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Master of Science in Energy and Nuclear Engineering

Master of Science Thesis

Techno-Economic Assessment of Local Energy Communities

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"There is no power for change
greater than a community
discovering what it cares about"

Margaret J. Wheatley

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Stefano Viti

Abstract

The European Union (EU) has set ambitious targets and policy objectives to move towards a society featured by high Renewable Energy Sources (RES) penetration, at least 32% share, and low GreenHouse Gas (GHG) emission, at least a 40% cut, by 2030. In the forthcoming energy transition, an increasingly key role is expected to be played by *Energy Communities* (EC): a legal entity where different actors satisfy their energy needs by cooperating in the energy production, trading, storage, and consumption. These medium-large scale installations help also to bring several benefits to the population, achieving unfeasible results on an individual basis. They aim at decarbonizing energy systems by promoting the distributed power generation and increasing citizens' awareness, as they are actively involved in the decision-making processes.

This thesis presents the techno-economic assessment of an EC made by residential and commercial members, comparing its performances to a scenario where such buildings act as *Single Self-Consumers* (SSCs). The first step of the EC modeling implements a methodology to determine the building load profiles, starting from the building shape. Then, a retrofit configuration is investigated for each EC member. Depending on the building, PhotoVoltaic (PV), Heat Pumps (HPs) and a gas-fed CHP engine coupled with an absorption chiller are installed. Simulations have shown that the EC strategy leads to an increasing of 156 MWh in self-consumption (+25%).

In the second phase of this work a quantitative economic model for the feasibility study has been developed. To this aim, an exhaustive regulatory framework analysis is provided to understand the context of the ECs. The *Renewable Energy Directive* (RED) and the new electricity market Directive (2019/944) issued by the EU aim at framing ECs from a regulatory point of view. These documents contain some guidelines but operative rules still lack, as they are left to the Member States (MSs); their transposition is expected within 2021 for Italy. Waiting for such a date, combining RED principles with Italian electricity market rules, three different economic scenarios are defined for the comparison. Such frameworks differs in the mechanism through which energy is sold, choosing between the *Net Metering* (NM) or the *FER* decree (the new Italian legislation about RES), the possible adhesion to the free market and the presence of possible incentives. Moreover, sensitivity analyses on system and transport charges, required to the EC for the public grid utilization when energy is exchanged, have been carried out.

The economic comparison provides the Net Present Value (NPV) and the Internal Rate of Return (IRR) for the SSCs and the EC configurations. Results have shown that the EC always brings to higher gains, up to 50% more, while the FER decree has turned out to be the best way to sell energy. Nevertheless, in every scenario, the additional charges impact is not negligible: they appreciably reduce the difference between the two configurations, making less attractive for investors and citizens an EC strategy.

Therefore, a correct regulatory framework is the basis for a large scale diffusion of ECs.

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List of Acronyms

BAU: Business As Usual
CAPEX: CAPital EXpenditure
CCHP: Combined Cooling Heating and Power
CE (It.): Conto Energia
CDD: Cooling Degree Days
CHP: Combined Heating and Power
COP: Coefficient Of Performance
DEA: Danish Energy Agency
DH: District Heating
DHW: Domestic Hot Water
DOE: Department Of Energy
EC: Energy Community
EU: European Union
GC: Green Certificate
GHG: GreenHouse Gas
GME (It.): Gestore Mercati Energetici
GSE (It.): Gestore Servizi Energetici
HDD: Heating Degree Days
HEC: High Efficiency Cogeneration
HP: Heat Pump
IRR: Internal Rate of Return
KPI: Key Performance Indicator
MS: Member State
NM: Net Metering
NPV: Net Present Value
PBT: Pay Back Time
PES: Primary Energy Savings
PU: Production Unit
PUN (It.): Prezzo Unico Nazionale
PV: PhotoVoltaic
REC: Renewable Energy Communities
RED: Renewable Energy Directive
RES: Renewable Energy Sources
RESC: Renewable Energy Self-Consumers
SC: Self-Consumption
SME: Small Medium Enterprise
SS: Self-Sufficiency
SSCs: Single Self-Consumers
UVAM (It.): Unitá Virtuali Abilitate Miste
WC: White Certificate

1 Introduction

The concept of the *Energy Community* (EC) is inserted in the European plan of the *Low-Carbon Societies* [1], aimed at decarbonizing the power production system. EC could help to this purpose by decentralizing the production, increasing the self-consumption and promoting RES. Their potential contribution in the energy transition of this century, strongly bonded to the future regulatory framework, has been already widely demonstrated on different levels [2]-[3]-[4].
Several EU projects, with funds and incentives, are trying to increase the penetration of RES through the implementation of *Renewable Energy Communities* (RECs) [1]. For instance, in UK new central government-funded programs have been started to support local REC projects [5], whilst part of the Interreg Europe funds ($1,268,505$ €) have been allocated to promote the COALESCCE project in seven EU countries, pushing for community-based approach to increase the local energy provision [6].

