from outside the community, thus bearing a cost. For completeness, if we consider the individual user, two cases can be created: who produces more energy than the one consumed, will share the excess energy with the members of the EC that consume more energy than the one produced; at this point we can deduce that there will be two different prices, for those who need to purchase energy, which are the market rates (so when the user goes to buy energy from the external market) and the prices that the user of the EC offers to other users (certainly lower than market rates).

For simplicity we will consider our EC as a single entity; therefore, trying not to give importance to the cost of the single user but more in general to the cost that the EC must support for the purchase of the energy from the external market. As for the investment in the photovoltaic system, we assume that each user maximizes the capacity at his disposal, self-financing the plant; this assumption implies that the stability of the EC must be in the long term.

3.4) BENEFITS OF ENERGY COMMUNITY

In this section, we analyze the various benefits that EC users can have, these benefits that must outweigh the costs to ensure they are encouraged to enter in an EC and stay there over the years. We will divide the benefit analysis into several points: starting from the initial benefits that can push the user to join the EC, we will continue to analyze the benefits perceived by users once they join the community and finally, we will evaluate any optimization constraints and phenomena which could increase the benefits over time. First, we see that the user perceives the benefit to join in an EC assuming a reduction in the quantity energy purchased by an external company (because is self-produced), perceives environmental benefits as the energy used is clean (although this will not be part of our analysis), and receives incentives at state level. In the following function we can denote all the incentives and benefits perceived by the EC's users:

$$\begin{aligned} Total\ savings = {} & Total\ incentive\ + Savings\ from\ total\ self consumption \\ & + Total\ revenues\ from\ network\ sales \end{aligned}$$

The main benefit of the user is related to the low-price level of the purchased energy. The energy purchased from the energy market has higher rates than the energy purchased from the user of the same EC. In addition to economic savings due to reduced tariffs, the energy producer will also receive an incentive from the EC itself (or its owner) to produce more clean energy. These two types of benefits are described by the variable Total incentive shown in the previous formula where in addition to the profits from the sale of the energy produced (which will then be divided according to the sharing principle decided at the time of the creation of the EC), energy producers will have another incentive financed by ARERA (as explained in Chapter 4) as you can see in the following formula:

$$Total\ incentive\ = valorization\ of\ energy\ shared\ + ARERA's\ incentive$$

The perception of these benefits, such that in a few years they allow the user to recover the investment, push other households to join the EC causing an effect that is explained in [3] as snowball effect. Following the formation of EC, households have an implicit incentive to join it, in this way they will benefit from the tariff reduction. So, the user who has invested in the photovoltaic system will have a reduction in time to recover the investment made. Given assumed the entity of the benefits, we can frame their maximization in a further cost reduction. Being that the energy cost differentiates in time slots (in terms of real cost), we can set the creation of the EC in such a way that it goes to buy energy when the energy costs less. We can do this only by setting the conformation of the community itself; so that individual users, without changing their needs, are complementary in order to achieve a balance. Clearly the optimization is relative, not being able to predict future consumption and future production can only be made an estimate. However, our model will be created trying to take advantage of those energy price differences that occur in different time slots. At this point we can see that for the user being part of the EC there will be incentive to remain part of it, exploiting in this way the benefits the EC in addition to being advantageous for its users, will be attractive also for the external users.

3.5) PRESENCE OF AGGREGATOR

In the model created, the service provider participates actively in the exchanges with the EC however it comes not previewed any purchase from it. In order to optimize the costs of users, the energy produced by the EC will be exchanged between the users themselves, while the energy deficit (existing because the energy produced will certainly be lower than the one required) is purchased by a service provider. For the reliability of our analysis, we will consider a service provider that sells energy with three different rates according to the daily time slot and according to the day of the week, we will divide these areas into F1 (red color), F2 (yellow color) and F3 (green color) as shown in Table 3[15].

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[15] The specification of areas F1, F2, F3 is inserted for clarity and completeness in the creation of our model. In data collection we do not enter 3 different rates, but we will calculate a single rate consisting of a weighted average of these 3 rates. This method does not make the model less reliable because the horizon considered will be 20 years, so the large sample of data collected allows us a correct and reliable approximation.

We see that the most expensive tariff is F1, the intermediate F2 and the cheaper F3.

Source: author's own elaboration.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Monday	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟨	🟩	🟩
Tuesday	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟨	🟩	🟩
Wednesday	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟨	🟩	🟩
Thrusday	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟨	🟩	🟩
Friday	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟨	🟩	🟩
Saturday	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩
Sunday	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

Table 3: different tariffs F1, F2, F3.

As demonstrated in [3], the direct participation of the Service Provider allows the EC to have a greater stability in the long period of time, thus providing the amount of energy required at the time required. This theory is also supported by [4] which argues that the presence of an aggregator which coordinates the activity of the EC is a positive factor that improves the efficiency of the EC and maximizes its social welfare. This theory, later demonstrated, therefore tells us that each user has a greater utility if in its EC there is an aggregator, rather than without it. The aggregation methodology seeks to achieve a high level of balance between users who present different consumption profiles. The goal is to create a community of users who produce more energy than consumed and users who consume more than produced, sometimes consuming energy produced by users of EC and sometimes consuming energy purchased from the market. This allows us to generate cash flows which maximize the utility functions of all users. In addition to this, an aggregation grid is created in order to have a close and strong cooperation between the aggregator and a possible manager of the EC and (if there is no reference manager) between the aggregator and the users of the EC. This aggregation methodology aims to minimize the costs of the EC as a unit, as it seeks to make the most of those who produce so much energy, selling it to other users at lower rates than those in the market. It will also take advantage of the difference in the market tariff plan, trying to ensure that users buy from the market mainly in F2 and F3, although this aspect is unpredictable and organizable. According to [5] the presence of the aggregator is considered fundamental for two reasons: its work aims to maximize the NPVs of the entire community; its presence allows the EC to implement targeted and efficient choices for it. The decision-making aspect is very important because a set of users not very experienced in the energy field, could make spoiled and hasty decisions, thus reducing any profits and benefits which could instead have at the suggestion of a more experienced third party. On [5] two different situations are analyzed: when choices are made internally and when choices are granted to an aggregator (possibly alongside an external EC manager). In the two proposed situations, the authors of the paper have found it more efficient to rely on an external expert, in this case an aggregator for taking technical decisions. We see in that model, the aggregator will propose the optimal design for the system, once the proposal, will await the approval of users who are part of the EC, and at a later stage will take charge of monitoring the development of the community. Since in the long run many variables can change, it is very important the interpretation that is made by a sectoral expert, in this case the aggregator; in order to make any changes both to the technical structure and possibly the conformation of the community. In this case, however, we assume that it is possible to enter additional users at a later time, and also the exit from the community of not satisfied users (see section 3.6). This concession is made to leave the aggregator free to maximize firstly the benefits of individual users, and secondly the benefits of the EC (aggregator included). Here are the key factors, listed by [5] that must exist in an outsourced system like this one:

- users join EC by mean of membership contracts;
- EC may economically support users in funding new installations;
- in the contracts exit clauses specify that any users leaving the aggregate shall reimburse the EC up a given economic amount;
- membership contract enables the EC and its technical advisors to access the real time consumption data to control some of user's devices;
- EC delegates the optimal design, maintenance and operation to an aggregator by means of a service contract with clauses that reduces the risk of agency problem;
- each user buys on the public market electricity absorbed from the grid and is paid from the public market for his extra production injected into the grid;
- the benefits of the aggregate are rewarded to the EC that distributes them between the aggregator and the user according to fair schemes.

In conclusion we therefore consider essential the presence of an aggregator outside the community, whether or not it interfaces with a representative manager; moreover we consider very important to leave to the aggregator the decisional possibility (at least the right to propose interventions and suggest solutions) regarding the management of the community from the more technical aspect of the case, where only those with certain professional skills can get to make the most efficient choice for the community itself.

3.6) EXIT FROM ENERGY COMMUNITY

In this paragraph we will consider the feasibility and consequences of leaving the EC. Since our EC will be built according to the principle of rationality (described in [5]), we should not present the exit cases, but for completeness we observe which effects could cause a possible exit of the user. First, the principle of rationality ensures that no user of the EC will have any benefit with the exit from the EC. Based on this principle we will set our EC in such a way that there are no incentives to exit, therefore looking for a solid stability and a general satisfaction of the users who compose it. However, as explained in [1], energy tariffs could sometimes create instability in the EC and therefore may push a user to find more convenient the exit (not incurring investment costs and paying the higher tariff plan for who is not part of an EC), this can occur if the user in question consumes more energy than the one produced; considering this case, the user is less affected by the benefits of the EC. Being our model asymmetric, will contain inside also individuals of this typology. Our objective remains to build an ideal situation to ensure that all users do not burden energy tariffs so as not to compromise too much the stability of the EC. We try to achieve an ideal situation to achieve complete stability of the community. If a user needs an exit, however, will have to face costs, we refer to the analysis that explains [5] to justify the presence of such exit costs. Since an EC is built on an equilibrium between users and energy sharing, the exit of a single user could cause economic damage to users who remain inside the EC. In particular, with the presence of an aggregator, the sustainability of a given investment is greatly affected by the equilibrium that is created between users and the exit of a single user leads to damage to others, damages incurred by the exit costs incurred by the outgoing user. In [5] we also understand that the period where the exit is most likely is the one after the first year, this is because in the first year the sustainability of a given investment does not require significant efforts, sustainability in subsequent years (especially if there are no major differences in the tariff plan) tends to decrease. This is why the exit costs are higher in the first year rather than in the following years, this also due to the fact that the more time passes, the more stability and equilibrium the EC finds; therefore, the output of a single user weighs less on the profitability of others. Now let's see how [5] calculates the exit costs and how we can fit them into our model. First of all, we report the formula[16] used:

$$\begin{aligned} Exit\ costs = {} & social\ total\ welfare\ -\ total\ user\ net\ present\ value \\ & -\ rest\ of\ social\ welfare\ after\ exit \end{aligned}$$

By setting the exit fee in this way, the user who decides to leave the EC will have to pay the reduction to the social welfare that causes his exit from the EC. By entering this exit fee, the user will choose more difficult to exit from the EC and this leads to greater overall stability. In our model, as much as we try to get closer to the most stable model possible, we also have to consider the small probability that a user wants to leave, for this reason we include the exit costs, so that they can guarantee benefits for all users and eliminate any penalties.

3.7) OPTIMIZATION OF ENERGY COMMUNITY

The first choice of our data collection was to not simulate the users of our EC but to take existing consumer's data. For privacy reasons, we were unable to take each individual consumer's data source, however, we derived realistic values by following the methodology explained in Chapter 4. However, the first EC analyzed not present the ideal characteristics listed in our model. We therefore decided to integrate the initial EC with precise subjects in order to reach the ideal EC that we have described in our model, thus carrying out the task which an aggregator could perform if it aims to make the most efficient the EC. The initial EC presented 7 users who are all energy producers (each user had its own photovoltaic system), moreover each of these was not a family unit or a residential building. These users were chosen for their good productivity and good energy self-consumption (during the day they consumed a lot of energy, while at night consumption was practically zero). To these 7 users were integrated 13 subjects without photovoltaic system, so consumers. These 13 users are residential users and are differentiated in their consumption profiles (as we have explained in Chapter 4). This addition has allowed us to increase the variable of energy shared within the EC, we will see how this leads to an increase in the gain for producers and an increase in savings for consumers. To highlight the efficiency and importance of optimization in data collection and analysis, we will provide the two comparison analysis frameworks.

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[16] We recall [5] for the explanation of the formula.

4) DATA COLLECTION

In this chapter will be presented and explained the methodology chosen for the data collection useful for the analysis of our model and then the data collected. Our study will start from the collection of real simulated data from an existing EC that will be integrated later with data of users chosen specifically to create an EC which respects the asymmetric characteristics of consumption and production profiles presented in the model in Chapter 3. This choice was made because a simulation with ideal users created by us for the entire EC would be less reliable than the proposed solution, in addiction this choice allows us to create an EC with the values of energy sharing and optimal self-consumption. The data collected are divided into four areas of analysis: the first related to energy production and energy consumption; the second related to the economic savings due to participation in a EC (will be compared the costs incurred with and without participation in a EC); the third related to the installation cost depending from the size (and consequently to the capacity of the plant) and finally the fourth, on the economic gain perceived by the society for the reduction of $C0_2$ emissions (caused by the use of clean energy produced in the EC). In this way we will have a general framework to verify an effective profitability by the user in joining a EC.

4.1) METHODOLOGY

The software chosen for the collection of data related to consumption profiles is PV-GIS, this choice was dictated by the fact that this database contains all the solar radiation history, in relation of: how is oriented the plant; panels' inclination; the power of the plant and the estimated losses of energy. We considered real users with detailed information about: solar radiation in a specific geographical area; the particular inclination of the solar panel; the plant's orientation; the inclination of the panels; the power of the plant and the estimate of energy losses. For privacy reasons we have not been able to collect the real data produced by users of EC taken into account, but using PV-GIS, through the electricity bills and the information available to these plants, we have been able to simulate reliably: the energy productivity of the plants; energy consumption; the share of energy consumed; the energy taken from the network; the energy injected into the network and the energy shared within the EC. We downloaded the hourly productivity for 20 years, then was made a weighted average (always on an hourly basis) for the 20 years considered. At the end of the data collection, the results (both in energy and economic terms) are then put together on the monthly panorama, to make easy the analysis and to have 12 reference values (one for each month) for each item. It was chosen, as indicated in the model, a restricted EC[17] located in a municipality in Veneto, composed of 7 different users: center for separate collection; primary school; sports center; town hall; gym; kindergarten and a church. Subsequently, were added 13 consumer users (not part of this EC) of which: 11 residential which reflect the 3 types of RES[18] of standard consumers listed by ENEA (with annual consumption of reference: 1.500kw/h for a single consumer; 2.200kw/h for a couple; 2.700kw/h for a family); an industry and a car bodywork. This addition has been made to complete the consumption picture of the EC taken into analysis, so as to have asymmetric consumption and production profiles and in order to optimize the shares of consumption and energy sharing (to best extrapolate the convenience of the EC). The data collection was made over a reference period of year 2022 and therefore count on a data collection carried out on 20 subjects with different consumption profiles and with plants of different power and size. The energy tariff chosen to buy energy from an external provider is 15 cents[19] per kW/h and we will keep it constant for the 20 years of investment. Our goal is to have an EC which use as much as possible the energy produced by local plants (so high peaks of production correspond to high peaks of consumption); this is why we have included industries into the EC (which will have high consumption profiles during the day this corresponds to higher production peaks). To respect the assumptions made we also add residential users who allowed us to frame and balance the consumption and energy production throughout the various daily phases.

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[17] For privacy reasons we cannot specify the area of the EC, the code that distinguishes it and the name of the users. For the identification of users, we will limit to distinguish them as typologies (e.g. families, companies, churches, etc.).

[18] These types of RES consumers are indicated in a model produced by ENEA (Italian public research body operating in the fields of energy, the environment and new technologies in support of policies of competitiveness and sustainable development).

[19] This is a reference tariff (which is used by companies involved in the studies of feasibility of EC) choses to avoid changes in energy prices, is calculated as an average of energy rates over the last 20 years (were added all energy tariffs up in the 20 years preceding the pandemic, considering also the different F1, F2, F3). Since in the last 3 years there have been strong price variations, is chosen a pre pandemic tariff to not spoil our analysis.

The results will be presented by combining four types of area's data:

- Energetic, consisting of: total energy produced, total self-consumed energy, total energy input, total energy withdrawn from the grid, shared energy, percentage of energy consumed and finally energy shared;
- Economic in relation to costs and energy savings, consisting of: valorization of shared energy, ARERA's[20] incentive, total incentive, savings from total self-consumption, total revenues from network sales, total savings, cost incurred without EC, cost sustained by the EC;
- Economic in relation to the installation costs of the photovoltaic plants present in the considered EC;
- Social-economic in relation to positive externality related to the benefit to society of reducing $C0_2$ emissions (in monetary terms).

In this way we can highlight the gain in economic terms and the gain in energy terms, very important aspect that concerns the benefits derived from the investment in an EC. To create a clear framework of our data collection, we decided to present the technical and economic summary before and after the addition of the 13 users (consumers), to provide a reference point with a real EC and an optimized EC. This allows us to motivate how the choices made are fundamental to allow us to create an optimized EC; because the general benefit can increase if the right choices are made and if the aggregator (or reference manager) grants access in the EC to the right users. The analysis of the economic framework proceeds with a calculation of the costs that would have sustain the subjects if they were not part of the EC, so as to have a definitive comparison with the savings and costs actually incurred by users who are part of the EC. This calculation was done for each individual subject in the year for each hour, but in our analysis, we will report the sum of all costs. This is because the comparison with the sum of all the savings would have been easier, inserting the single calculation for each subject would have burdened the analysis and data collection too much. It remains correct to specify that the data collection was made for the individual subject but by choice we decided to consider

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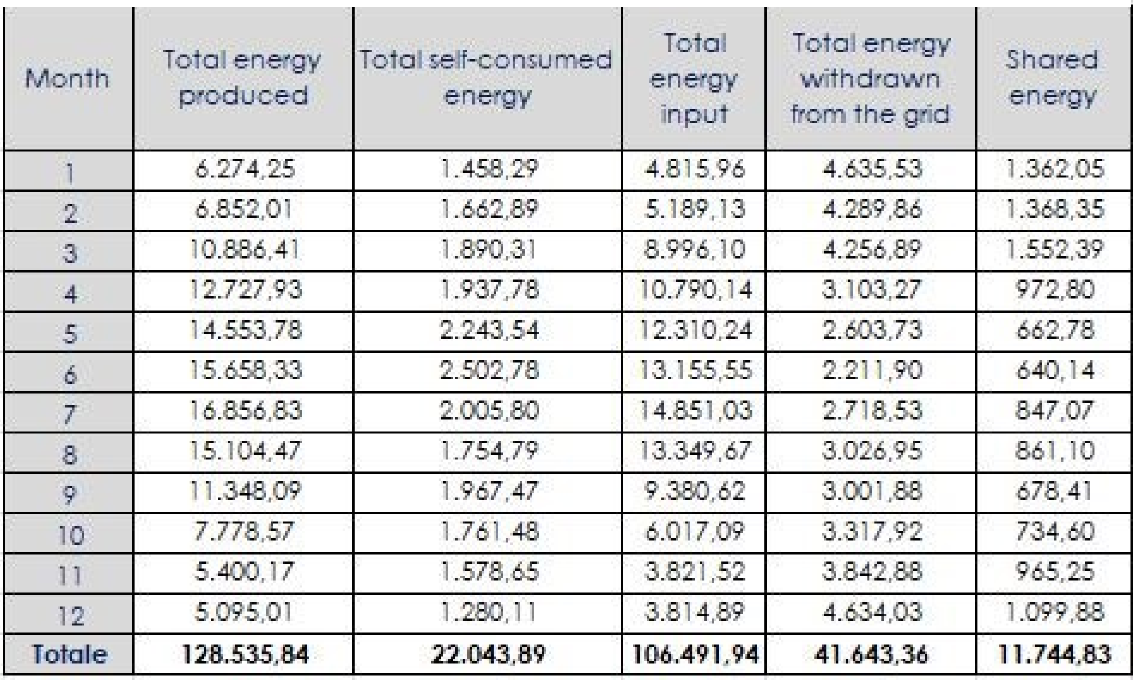
[20] The Regulatory Authority for Energy Networks and Environment (ARERA) is an independent administrative authority of the Italian Republic that has the function of encouraging the development of competitive markets in the electricity chains, natural gas and drinking water, district heating/cooling and waste disposal, mainly through tariff regulation, network access, service quality standards, the functioning of markets and the protection of customers and final users.

the users of the EC as a single individual and then report a single item summary of costs, savings and all the variables listed (energy and economic). The calculation of the cost of the plants instead will be done specifying the cost of the single system and the total cost of the EC, being 6 photovoltaic plants a restricted number, we can afford to insert the single costs. Finally, was made a choice of calculation of positive externalities to provide a comparison of how the presence of an EC is beneficial to society, including also perceived gain (in economic terms) in the value function of the EC but the calculation made is an approximate and not detailed.

4.2) DATA

In this paragraph will be reported the data collection, will be also reported the explanation of the reasons for which certain data have been selected. The reported data (in the tables) were collected in the year 2022, so the energy values and the economic values reported are related to a single year (the only value based on a 20-year horizon is the positive externality perceived by the society during the life of the EC). In Table 4 we see the energy summary of starting EC (the one without consumers) while in Table 5 we see the energy summary of the optimized EC after adding the 13 subjects (energy consumers) listed in paragraph 4.1.