The lack of a precise regulation, together with the multi-faceted declensions given to it, may cause ambiguity when it comes to precisely define an EC. This matter has been well highlighted in the work done by Walker et al. [7]; they analyzed 12 initiatives promoted by public and private institutions which made the word *"community"* their mainstay, finding various inconsistencies among them. Afterward, to bring order to the subject, they proposed two essential features for an EC:

1. The project must be carried out by a group of local people, who take charge of the technologies to be installed and the management aspects.
2. The project must bring benefits, at least, to the same group of local people.

Even though these constraints are quite generic, they are a good starting point when this topic is coped with: communities are involved in the decision-making process and directly take advantage of the project [1].
Another definition reasserting the active role that members could have it is the one provided by REScoop, the EU network of EC [8]:

> *"An Energy Community is a legal entity where citizens, SMEs and local authorities come together, as final users of energy, to cooperate in the generation, consumption distribution, storage, supply, aggregation of energy from renewable sources, or offer energy efficiency/demand-side management services."*

In the scientific literature, the first reference to such a concept is provided by McCulloch et al. [9], who coined the term *Solar total Energy Communities* to describe a set of residential buildings satisfying their needs using only the Sun as a primary source. From this pioneering publication, the debate took place and the number of documents about the topic started to grow up rapidly [Fig. 1].
Probably, the most complete study about the term has been done by Moroni et al. [10]. They defined ECs as *"groups of individuals who voluntarily accept certain rules for the purposes of shared common objectives (only or also) relating to energy"*. This entity must have at least one of the following:

1. It purchases energy as a group;
2. It manages demand and supply;
3. It generates energy.

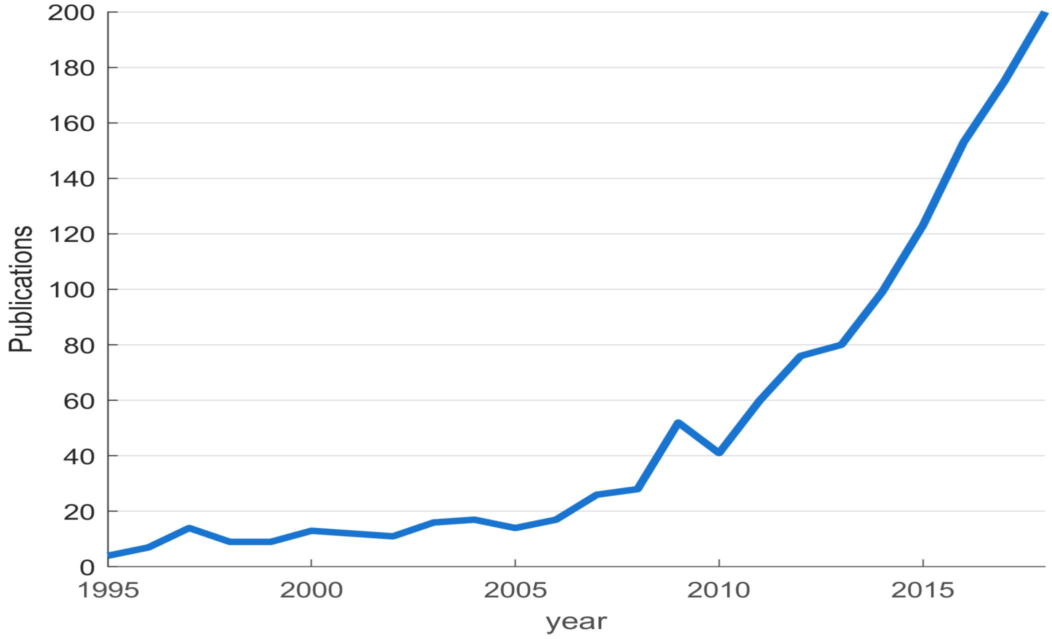

Figure 1: Number of publications about Energy Communities. **Source**: Elsevier.

In this definition, the concept of EC is untied from RES and here it is linked to the existence of a group [11].
An exhaustive summary of EC typologies can be found in the work of Koirala et al. [12], where it is deeply analyzed the so-called Integrated Community Energy Systems (ICESs), stressing the importance of the integration with neighboring systems to provide ancillary services.

ECs could play also a key role in promoting the active position of the people, achieving the so-called *"Democratization of Energy"* [13] and unlocking the system to new actors [14] by boosting their awareness on energy themes. The citizen can exercise this role mainly on three different levels [15]: the first concerns the possibility to choose the energy supplier, acquiring awareness about offers and bill composition, the second is about the adoption of highly-efficient energy production and storage system, while the third concerns load shifts due to signs price changes (demand response management) [17]-[18].
The theoretical possibility of establishing new ECs has been consistently addressed, as they often turn out to be positive investments [19]. Considering the case of Italy, studies have demonstrated that nowadays the energy share produced and consumed *in the same place* amounts only to 28 TWh (the 9% of the total consumption), of which only 4.2 come from RES [15]-[16]. Therefore, being the PV roofs potential equal to 90 TWh [Fig. 2], the opportunity for the institution of RES based ECs is reinforced by the current situation.
Nevertheless, this diffusion needs the help of suitable policies at national and European level [19]-[20]. The central role of the governments, widely discussed in this thesis, is a pivotal element for ECs promotions among citizens: establishing special electricity tariffs for promoting RES [21], limiting the additional charges for the possible use of the public grid or driving the citizens in this process [22] are all valid examples through which ECs can be fostered.

Starting from these considerations, this thesis aims at showing when and why an EC strategy is energetically and/or economically convenient for a group of prosumers.

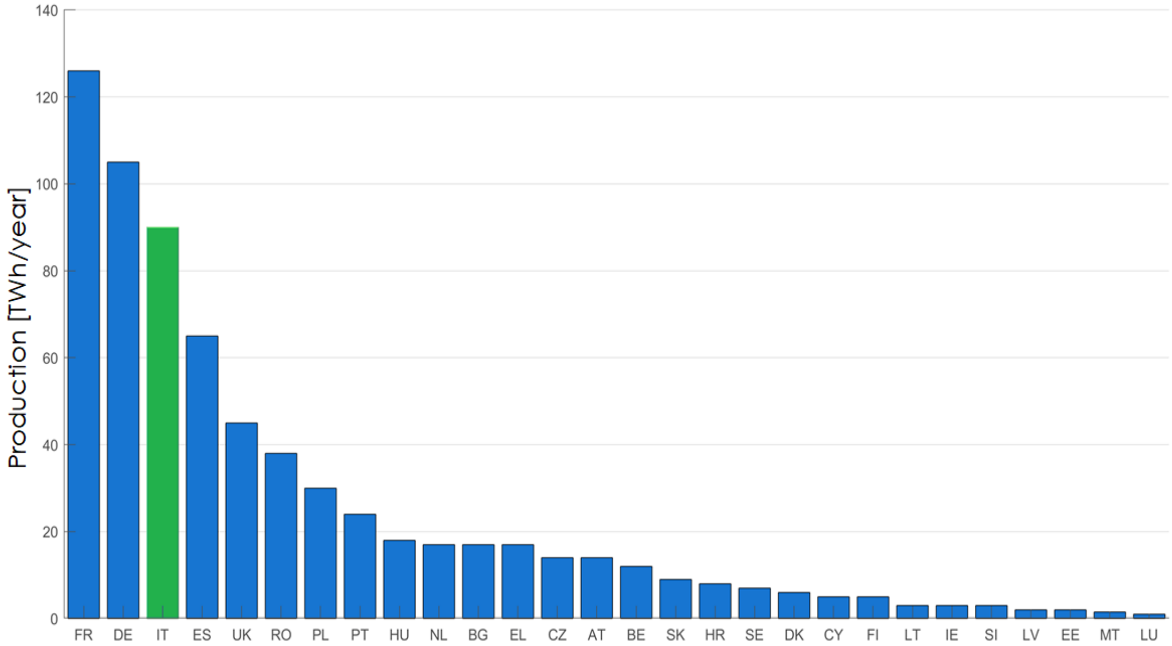

Figure 2: PV roof potentiality in EU roofs; Italy is highlighted [15]-[16].

More precisely, its benefits are evaluated with respect to a Single Self-Consumers (SSCs) configuration, computing to which extent such strategy is more worthwhile.
After this brief introduction to frame the problem, some practical examples of ECs and results already achieved by previous scholars about the theme are provided [Section 2], as well as a regulatory framework review (EU and Italian only, draft and already published) [Section 3]. Section 4 is focused on describing how the EC has been modeled in MATLAB: it deals with a methodology to define load profiles, the physical model of the community, the technology installation and the techno-economic indicators used in the final comparison. Section 5 presents the results of the thesis, arguing when ECs are worthwhile for citizens. Finally, Section 6 summarizes the main findings of the work, providing also suggestions for future studies.
The true step ahead of this work is an in-depth study to evaluate how the potentialities of the EC with respect to a SA strategy are affected by the regulatory framework that is closed to be clearly defined. Therefore, the thesis is intended to be a guide that answers the question *when and to which extent is it convenient for citizens to join a community*?

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2 Energy Communities: current status

This section aims to show what is the *State of the Art* about ECs. The analysis has been carried out on two levels: the first concerns the study of already existing communities, to see some practical examples, while the second is about techno-economical ECs assessments present in the scientific literature, to understand how the present work stands concerning previous works.