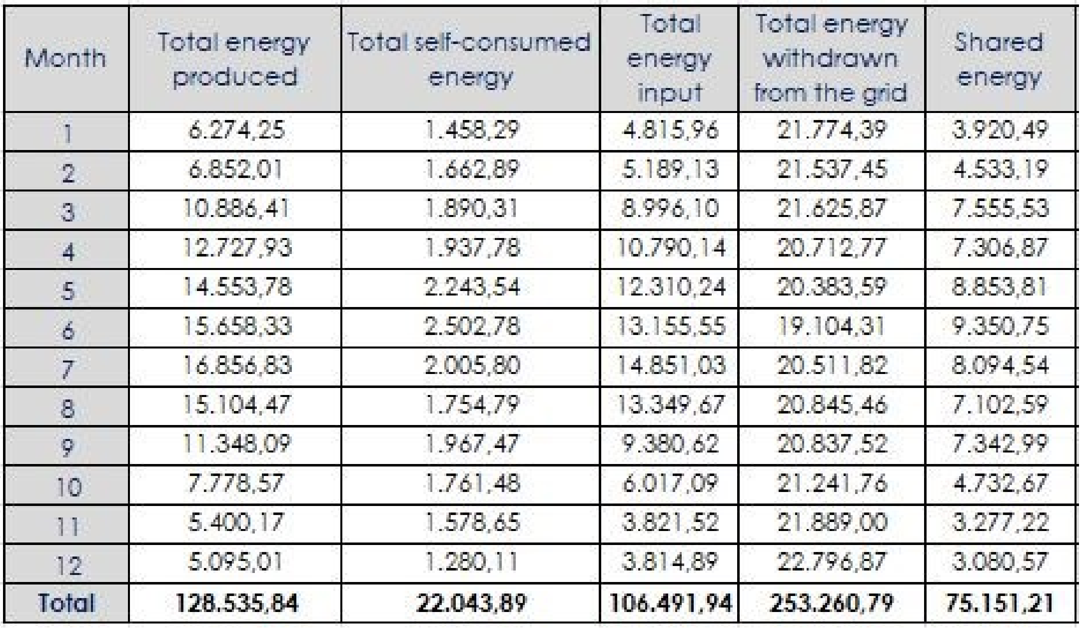
Table 4: energy values – initial energy community.



Month	Total energy produced	Total self-consumed energy	Total energy input	Total energy withdrawn from the grid	Shared energy
1	6.274,25	1.458,29	4.815,96	4.635,53	1.362,05
2	6.852,01	1.662,89	5.189,13	4.289,86	1.368,35
3	10.886,41	1.890,31	8.996,10	4.256,89	1.552,39
4	12.727,93	1.937,78	10.790,14	3.103,27	972,80
5	14.553,78	2.243,54	12.310,24	2.603,73	662,78
6	15.658,33	2.502,78	13.155,55	2.211,90	640,14
7	16.856,83	2.005,80	14.851,03	2.718,53	847,07
8	15.104,47	1.754,79	13.349,67	3.026,95	861,10
9	11.348,09	1.967,47	9.380,62	3.001,88	678,41
10	7.778,57	1.761,48	6.017,09	3.317,92	734,60
11	5.400,17	1.578,65	3.821,52	3.842,88	965,25
12	5.095,01	1.280,11	3.814,89	4.634,03	1.099,88
Totale	**128.535,84**	**22.043,89**	**106.491,94**	**41.643,36**	**11.744,83**

Source: author's own elaboration.

Table 5; energy values – optimized energy community.



Month	Total energy produced	Total self-consumed energy	Total energy input	Total energy withdrawn from the grid	Shared energy
1	6.274,25	1.458,29	4.815,96	21.774,39	3.920,49
2	6.852,01	1.662,89	5.189,13	21.537,45	4.533,19
3	10.886,41	1.890,31	8.996,10	21.625,87	7.555,53
4	12.727,93	1.937,78	10.790,14	20.712,77	7.306,87
5	14.553,78	2.243,54	12.310,24	20.383,59	8.853,81
6	15.658,33	2.502,78	13.155,55	19.104,31	9.350,75
7	16.856,83	2.005,80	14.851,03	20.511,82	8.094,54
8	15.104,47	1.754,79	13.349,67	20.845,46	7.102,59
9	11.348,09	1.967,47	9.380,62	20.837,52	7.342,99
10	7.778,57	1.761,48	6.017,09	21.241,76	4.732,67
11	5.400,17	1.578,65	3.821,52	21.889,00	3.277,22
12	5.095,01	1.280,11	3.814,89	22.796,87	3.080,57
Total	**128.535,84**	**22.043,89**	**106.491,94**	**253.260,79**	**75.151,21**

Source: author’s own elaboration.

The data collection was made on an hourly basis every day of the year; subsequently, in order not to burden the elaborated and the data collection, were collected the hourly surveys in monthly reports. The 12 rows correspond to each month of the year (including all hourly measurements taken within the month). In each column we see reported a data collection, the respective items indicate:

- Total energy produced: indicates the EC’s energy production for each month (in the last row we find the total energy produced in the year 2022), reported values are in kW/h. Note the equality of values between Table 4 and Table 5, this because the individuals added to the EC for general optimization are not producers but only consumers.
- Total self-consumed energy: corresponds to the consumption of energy produced by the same users of EC, also in this case the value is equal in Table 4 and Table 5. This equality is explained by the fact that the calculated variable tells us how much energy (self-produced) is consumed by energy producers, who are the same in both EC (before and after the optimization process).
- Total energy input: is the difference between total energy produced and total self-consumed energy; corresponds perfectly to the energy produced injected into the network. Again, there is no difference between the amount of energy fed into the initial EC and the amount of energy fed into the optimized EC.

- Total energy withdrawn from the grid: corresponds to the energy needs of the whole EC, this item does not only consider the energy produced and consumed within the EC, but also includes energy purchased from outside to meet energy needs. In Table 5 we see a quantity of energy taken from the network, greater than the quantity indicated in Table 4, this can be explained simply by the greater number of users present in the optimized EC.
- Energy shared: indicates the amount of energy that has been injected into the EC’s network and then used by users of the EC. In fact, we see that not all the energy injected can then be used, but only a portion, the remaining portion is then sold to an external service provider.

Data collection for the two EC taken into consideration, from the energy point of view, concludes with the consideration of two percentages that are useful for understanding the correct functioning of the EC and how an optimization of it can greatly affect: % self-consumption and % of energy shared (Table 6).

Table 6: initial energy community and optimized energy community – energy values comparison.

Energy Community	% self-consumed energy	% energy shared
Starting Energy Community	17%	11,30%
Optimized Energy Community	17%	71%

Source: author’s own elaboration.

The share of self-consumed energy shows us how the plant is functional to the energy needs of the user, a high self-consumption means that the user use as much as possible the energy that is produced by their plants. The share of self-consumed energy is calculated:

$$\% \, self - consumed \; energy = \frac{total \; self - consumed \; energy}{total \; energy \; produced}$$

The share of energy shared indicates the part of the energy injected into the EC’s grid; we know that all the excess energy (so the energy which cannot be used from the EC) is sold to the provider, the share of energy which is used by the members of the EC is considered energy shared.

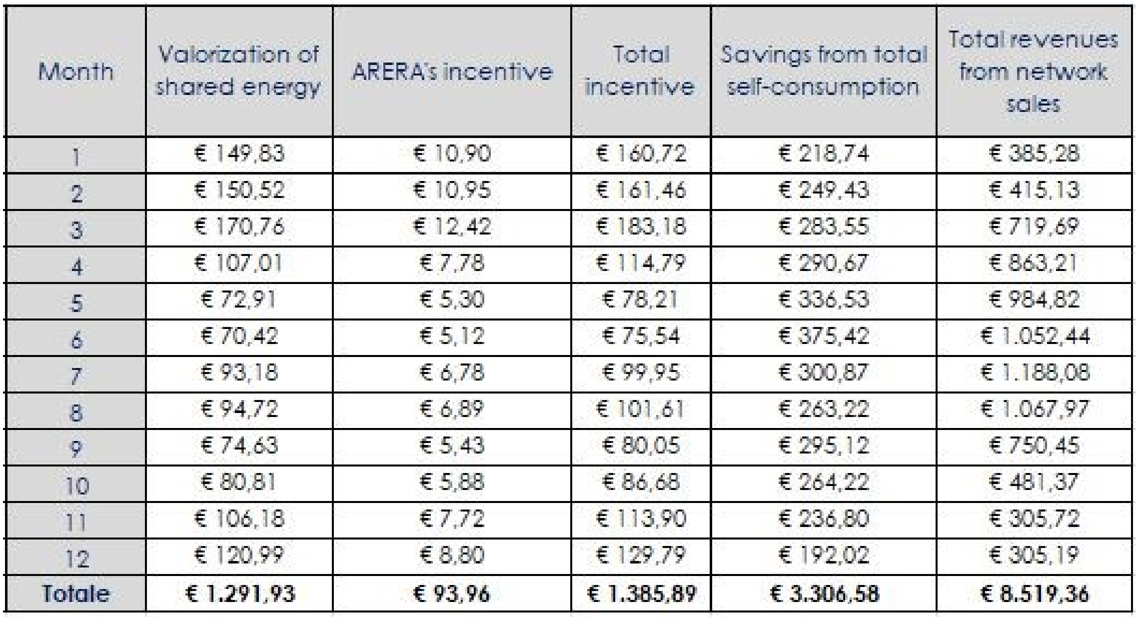
The calculation of this share:

$$\%\, energy\ shared\ = \frac{energy\ shared}{total\ energy\ input}$$

Initial EC has a low percentage of shared energy but we try to optimize by adding consumer users in the EC, in this way we increase the average energy need of the community. However, is very difficult to reach a rate of 100% (which would still be the optimal solution) however a percentage of energy shared of 71% is considered good and beneficial for the user.

We proceed the data collection highlighting the economic variables, starting from the economic savings (and gains) perceived by users of the initial EC (Table 7) and by users of the optimized EC (Table 8).

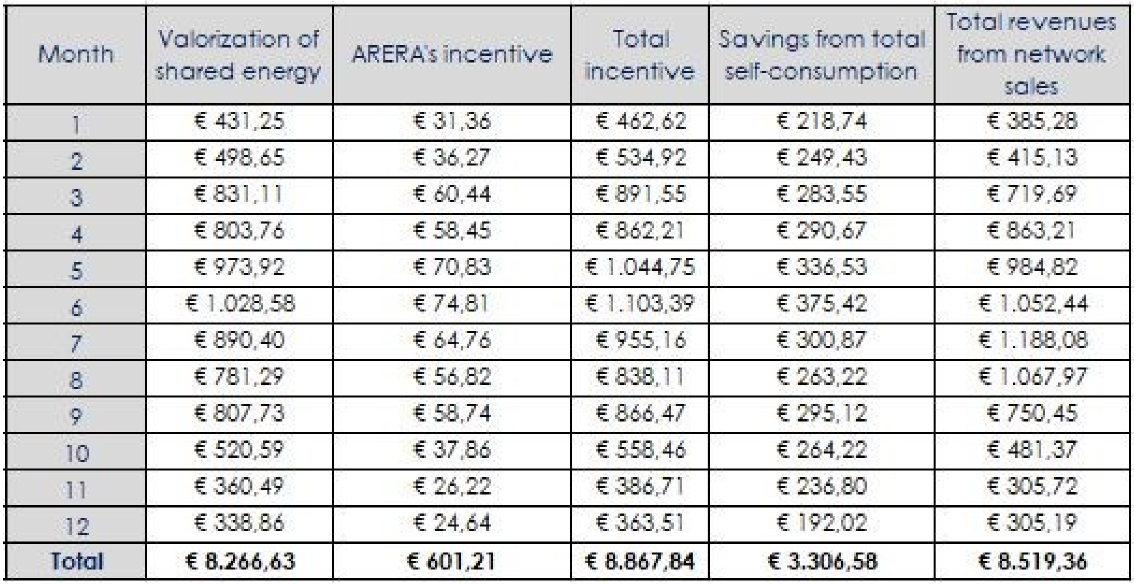
Table 7: initial energy community – economic values.



Month	Valorization of shared energy	ARERA's incentive	Total incentive	Savings from total self-consumption	Total revenues from network sales
1	€ 149,83	€ 10,90	€ 160,72	€ 218,74	€ 385,28
2	€ 150,52	€ 10,95	€ 161,46	€ 249,43	€ 415,13
3	€ 170,76	€ 12,42	€ 183,18	€ 283,55	€ 719,69
4	€ 107,01	€ 7,78	€ 114,79	€ 290,67	€ 863,21
5	€ 72,91	€ 5,30	€ 78,21	€ 336,53	€ 984,82
6	€ 70,42	€ 5,12	€ 75,54	€ 375,42	€ 1.052,44
7	€ 93,18	€ 6,78	€ 99,95	€ 300,87	€ 1.188,08
8	€ 94,72	€ 6,89	€ 101,61	€ 263,22	€ 1.067,97
9	€ 74,63	€ 5,43	€ 80,05	€ 295,12	€ 750,45
10	€ 80,81	€ 5,88	€ 86,68	€ 264,22	€ 481,37
11	€ 106,18	€ 7,72	€ 113,90	€ 236,80	€ 305,72
12	€ 120,99	€ 8,80	€ 129,79	€ 192,02	€ 305,19
Totale	**€ 1.291,93**	**€ 93,96**	**€ 1.385,89**	**€ 3.306,58**	**€ 8.519,36**

Source: author's own elaboration.

Table 8: optimized energy community – economic values.



Month	Valorization of shared energy	ARERA's incentive	Total incentive	Savings from total self-consumption	Total revenues from network sales
1	€ 431,25	€ 31,36	€ 462,62	€ 218,74	€ 385,28
2	€ 498,65	€ 36,27	€ 534,92	€ 249,43	€ 415,13
3	€ 831,11	€ 60,44	€ 891,55	€ 283,55	€ 719,69
4	€ 803,76	€ 58,45	€ 862,21	€ 290,67	€ 863,21
5	€ 973,92	€ 70,83	€ 1.044,75	€ 336,53	€ 984,82
6	€ 1.028,58	€ 74,81	€ 1.103,39	€ 375,42	€ 1.052,44
7	€ 890,40	€ 64,76	€ 955,16	€ 300,87	€ 1.188,08
8	€ 781,29	€ 56,82	€ 838,11	€ 263,22	€ 1.067,97
9	€ 807,73	€ 58,74	€ 866,47	€ 295,12	€ 750,45
10	€ 520,59	€ 37,86	€ 558,46	€ 264,22	€ 481,37
11	€ 360,49	€ 26,22	€ 386,71	€ 236,80	€ 305,72
12	€ 338,86	€ 24,64	€ 363,51	€ 192,02	€ 305,19
Total	**€ 8.266,63**	**€ 601,21**	**€ 8.867,84**	**€ 3.306,58**	**€ 8.519,36**

Source: author's own elaboration.

The valorization of shared energy are the economic revenues derived from the sale of the energy produced (from the plants of the EC) to the EC's members. This variable is calculated as follow:

$$Valorization\ of\ shared\ energy\ =\ shared\ energy\ *\ 11\ cents\ per\ kW/h$$[21]

These economic revenues are collected in the EC's pool and then are divided among users following the revenue sharing method chosen during the creation of the EC.

The third column corresponds to an economic incentive called ARERA's incentive, calculated as follow:

$$ARERA's\ incentive = \ energy\ shared\ *\ 0{,}008\ €\ per\ kW/h$$[22]

Since the user uses self-produced the energy, ARERA does not have to control the share of energy produced and shared by the user (less costs for ARERA, and incentive for the user). However, this incentive is provided directly to the user producer and not put in the pool of the EC as the item indicated above. Total incentive shows us the positive cash flow that users have with the participation in the EC, it is calculated as follow:

$$Total\ incentive\ =\ valorization\ of\ energy\ shared\ + ARERA's\ incentive$$

---

[21] This price is chosen because is the one proposed by UE as an indicative price for the valorization of energy shared into the EC. This incentive will become variable in the next years because a fixed tariff in pricing the energy shared brings benefits only in the long term.

[22] The premium of 0,008 € per kW/h corresponds to the compensation for the reduction of energy dispatching.

The fifth column calculates the savings from self-consumption, that is the amount of money saved by not buying energy from the public grid at a price of 15 cents per kW/h[17]. This value is obtained:

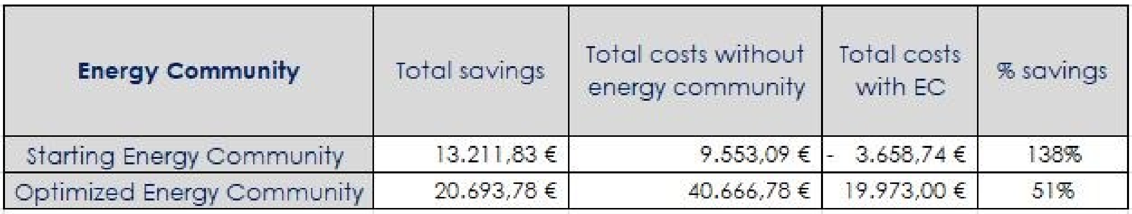
$$\begin{aligned}&Savings\ from\ total\ self-consumption\\&\qquad = Total\ self-consumed\ energy\ *\ 15\ cents\ kW/h\end{aligned}$$

The last column shows total revenues from network sales, is obtained:

$$\begin{aligned}&Total\ revenues\ from\ network\ sales\\&\qquad = Total\ energy\ input\ *\ 8\ cents\ per\ kW/h^{23}\end{aligned}$$

This also indicates a positive cash flow and indicates the economic gain from the sale of energy produced outside the EC network. To compare the two ECs (initial and optimized) at the economic level we report in Table 9 some items which can summarize and highlight the effectiveness of participating in a EC.

Table 9: initial energy community and optimized energy community – economic values comparison.



Energy Community	Total savings	Total costs without energy community	Total costs with EC	% savings
Starting Energy Community	13.211,83 €	9.553,09 €	- 3.658,74 €	138%
Optimized Energy Community	20.693,78 €	40.666,78 €	19.973,00 €	51%

Source: author's own elaboration.

As a first calculation we found the total savings (for the year 2022) of the EC (in the case of the initial EC savings are economic gain), summing the values as follows:

$$\begin{aligned}&Total\ savings\\&\quad = Total\ incentive\ +\ Savings\ from\ total\ self-consumption\\&\quad + Total\ revenues\ from\ network\ sales\end{aligned}$$

This item shows us the general and inclusive saving of all the economic incentives and gains that can involve participation in a EC. Later we calculated the consumption of each individual subject; consumption that is certainly affected by the fact that it was made by subjects owning a photovoltaic system, but in any case, corresponds to the total amount

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[23] This price is chosen following the weighting of the average over 20 years of the prices paid by the service provider, to buy energy from EC's private users.

of energy consumed. Then we have found the total cost sustained by all the users in the case they are not participating in the EC, doing this calculation:

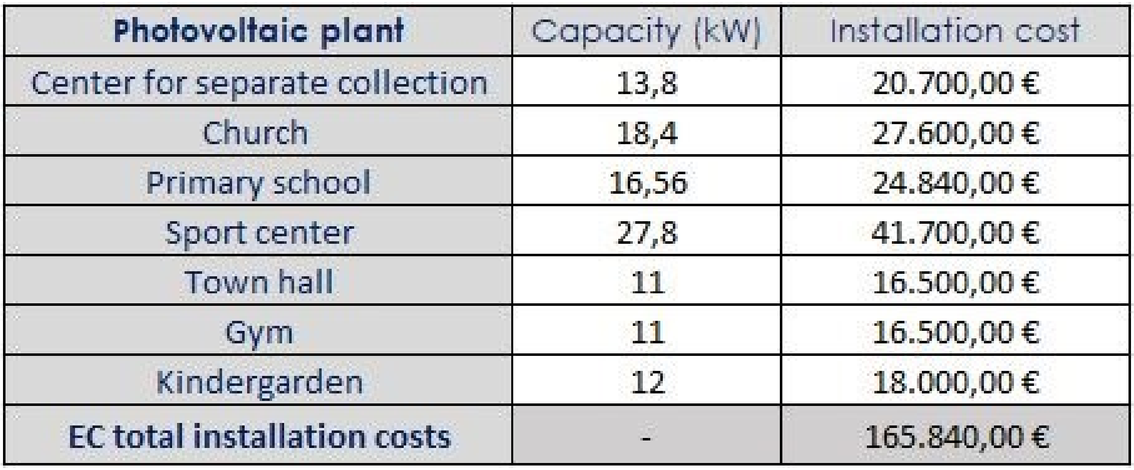
$$
\begin{aligned}
&\mathit{Total\ costs\ without\ EC} \\
&= \mathit{Total\ consumption\ of\ each\ user} * 15\ \mathit{cents\ per\ kW/h}^{17}
\end{aligned}
$$

Then we have computed the costs sustained by all user in the EC:

$$\mathit{Total\ costs\ with\ EC} = \mathit{Total\ costs\ without\ EC} - \mathit{Total\ savings}$$

This could be a particular item considering the two communities (initial and optimized ECs) because it seems that the initial EC was more efficient then optimized one (the negative value of -3.658,74€ in the initial EC means an economic gain of 3.658,74€) but this can explained by the fact that in the optimized EC there are higher general costs because there are more consumer (while in the initial EC there are only producer). The economic gain for the same producer in the optimized EC is higher than in the initial situation. After the analysis of consumption, costs and energy savings we proceed in the data collection with an estimate of the total cost sustained for the installation of photovoltaic plants, see Table 10. Being the photovoltaic systems are the same in the initial and optimized EC, we report only one item of values, but specifying the cost of the individual plant (for each user who owns it) and the total cost of EC.