2.1 Examples of existing Energy Communities

Even though the term still raises some issues, some examples of energy-sharing communities were present in Europe since the first half of the 20^{th} century [1]. Below a list of case studies spread throughout Europe is proposed:

- *Ulfborg, Denmark*: Born in 1978 in the framework of the Tvindkraft project, this is an example of how the willingness for sustainability can be traduced into practice by local people. Local teachers have promoted the construction of a wind mill to provide their school with clean energy. The result was the biggest wind turbine ($2\,MW$) in the world at that time to provide energy for all the neighborhood, in response to the oil crisis [2].

- *Samsø Island, Denmark*: Through strategies such as consumption monitoring, promoting heat pump installation and RES (solar and wind) penetration [3], this Danish island community born in 1997 aims at a fossil fuel-free energy system by 2030 [4].

- *Eno Energy, Finland*: Established in 1997 by 12 local forest owners to produce heating for the community using biomass resources (local wood), it has extended over the years, being nowadays composed by 55 individuals [5].

- *Rabat, Malta*: This EC is a bit different from the others. The big roof of the Tal-Fiddien Water Reservoir [Fig. 3] has been initially covered with $4,000$ PV panels (power output of $999\,kWp$) purchased at $1,500$ €$/kWp$. Citizens who join the project can benefit from a feed-in tariff for electricity generated [6]. The idea behind the community is simply but forefront: give roof to households without it.

Moreover, before the nationalization of electricity in Italy (1962), there were several local communities, while today only a few consortia and historical cooperatives have survived [7]. Some examples of such organizations are:

- *Sudtiroler Energieverband*: Taking advantage of the $549,400$€ from EU, this big EC, counting 299 members, is strongly focused on RES with its 150 PV installation, 116 hydro-power plants and 46 district heating biomass-based plants [8].

- *Benetutti municipality*: Located in Sardinia, the project concerns the construction of a smart grid owned by local municipalities fed by PV [Fig. 4], which provides the service of transmission for all the final customers [9]. This community is made by 1200 users with a total yearly consumption of $3.7\,GWh$; for such project the Region has allocated $1.75\,M$€ [10].

- *ACSM group*: This consortium, born in 1901, has expanded over the years having now $125\,MW$ for producing electricity (13 hydro power and 1 CHP biomass-fed plants). Their actual numbers are very considerable, with 11,922 pod and 250 $ktons$ of CO_2 saved every year [11].

Figure 3: The big roof of the Tal-Fiddien Water Reservoir.

Figure 4: shared PV installation feeding the municipality of Benetutti.

- *CVA group*: Known as Valle d'Aosta water company, it provides energy to local people using only RES, mainly wind turbines, PV field and logical hydroelectric basins [12].

These are only a limited number of case studies that help to understand how an EC practically works; more examples can be found, for instance, in [1]-[13]. Therefore, even if common EU guidelines had not yet been issued, communities sharing the same production plants already exist since the $19th$ century all over the continent.

2.2 Energy Communities in the scientific literature

The scientific literature has plentifully tackled the theme of ECs, understood in their large meaning of customer association, sharing load and energy production, to analyze their environmental and economic benefits.

An exhaustive techno-economic assessment of EC is provided in the work by Rehman et al. [14]. Considering only residential users, they put together 100 houses served by a PV field and a wind farm, to develop a multi-objective optimization algorithm evaluating various EC configurations. Their results show how the SC of the community decreases when RES capacity increases and storage is not installed. Economic results of the project, when wind turbines and batteries are installed, are always negative due to high investment cost. Baneshi & Hadianfard [15] analyzed the techno-economical parameters of a hybrid diesel/PV/wind/battery system for supplying energy in a non-residential neighborhood. They have simulated both an off-grid and an on-grid configuration, finding an optimum that minimizes the cost of electricity and showing the techno-economic impact of the batteries.

Awad & Gül [16] have simulated a cluster of 42 residential units comparing two scenarios: the one in which every dwelling is served by a single PV system and the other where there is a single large PV system. After generating the profile using a stochastic Monte Carlo approach, they applied a multi-objective optimization for the EC, finding the optimal size, orientation and inclination for PV. Results have shown a 16.18% increase in the yearly revenue for the optimized configuration. Even though they have done something very similar to the *PV sharing* proposed in this work, what is missing is a comparison with the same size between the community and the baseline scenario to evaluate, for instance, the enhancement in the self-consumption fraction. Going down the same path, Thakur & Chakraborty [17] proposed a distributed PV system as an alternative to individual rooftop PV to make indeed financially feasible the investment. Even though they never explicitly mentioned ECs, their proposal goes exactly in this direction, since both these works exploit the potential of shared (i.e., multiple users) photovoltaic systems. The same idea has been developed by Rathore et al. [18], who assessed the potentiality of decentralized solar rooftop photovoltaic in India to avoid transmission and distribution losses that affect big power plants. In their work, they present and discuss the policy incentives aimed at increasing the PV share in India.