Table 10: plants' installation costs.



Photovoltaic plant	Capacity (kW)	Installation cost
Center for separate collection	13,8	20.700,00 €
Church	18,4	27.600,00 €
Primary school	16,56	24.840,00 €
Sport center	27,8	41.700,00 €
Town hall	11	16.500,00 €
Gym	11	16.500,00 €
Kindergarden	12	18.000,00 €
EC total installation costs	-	165.840,00 €

Source: author's own elaboration.

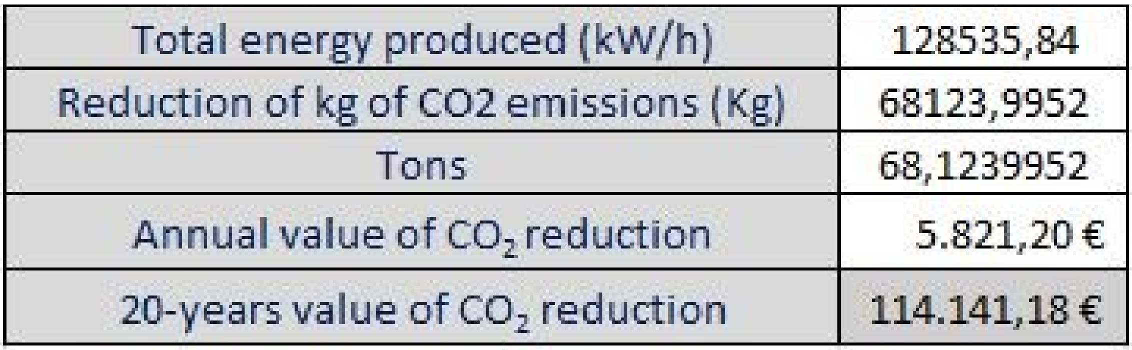
We report in Table 10 also the capacity in kW because is an important variable for the calculation of installation cost of the plant as reported in the formula:

$$Installation\ cost\ =\ Capacity\ *\ 1.500€\ per\ kW^{24}$$

For privacy reasons we were not able to access the exact economic data for the individual user, however this calculation was approximated using average reference values. While the capacity of the plant is a variable that we were able to derive from the productivity of the plant and the location of the buildings.

We conclude the data collection by making a small calculation in favor of the positive externalities (caused by this EC) perceived by the society. The positive economic value of this EC is linked to the reduction of $C0_2$ emissions due to the use of solar energy rather than another non-renewable energy source. Again, the variable to be taken into account is energy production, which is the same in both ECs, so we will report a single entry of values (see Table 11):

Table 11: economic value of positive externalities.



Total energy produced (kW/h)	128535,84
Reduction of kg of CO2 emissions (Kg)	68123,9952
Tons	68,1239952
Annual value of CO_2 reduction	5.821,20 €
20-years value of CO_2 reduction	114.141,18 €

Source: author's own elaboration.

This calculation was made starting from the total energy produced by the EC then we found how many kg (and consequently tons) of CO_2 were saved (during 2022) with the use of that energy, through the following calculation:

$$Reduction\ of\ CO_2\ emission\ =\ Total\ energy\ produced\ *\ 0{,}53\ kg\ per\ kW/h^{25}$$

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[24] The price of € 1,500 per kW was chosen because in Italy it can be considered as the average price for the installation of a photovoltaic system of a medium quality (there is a large variation in price between low and high-quality plants) as explained in [46], [47], [48].The price per kW is variable depending on how large the capacity of the installed system is and our calculation is approximate using an average value of different components: photovoltaic panels, photovoltaic inverters, support structures and storage systems.

[25] The value of 0,53 kg per kW/h was derived from [40] and [41], which indicate the official conversion factors in Europe for the year 2022.

Then we converted the reduction of CO_2 emissions to an economic level (again for the year 2022) with the formula below:

$$\begin{aligned} &Economic\ value\ for\ the\ reduction\ (of\ CO_2\ emission) \\ &\qquad = Reduction\ of\ CO_2\ emission\ *\ 85{,}45€\ per\ Ton^{26} \end{aligned}$$

Then we calculated the discounted value of the cash flows over a 20-year time horizon (equal to the duration of the investment in photovoltaic plant), using a discount rate of 2%[27]. This value, however, is not entirely reliable because the ETS which regulates the price of CO_2 emissions is a variable title and making predictions for 20 years would have complicated our calculation (which wants to be only informative). In addition, this value does not represent the net positive externality because to provide a complete analysis we would have to count the pollution that involves the transport and installation of photovoltaic plants and negative externalities due to the disposal of the plant at the end of 20 years. However, it remained correct to give an approximate idea of how much the existence of an EC could decrease the CO_2 emissions.

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[26] This is the value of the European ETS regulating $C0_2$ emissions, regulated by the UE emissions system (as indicated in [42], [43], [44]). This is the value assumed by the title at the end of 2022.

[27] This discount rate was chosen because is indicated by the Bank of Italy in the annual report, as mentioned in [45].

5) DATA ANALYSIS

In this chapter we analyze the data collected and listed in Chapter 4. The analysis is done firstly from an energy point of view, motivating the choice and the utility of EC optimization. This is because we believe it is important to highlight the importance of a possible aggregator and/or a manager who can carefully choose the users to enter the EC. Subsequently, we conduct an economic analysis, will be considered savings in 20 years (which is the time horizon chosen for the entire life of the investment) and the investment cost for the installation of photovoltaic plants. We hypothesize two different scenarios: the first scenario assumes that the prices of energy tariffs remain constant for the 20 years of the investment; the second scenario assumes that the prices of energy tariffs have a positive trend of growth (for 20 years). For simplicity we have chosen to consider the EC as a single individual. We will not include positive externalities in the valuation of profitability because the calculation made in Chapter 4 is a very approximate calculation which tells us only indicatively the economic gain perceived by the society for CO_2 reduction, because, other important variables (always at the level of externalities) are omitted, the absence of these variables affects negatively the reliability of the analysis.

5.1) OPTIMIZATION

In the first part of paragraph 4.2 are collected the energy aspects of the initial EC and the optimized EC. The choice of entering both data collections was dictated by the desire to demonstrate the importance of optimizing the EC. The tables that we take into analysis in this paragraph are initially Table 4, Table 5 and Table 6; finally, we conclude the analysis on optimization by also taking into analysis some items of Tables 7,8 and 9. The first 3 items of Tables 4 and 5 are not relevant because they are equal in both tables. This can be explained by the fact that Total energy produced, Total self-consumed energy and Total energy input concern the same individuals present in both ECs (before and after optimization); in fact, we see that these quantities affect only producers of energy, and with the optimization have added only consumers. Since energy producers are the same, these 3 items are irrelevant to demonstrate the effectiveness of EC optimization. The items Total self-consumed energy (Tables 4 and 5) and %self-consumed energy (Table 6) are useful to highlight an economic saving on the amount of energy purchased by the external provider, these producers mostly have peaks in consumption which correspond to production peaks and that therefore they will have less need to buy energy from outside. Let’s now turn our attention to the items (in Tables 4 and 5) Total energy withdrawn from the grid, Shared energy and the item (in Table 6) %Energy shared, these are the items which demonstrate the importance of optimization the EC. Total energy withdrawn from the grid corresponds to the energy needs of the entire community, it is noted that in EC optimized this amount increases: from 41.646,36 kW/h (in the initial EC) to 253.269,59 kW/h (in the optimized EC). This value is not very significant taken individually since the increase in energy requirements is an obvious consequence of the increase in the number of users in the EC. The increase in energy needs, however, also means, assuming that the consumption profiles of users (consumers) entered (with optimization) are complementary to the production peaks, so energy sharing increases and consequently also profit and economic savings increase. The energy sharing aspect is seen clearly in Shared energy (in Tables 4 and 5) and in %Energy shared (in Table 6). This variable is the most important since it indicates the level of efficiency in the EC. A high %Energy shared means that producers sell a large part of the energy produced to EC users and this leads to economic gains from the point of view of ARERA’s incentives, the valorization of the energy sold (therefore real sales revenues). As already mentioned in Chapter 4, the ideal level of %Energy shared should be 100%, so that the EC makes the most of its conformation and productivity (thereby increasing producers' revenues and consumer savings). With our optimization, however, we went from a very low percentage (11.3%) to a mostly satisfactory percentage (71%). This item tells us, in addition to a better exploitation at the technical level of the energy produced, with optimization there will be higher revenues for energy producers and greater savings for consumers who participate in the EC (the economic aspect will be analyzed in paragraph 5.2).

5.2) PROFITABILITY OF PARTICIPATION IN AN ENERGY COMMUNITY

In the analysis of the profitability of the investment and participation in an EC, we will first analyze the investment supported by the EC for the installation, maintenance and disposal of photovoltaic plants. Usually, the life of photovoltaic plants is 20 years, which is why we will calculate the general framework of the investment over 20 years (as in paragraph 4.2 to enhance the reduction of CO_2 emissions caused by the EC in its useful life). Secondly, we propose an analysis of the savings due to participation in an EC, initially we will analyze the year in which the data are collected (2022). We then complete the analysis framework by calculating savings over 20 years, proposing two scenarios: the first with the constant energy tariffs; the second with rising energy tariffs. In this way we would have all the components to calculate the profitability in participating in an EC (not considering in this calculation the positive externalities computed in paragraph 4.2). In Table 10 we can see the installation costs of the photovoltaic systems, the sum of which give us the entire investment value of the EC in photovoltaic systems (165.840€). This sum will be useful in the final calculation of the profitability of the investment as it can be approximately inclusive of the various costs of maintenance and disposal of the plants. This is because the price of 1,500 € per kW could be considered an ideal price inclusive of all the costs attached to the photovoltaic system. We see that each plant has a different cost, this because the investment is linked to the capacity (and therefore the size) of the plant installed.