In this framework, the work presented by Schiera et al. [19] provides a relevant approach; authors have developed an agent-based model (ABM) to assess the diffusion of PV in a Turin neighborhood. Two different scenarios have been simulated: a *one-to-one* configuration where each dwelling of a condominium was fed by its PV panels and a *one-to-many* business based on rooftop sharing (i.e. all the dwellings share the same PV system). The second scenario is an example of EC, the so-called *collective self-consumer* [20], a set of pods living in the same building that can exchange energy without using the national grid; it is worth noting that nowadays in Italy even such configuration is not yet recognized. Results have shown how the second scheme can bring to self-consumption rates greater than 50% [Fig. 5] and to an 80% increase in installed capacity. Similar results for the self-consumption will be presented in this work with detailed economic analyses, even though no difference in the PV capacity has been considered since it will be hypothesized that tenants install the same PV area in both configurations. Adopting always an ABM, Mittal et. al [21] have evaluated how zero energy goals can be achieved at community level, modeling users' behavior before and after the aggregation. Among their results, they defined the minimum *feed-in-premium* subsidy on the produced energy such that significant targets could be reached. Similar results showing the impact of Zero Energy Communities (ZEC) could be found in [22]-[23].

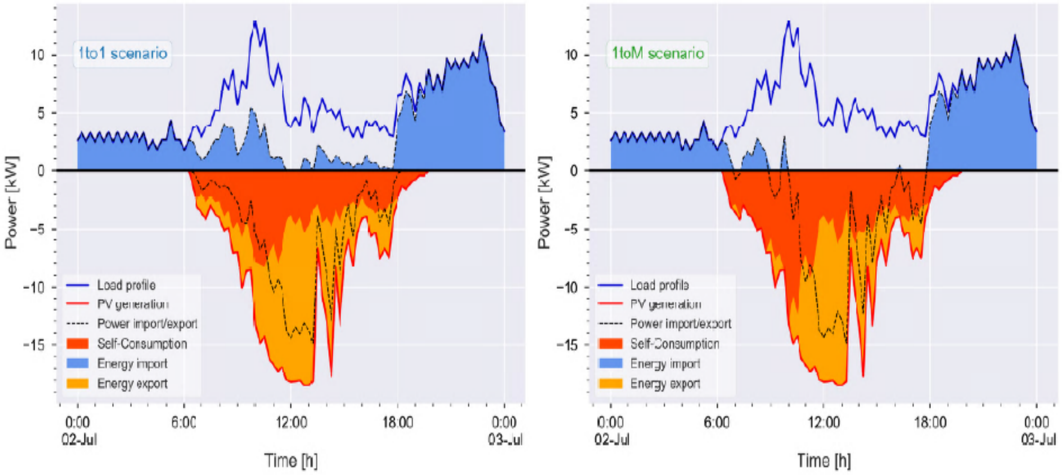

Figure 5: Self-consumption increase in the *one-to-many* configuration [19].

ECs exchanging also heat through a District Heating (DH) internal network have been assessed by Kim et al. [24]. Considering an area with 300 houses and 6 non-residential buildings, they compare three scenarios differing in terms of technology installed: traditional boiler and cooling system, centralized heat pump and solar thermal-PV assisted heat pumps. Fig. 6 shows the scheme of this community: it allows understanding how an EC is made and where technologies are installed for the buildings they serve. In the end, the third system has achieved much lower CO_2 emissions and shorter Pay-Back Times (PBTs). Similarly, Rosati et al. [25] simulated a district heating network for residential and school buildings in Naples: such system has shown a positive impact on the primary energy savings, but its PBT is still too high (around 40 years) due to the high initial investment cost to be paid for building the network; these results have then been confirmed also by [26]-[27] when DH is coupled with seasonal storage. For this reason, to avoid investments impossible to recover, in the present thesis DH networks will not be considered and the only energy exchanged will be the electrical one.

Gonzalez et al.[28] made a complete description of the status of Scottish ECs. They reported the definition of EC provided by the Scottish government: *"projects led by constituted non-profit-distributing community groups established and operating across a geographically defined community"*. Then, they observed the increase of ECs, highlighting the share of every RES in terms of capacity: from 2013 to 2018 the number of MW installed is doubled [Fig. 7]. For obvious climatic characteristics, wind is the most exploited natural resource since the majority of ECs are built on islands. Due to their particular position, islands are probably the place that best suits the construction of ECs, with local grids built to avoid the electricity transfer under the sea [29]-[30].