In Tables 7,8,9 we can analyze the composition of savings and the total savings for the year of data collection (2022). These values will be useful later for the calculation of the total savings in the 20 years of investment. Table 9 summarizes the savings and costs of the EC: an interesting data that we consider important to explain is the item Total cost with EC. We see that in the initial EC there is a negative value, this indicates that in the starting community there were positive cash flows (real gains) for 3,658.74€. We see that this amount translates into a cost in the same item of the optimized EC, 19.973€. This does not mean that for the producers the participation of the consumers is a deficit for their revenues, because the same producers, after optimization, have obtained revenues more than 3.658,74€. This is explained by the fact that with higher energy shared, producers can afford to sell energy at a more advantageous price (to EC users) rather than sell it to an external service provider (in 2022 the price for selling energy to EC users is 11cent kW/h while the price for selling energy to an external provider is 8cent kW/h). On the other hand, we see that the item Total Savings (in Table 9) has a strong increase following the optimization of the EC: this because in addition to the greater gains by the producers of the EC; we have greater savings by consumers (the rates offered by EC producers are 11cent kW/h which are cheaper than those offered by service providers which are 15cent kW/h). As we have explained in paragraph 4.2, Total Savings is composed of the following items (see Tables 7 and 8): Total incentive; Savings from total self-consumption; Total revenues from network sales. Savings from total self-consumption and Total revenues from network sales are two items that do not change with optimization because they are linked only to producers (which, as we said, do not change). The item that greatly affects the annual savings are the total incentives which correspond to the sum of Valorization of shared energy and ARERA's incentive. The item which has a greater impact in the Total savings is the Valorization of shared energy since it is the aspect that more increase after the optimization of the EC. This item goes from 1.291,93€ to 8.266,63€ which is about 6 times the initial value. This is to show how the optimization of the EC has brought both advantages from the energy and economically point of view. The item ARERA's incentive increases (since it is still linked to the amount of energy shared) however does not affect much in the final amount of incentives because it increases from an amount of 93.96€ (in the case of the initial EC) to an amount of 601.21€ (in the case of optimized EC). For completeness we clarify that these incentives have a different impact even in the users because: ARERA's incentive is a sum of money that is given directly and only to energy producers, therefore it is a revenue only to the subjects who have the photovoltaic system; Valorization of shared energy instead is an economic incentive that is collected in a common pool (of the EC) is then divided according to the directives and rules of energy sharing decided in the agreements signed at the creation of the EC. In calculating the savings over 20 years, and finally the profitability in participating in an EC, we will use the numbers and data of the optimized EC because from assumptions of our model we assumed that the EC had characteristics similar to those presented by the optimized EC. As already mentioned in paragraph 3.3, the profitability of investing (and then participating) in the EC is calculated by the difference in savings over the 20 years and the investment costs to install the photovoltaic plants. In fact, our EC was created with the aim of pure saving and energy independence and not with the aim of having an economic profit.

Before proceeding to the evaluation of the scenarios we evaluate the efficiency of the EC through two simple calculations: $\frac{Total\ self-consumed\ energy}{Energy\ demand}$ and $\frac{Total\ energy\ produced}{Energy\ demand}$. These two calculations allow us to understand the impact of production and self-consumption in the amount of energy demanded. In the optimized EC we see a percentage of energy self-consumed (on the energy demanded) of 8% while we see a percentage of energy produced (on the energy demanded) of 47%. This data is influenced by the fact that there are more consumer users than producer users, in fact, if we analyze the same relationships in the EC not optimized (so with the producers only) we see that the percentages become: 35% and 201,82% respectively. As explained above, the amount of self-consumed energy and the amount of energy produced are the same before and after optimization, while the amount of energy demand increases (this because there are the more users and more needs of energy). Our EC is therefore very efficient from the point of view of production because it has plants allow very large production volumes, these percentages can increase with the inclusion of additional producers, this inclusion but would increase investment costs (as more photovoltaic plants are installed) and could cause a decrease of %Energy shared. This could reduce total EC savings (less shared energy would mean more energy sold to a service provider and therefore less sales revenue).

5.2.1) Scenario 1 – constant tariffs

In the first scenario we assume that energy rates remain constant[28] throught 20 years of the investment. As a methodology to define the current value of the investment and therefore to understand the profitability or not in the participation to the EC we will use the NPV[29]. To compute the NPV we need a discount rate that allows us to discount the cash flows (savings) for the 20 years of the duration of the investment. The discount rate chosen is the one for Italian government bonds (in 2022) with a maturity of 20 years[30]: 4,26% as indicated in [51] and [52].

$$NPV = \sum_{t=1}^{20} \frac{Annual\ savings}{(1 + discount\ rate)^t} - Investment\ costs$$

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[28] To hold the constant rates along the 20 years can be corrected if we think that the course of the commodities in the long period assumes values not much departing from the average value. With a long investment horizon, fluctuations in raw materials are avoided.

[29] [49]: Net present value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period. NPV is used in capital budgeting and investment planning to analyze the profitability of a projected investment or project.

[30] We chose this discount rate because it is linked to a low-risk investment, being considered a low-risk investment also in EC, we consider it appropriate to use the same discount rate.

To measure the effective return on investment we calculated the IRR [31]:

$$NPV = 0 = \sum_{t=1}^{20} \frac{Annual\ savings}{(1 + IRR)^t} - Investment\ costs$$

In Table 12 we see the reference values of investment costs and savings in 20 years discounted (discounted to year 1):

Table 12: profitability in scenario 1.

Discount rate	4,26%
Investment cost	165.840,00 €
Total savings (discounted)	274.869,85 €
NPV	**104.513,43 €**
IRR	**11%**

Source: author's own elaboration.

The savings discounted over the 20 years of the entire EC amount to 274.869,85€ exceeding the amount invested (165.840€). As can be seen from the positive value of the NPV of € 104.513,43 we can consider the investment and the participation into the EC profitable for users. We consider it appropriate to indicate that the positive cash flows used in the NPV calculation correspond to economic savings and not returns. Observing the IRR, we see that in scenario 1 (constant prices) in addition to has a positive NPV, this investment project has also an IRR of 11%. The actual yield of this project (always considered as expected cash flows) is therefore higher than the yield of 20-year Italian government bonds (which have a yield of 4.45%). As for the NPV, this comparison was chosen because this investment is not considered risky, nor is it considered risky to invest in government bonds. In addition to profitability, we therefore also have the convenience (by the user) to invest in photovoltaic systems (join the EC) rather than invest money elsewhere.

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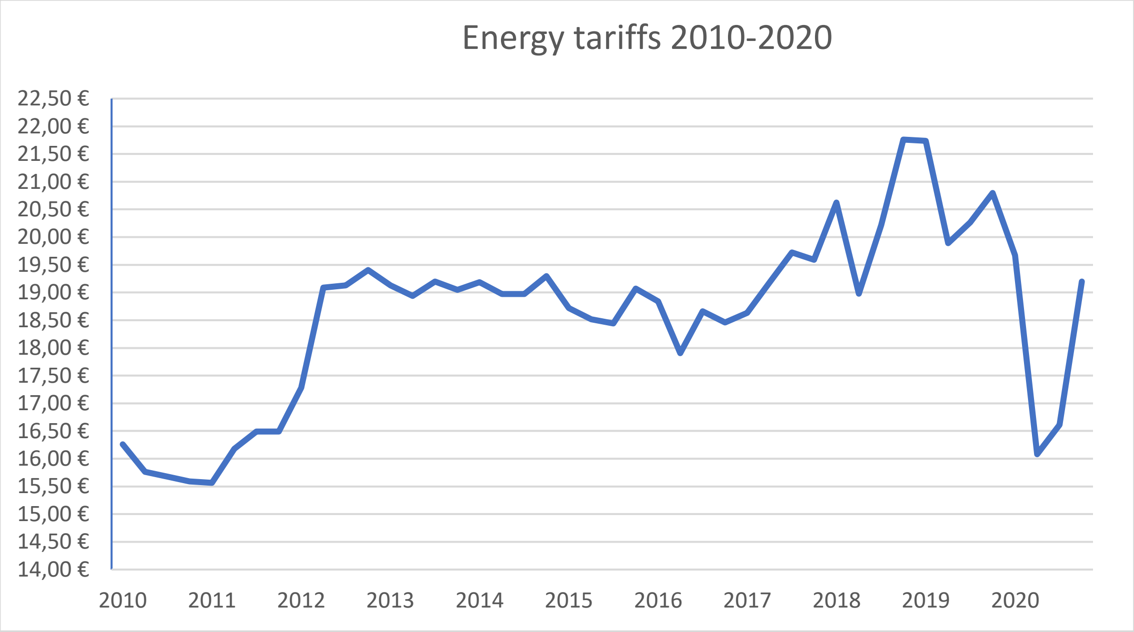
[31] The IRR measures the profitability of an investment project, is defined as the specific discount rate for which the NPV is 0 and thus expresses the effective return of the project.

5.2.2) Scenario 2 – growing tariffs

In this scenario we assume that energy tariffs will increase at a constant annual rate over the 20 years of the investment period. The annual growth rate has been based on the growth trend of energy tariffs in Italy in the 10 years before 2021[32] (from 2010 to 2020), values found in [50], as we can see in Figure 6:

Figure 6: energy tariffs from 2010 to 2020.



Source: author's own elaboration.

As we mentioned in footnote 32, we have not inserted in the computation the most recent years, this because 2021, 2022 and 2023 are characterized by events (which had macroeconomic effects and which have greatly shifted economic balances, in our case also energy tariffs).