An example of an economic assessment for a hybrid renewable EC (biogas produced from solid waste, PV and wind turbines) has been published by Tiwary et al. [31]. Their findings indicated a positive Net Present Value (NPV) and a levelized cost of energy equal to 0.222 $£/kWh$. A literature review paper about how policy-makers have promoted (and

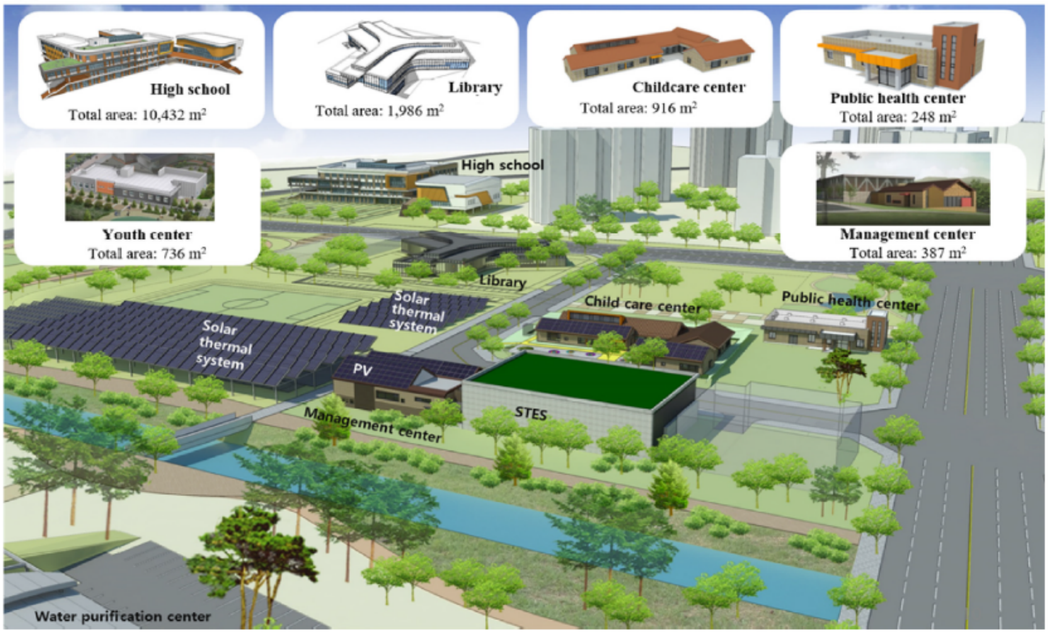

Figure 6: Example of an EC scheme, from [24].

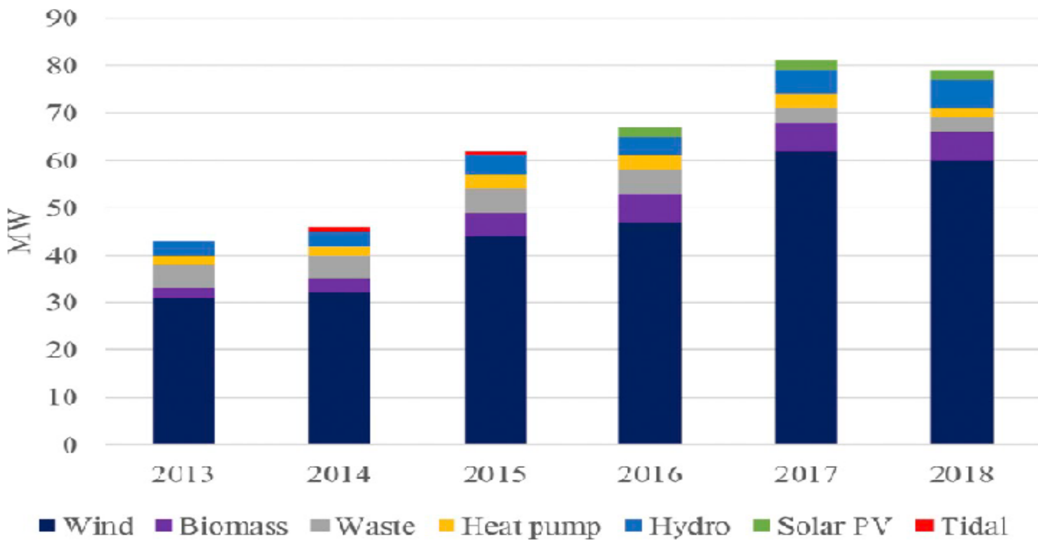

Figure 7: Installed capacity of ECs projects in Scotland [28].

should promote) EC to drive the next energy transition is the one written by Mah [32]. She has considered two case studies, one in Foshan and the other in Seoul, explaining how they can benefit from different governmental strategies and stakeholder approach. Yadav et al. [33] discussed how the Indian capital subsidy scheme should be reformed to advocate the development of poor rural areas with ECs. Their work is interesting mostly because they depicted incentivized ECs as a mean to fix social problems; subsidies and cooperation among banks and private firms are essential to deliver solar system in these zones. The central role that ECs could play in promoting the development of poor areas belonging to second-third world countries has been repeatedly underlined by scholars [34]-[35]. Among these papers, the one by Krishan et al. [36] deserves a mention; they made the techno-economic assessment of three different Hybrid RESs to meet the residential and agricultural load of an Indian energy-poor community in responding to the lack of grid power [37]. Implementing a detailed PV model, they find the optimal size of PV, battery and wind turbines to achieve the most cost-effective configuration.

A more detailed economic evaluation in different regulatory scenarios has been done by Ma et al. [38], who considered also tariff, incentives and subsidies in the Chinese market. Taking seven cities as case studies, they provided several sensitivity analyses changing legislation parameters, to observe how they affect the community. Fig. 8 [1] shows the Net Present Cost (NPC) (i.e. the opposite of the NPV) when incentives, feed-in tariff, ancillary charges, grid tariff, and natural gas prices vary, as well as the effectiveness of the investment as accessible subsidies change. Similar results, for the Italian market and legislation, are the aim of this thesis, but always comparing the EC with the SSCs configuration.

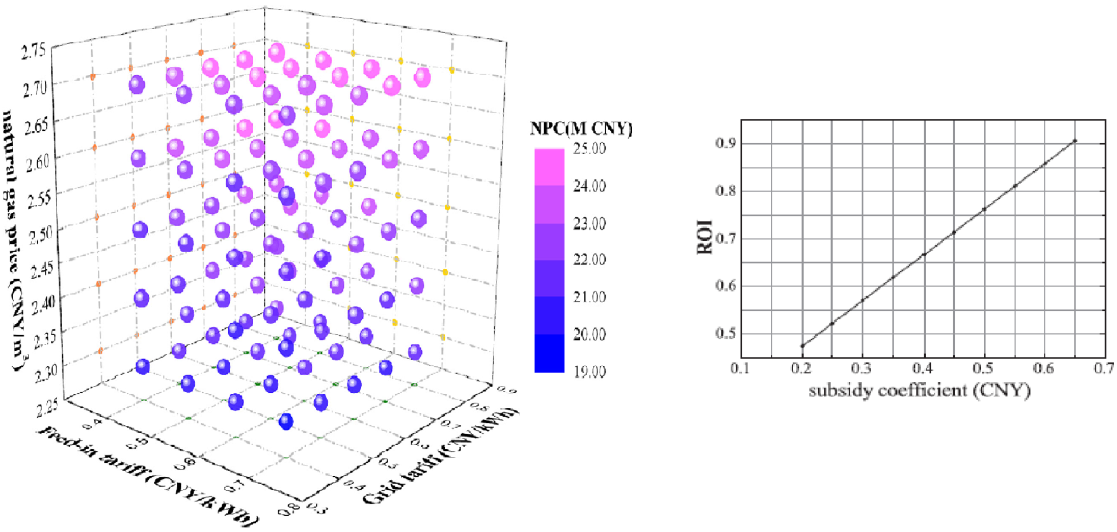

Figure 8: EC potentiality as the economic scenario changes [38].

Other examples of work about techno-economic assessment/optimization of ECs can be found in the literature. Amiri et al. [39] proposed a linear optimization to size a bio-fuel combined heat and power (CHP) plant through which an energy company can efficiently cooperate with two industries (a paper mill and a sawmill). With the hypothesis of a deregulated European electricity market, they found how such cooperation can bring benefit to every user, leading to an operational cost reduction by 2.18 $M€/y$, distributed among all members [Fig. 9]. Hybrid RES-CHP systems have been analyzed also by Maleki et al. [40]: considering a complex mix of technologies, with storage systems and fuel cells, they optimized the community with a meta-heuristic algorithm, without however providing a comparison with the stand-alone configuration.
To sum up, especially in the last year, the literature is plenty of publications about ECs which analyze all their aspects. The community can be understood as a catalyst to push RES and decentralized energy production, thus several papers [16]-[18]-[19]-[22] have studied shared rooftop PV. On the other hand, since community does not mean RES, scholars have also studied CHP plants at a neighborhood scale [39]-[40] and even others argue that ECs could help the social and cultural development of poor areas [33]-[34]. Finally, many works reporting detailed economic analyses have been published to assess the community under different economic scenarios [17]-[38]-[39], especially for the Asian electricity market.