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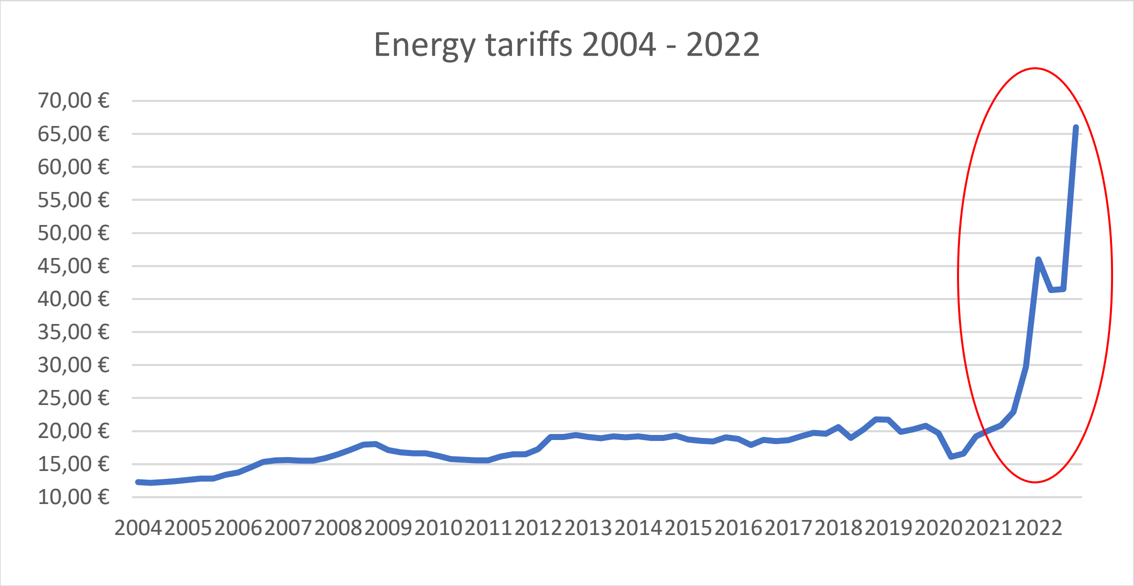
[32] We have chosen a shorter temporal horizon (10 years; from 2010 to 2020) because the price of the commodities in the long period tends to remain stable, concentrating on a reduced period we would have been able to isolate better an effective increase of the rates. Moreover, we did not go beyond 2020 because during and after anomalous events (see war between Russia and Ukraine) the price of energy recorded very high growth rates, this would have unbalanced the values in our forecast.

We can see a sharp increase in energy tariffs in these years by observing the red circle in Figure 7:

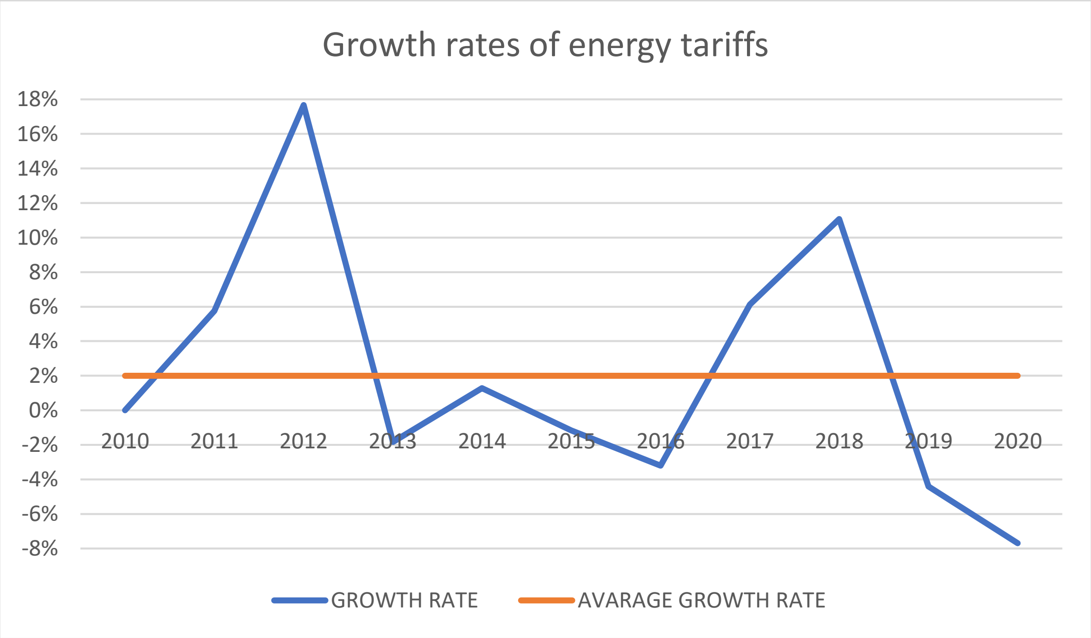
Figure 7: energy tariffs from 2004 to 2022.



Source: author’s own elaboration.

The choice has been therefore to calculate all the rates of annual increase of the electronic rates (see Table 13, Appendix) using the present values in [50]. We have obtained an average growth rate of 2%, we plotted data of Table 13 in Figure 8:

Figure 8: energy tariffs growth rates (from 2010 to 2020).



Source: author’s own elaboration.

This growth rate was applied to the items of savings affected by the price of electricity. We have seen how the calculation of Total Savings consist of:

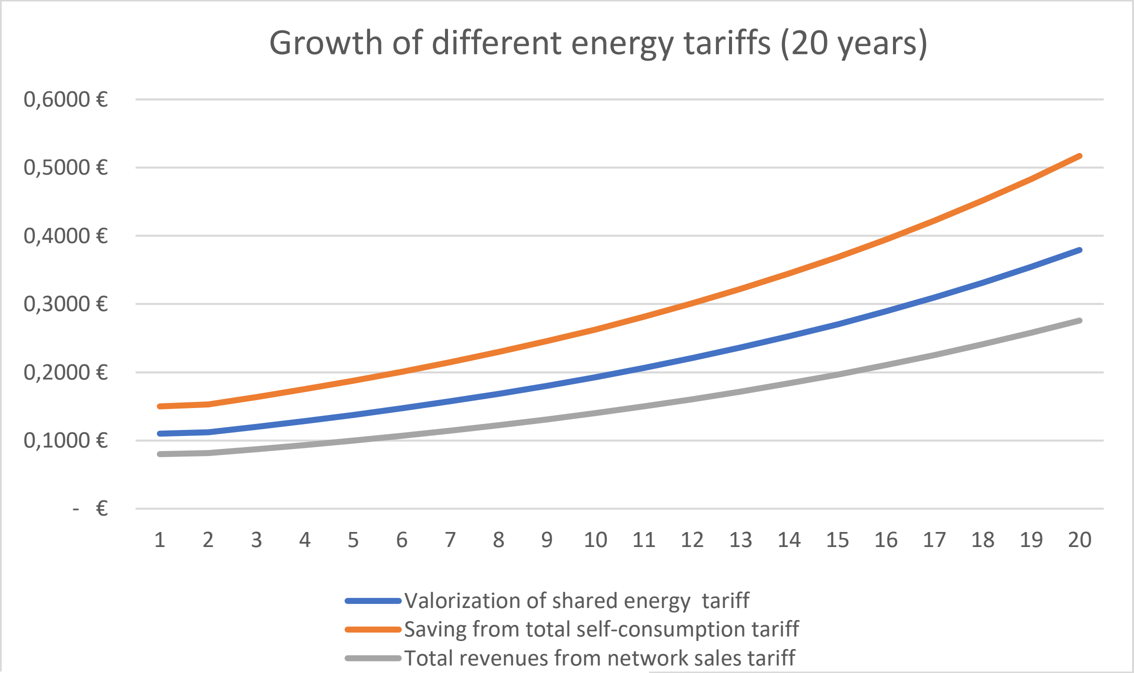
- savings from total self-consumption;
- total revenues from network sales;
- total savings (in turn composed by: ARERA's incentive; valorization of shared energy).

The growth rate is applied to these energy tariffs[33]:

- 15 cent kW/h (relative to the item: Savings from total self-consumption);
- 8 cent kW/h (relative to the item: Total energy input);
- 11 cent kW/h (relative to the item: Energy shared).

While we have not applied any growth rate to the ARERA's incentive since we have seen that over the years has not suffered any influential changes (the value of ARERA's incentive is not related to energy tariffs). The energy tariffs represented in Table 14 (Appendix) are the different rates that affect total savings (as described above) for the 20 years of the duration of the investment. At these rates we applied the average growth rate of 2%, then grow proportionally (as seen in Figure 9):

Figure 9: growth of the 3 different energy tariffs (during the 20 years of investment).



Source: author's own elaboration.

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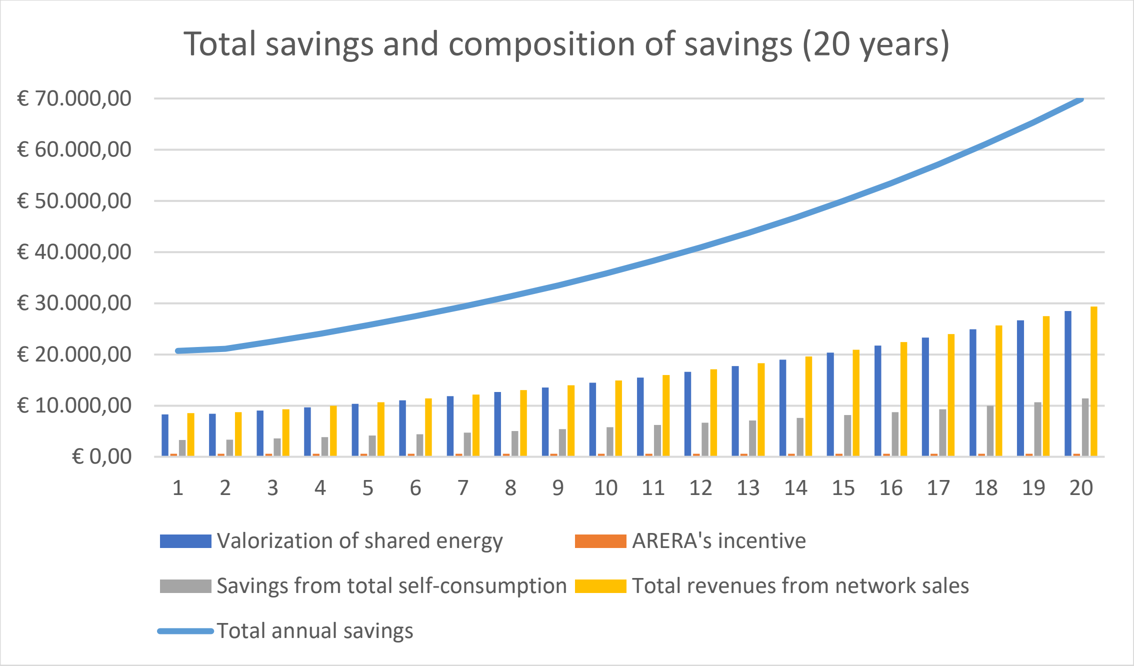
[33] We have assumed a proportional growth of the following energy tariffs, therefore all 3 tariffs considered grow at the same annual growth rate chosen.

Once we calculated the growth of the annual energy rates, we applied them to the savings to be able to have a final figure regarding the economic saving that involves the investment in this EC. We can see the annual savings (for each year of the 20 years related to the investment) in Table 15 (Appendix). Then we have plotted the data of Table 15 in Figure 10, in this way we can observe the growth of the savings during the years of the investment (increase that follow the increase of energy tariffs) and also the composition of these savings.

Figure 10: composition and growth of annual savings (computed with a growth rate of energy tariffs).

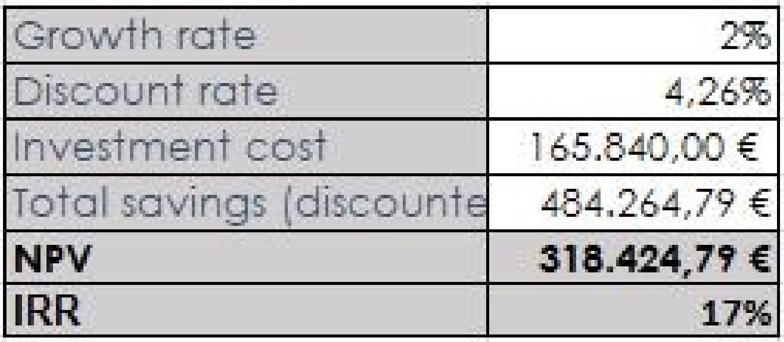


Source: author’s own elaboration.

Total annual savings indicates the sum of all the annual savings components, which are indicated in the previous columns (Table 16, Appendix). Each individual annual savings value was used to calculate the discounted value of the savings over 20 years and then to compose the final NPV using the same discount rate as used in scenario 1 (20-year government bonds: 4.26%). The same data (total annual savings) are used to also compute the IRR of the investment project.

In Table 16 we represent the summary and the value of the discounted investment.

Table 16: profitability in scenario 2.



Growth rate	2%
Discount rate	4,26%
Investment cost	165.840,00 €
Total savings (discounte	484.264,79 €
NPV	**318.424,79 €**
IRR	**17%**

Source: author's own elaboration.

As we can see the value of the NPV of € 318,424.79 shows us the profitability of the investment if energy rates grow at a constant annual rate of 2%. In scenario 2 we can consider profitable the user participation in the EC. With growing energy rates, in addition to the NPV also increases the IRR of the investment project, from an 11% to a 17%. This investment assuming a scenario that reflects the trend of energy rates in previous years, is more attractive for the user who wants to participate in the EC. We therefore note that the riskiness of this investment project could increase with the reduction of energy rates, thus reducing the actual energy savings, however with the increase of the tariffs (as we have seen to be successful in recent years) yield tends to increase.

CONCLUSION

Nowadays investment in renewable energy is becoming more frequent. In addition to the economic aspects, they also have a strong impact on the ecological aspects. As we have seen, the CO_2 reductions which a single EC can entail are a significant amount. From the economic point of view, we see that investing in renewable energy (in this case in photovoltaic systems) can be profitable for the investor user and for other users who benefit from the ecological and sometimes economic advantages of that investment.

ECs are a collective that, as we have shown, can have a strong economic impact on the users who are part of it. We conclude our analysis by specifying that we have demonstrated the actual gains of the entire community considering it as a single individual. However, if we go to take every single user within it, we will see that there will be different economic revenues: energy producers tend to have positive cashflows periodically, as their gain comes from the sale of energy (in addition to the gain from not incurred expenditures), this is to support investment and make it more attractive; from the point of view of consumers, which as we have explained will not have real revenue, we see that the decrease in electricity expenditure will have a big impact on their annual budget.

The management of an EC must be assigned to an expert in the field, since the optimization of its conformation is considered fundamental for the maximization of revenues. The model created by us tries to better respect what are the aspects considered most efficient (based on the analyzed papers) that may concern an EC. Having to collect and simulate real and therefore more reliable data as possible, we have eluded some aspects; however, we have seen that by optimizing an initial EC, we can greatly improve its effectiveness (both from an energy and an economic point of view).

We therefore consider the presence of an aggregator and/or an experienced manager essential for the success of an investment of this type. We also consider the presence of consumer users and producer users fundamental, because to be considered such a profitable investment is necessary that there are internal buyers that allow to maximize the economic revenue and their own savings. The high reliability of the data used allows us to see with certainty that an investment of this type (and even the entry into an EC) can be attractive and convenient for any type of user (we analyzed an EC composed of different users with different needs).

This paper can be integrated mainly in two fields: the first is the economic analysis of the individual user, so not considering the EC as a single individual but analyze the cash flows of each user and make further changes (regarding the conformations) that can further optimize the EC’s gains; the second integration is related to the scenario where the price of energy falls sharply (as a reduction in energy tariffs would make such an investment less attractive) in the past we have seen that in the long run there have never been any decreasing trends, however there is a phenomenon that can mark the change of this market and a sharp decrease in electricity prices, the birth of nuclear fusion (currently we do not have enough data for the creation of a similar scenario).

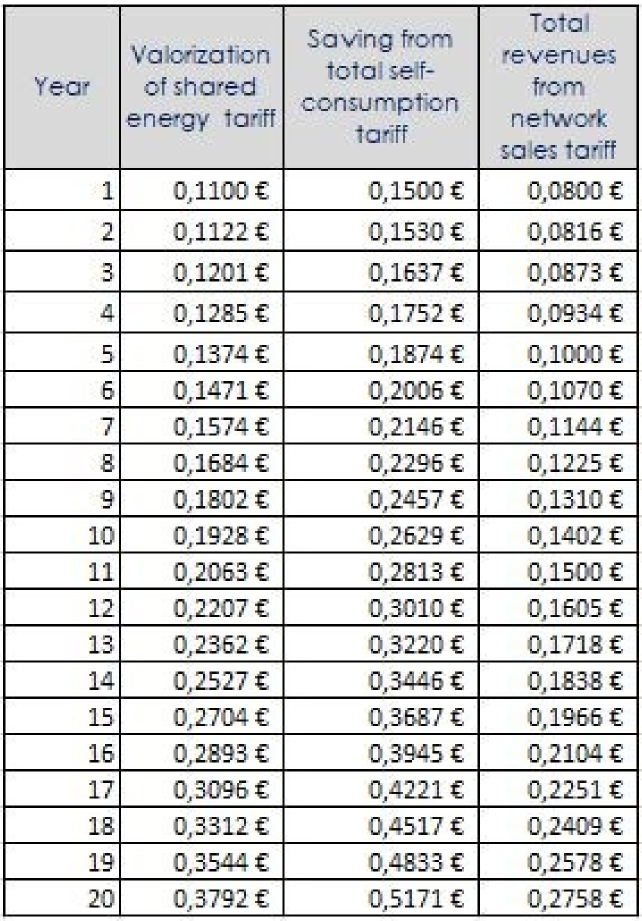
APPENDIX

Table 13: Growth rates of energy tariffs.

YEAR	PRICE (c€/kWh)	GROWTH RATE
2010	15,593	-
2011	16,490	6%
2012	19,404	18%
2013	19,049	-2%
2014	19,295	1%
2015	19,070	-1%
2016	18,460	-3%
2017	19,590	6%
2018	21,760	11%
2019	20,800	-4%
2020	19,200	-8%
		2%

Source: author’s own elaboration.

Table 14: annual energy tariffs (computed with a growth rate).



Year	Valorization of shared energy tariff	Saving from total self-consumption tariff	Total revenues from network sales tariff
1	0,1100 €	0,1500 €	0,0800 €
2	0,1122 €	0,1530 €	0,0816 €
3	0,1201 €	0,1637 €	0,0873 €
4	0,1285 €	0,1752 €	0,0934 €
5	0,1374 €	0,1874 €	0,1000 €
6	0,1471 €	0,2006 €	0,1070 €
7	0,1574 €	0,2146 €	0,1144 €
8	0,1684 €	0,2296 €	0,1225 €
9	0,1802 €	0,2457 €	0,1310 €
10	0,1928 €	0,2629 €	0,1402 €
11	0,2063 €	0,2813 €	0,1500 €
12	0,2207 €	0,3010 €	0,1605 €
13	0,2362 €	0,3220 €	0,1718 €
14	0,2527 €	0,3446 €	0,1838 €
15	0,2704 €	0,3687 €	0,1966 €
16	0,2893 €	0,3945 €	0,2104 €
17	0,3096 €	0,4221 €	0,2251 €
18	0,3312 €	0,4517 €	0,2409 €
19	0,3544 €	0,4833 €	0,2578 €
20	0,3792 €	0,5171 €	0,2758 €

Source: author’s own elaboration.

Table 15: annual savings (computed with a growth rate of energy tariffs).

Year	Valorization of shared energy	ARERA's incentive	Savings from total self-consumption	Total revenues from network sales	Total annual savings
1	€ 8.266,63	€ 601,21	€ 3.306,58	€ 8.519,36	€ 20.693,78
2	€ 8.431,97	€ 601,21	€ 3.372,72	€ 8.689,74	€ 21.095,63
3	€ 9.022,20	€ 601,21	€ 3.608,81	€ 9.298,02	€ 22.530,24
4	€ 9.653,76	€ 601,21	€ 3.861,42	€ 9.948,89	€ 24.065,28
5	€ 10.329,52	€ 601,21	€ 4.131,72	€ 10.645,31	€ 25.707,76
6	€ 11.052,59	€ 601,21	€ 4.420,94	€ 11.390,48	€ 27.465,22
7	€ 11.826,27	€ 601,21	€ 4.730,41	€ 12.187,81	€ 29.345,70
8	€ 12.654,11	€ 601,21	€ 5.061,54	€ 13.040,96	€ 31.357,81
9	€ 13.539,89	€ 601,21	€ 5.415,84	€ 13.953,83	€ 33.510,78
10	€ 14.487,69	€ 601,21	€ 5.794,95	€ 14.930,60	€ 35.814,44
11	€ 15.501,83	€ 601,21	€ 6.200,60	€ 15.975,74	€ 38.279,37
12	€ 16.586,95	€ 601,21	€ 6.634,64	€ 17.094,04	€ 40.916,84
13	€ 17.748,04	€ 601,21	€ 7.099,07	€ 18.290,62	€ 43.738,94
14	€ 18.990,40	€ 601,21	€ 7.596,00	€ 19.570,96	€ 46.758,58
15	€ 20.319,73	€ 601,21	€ 8.127,72	€ 20.940,93	€ 49.989,59
16	€ 21.742,11	€ 601,21	€ 8.696,66	€ 22.406,80	€ 53.446,78
17	€ 23.264,06	€ 601,21	€ 9.305,43	€ 23.975,27	€ 57.145,97
18	€ 24.892,54	€ 601,21	€ 9.956,81	€ 25.653,54	€ 61.104,10
19	€ 26.635,02	€ 601,21	€ 10.653,78	€ 27.449,29	€ 65.339,31
20	€ 28.499,47	€ 601,21	€ 11.399,55	€ 29.370,74	€ 69.870,97

Source: author's own elaboration.

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