[1] $1\ CNY = 0.13$ €. **Source**: *Il Sole 24 Ore*, 27 July 2019

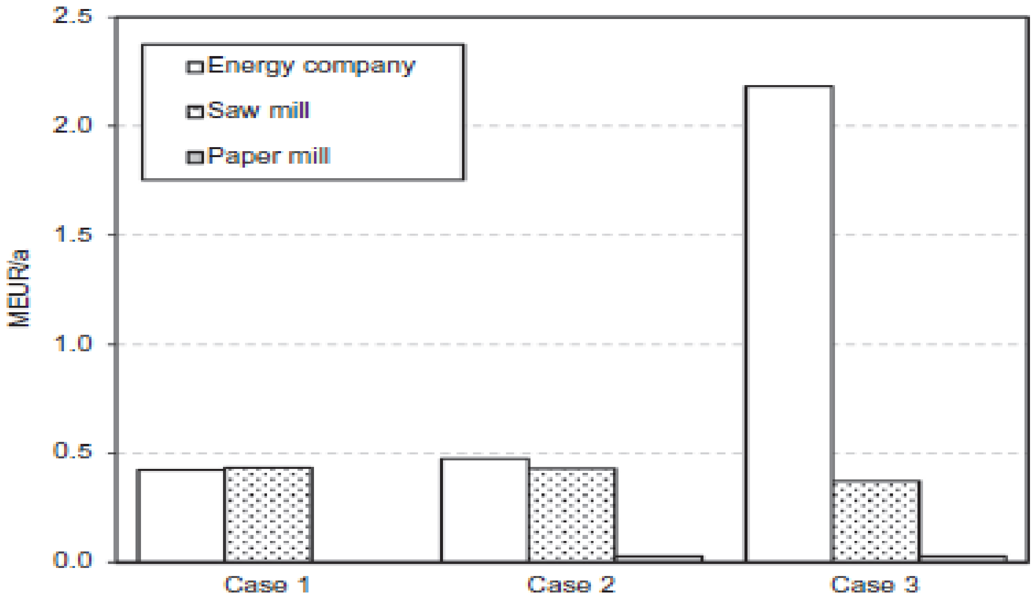

Figure 9: Operational cost reduction thanks to the cooperation [39].

The present work aims to give its further contribution in demonstrating the potentiality of ECs, by comparing for an exploratory case study in Piedmont two different scenarios: a Single Self-Consumers (SSCs) configuration, where prosumers (building of different types) operate separately, and an EC scenario, where the same buildings with the same generation asset share such devices. To this aim, the case study, a mix of residential and commercial buildings, undergoes firstly an optimized technological retrofit to being then compared in the two configurations. This techno-economic comparison is the best way to assess when and to which extent ECs are more worthwhile for citizens. Considering such a wide mix of users and technologies is surely a step ahead concerning the present scientific literature.
Finally, this thesis wants to be pioneer also in exploring future economic scenarios that, according to the present Italian electricity market settings and EU Directives about ECs, may be introduced to regulate such an entity.

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3 Regulatory framework analysis

This section presents an insight into the regulatory knowledge necessary to fully comprehend the subsequent hypotheses and analyses. The first part is a review of the EC concept as defined in the present EU legislation, with a logical deepening on the Italian situation. Then, considering the Italian electricity market, the final users' electricity bill and RES-CHP incentives enjoyable by the community are analyzed, to suggest the most promising support schemes for ECs.

3.1 Energy Community in the existing legislation

On November 21^{st} 2018 the European Parliament, to establish the new objectives to boost RES diffusion, published the RED (Renewable Energy Directive) II [1]. In this document (Art. 2), there are the definitions of:

- *Renewable Energy Self-Consumer*: A final customer who, operating on his own sites located within defined boundaries or, if permitted by a MS, on other sites, produces renewable electricity for his own consumption and may store or sell self-produced renewable electricity.
- *Collective Renewable Energy Self-Consumers [RESCs]*: Group of at least two people in the same building (residential or not) who produce and consume (and possibly sell) electricity from RES. If a member is not a family, this activity cannot be his main commercial employment.
- *Renewable Energy Community [REC]*: Legal entity formed by voluntary members who own and live near the production energy systems; members can be physical persons, local authorities or SMEs (Small and Medium Enterprises). Its main purpose must be to provide social and economic benefits to its members and/or to the area in which it operates, rather than financial profits.

The articles 21 and 22 describe the benefits of the last two entities:

- *RESC, Art. 21*: Each Member State (MS) undertakes to authorize RESC to produce, store and sell energy *without* applying any discriminatory charge. The energy exchanged among internal members (in the same building) may be subjected to network and accessory charges. RESC can receive incentives for the energy they feed into the grid, considering its social and environmental benefit. Governments can apply additional charges on the self-consumed energy if: there are already support schemes for the self-consumed renewable energy, the total quota of plants in self-consumption exceeds 8% of the total installed electric power (from 1^{st} December 2026) or the total installed electric capacity is bigger than 30 kW.
- *REC, Art. 22*: Likewise the RESCs, the RECs can produce, store, sell and use the self-produced energy. Besides, members can exchange energy with each other, provide energy or aggregation services or other commercial energy services and participate in the free electricity market jointly or alone. Again, governments agree to not apply discriminatory fees on the self-consumed electricity. Finally, countries may decide in favor of cross-border participation.

To clarify these definitions, an example of a RESC could be a condominium sharing a PV system, while a REC is made up of physically separated buildings.

Even if this is a good starting point for ECs, operative rules are still missing. No quantitative limits have yet been set, for instance, on additional charges that ECs may pay. Waiting therefore for more precise regulations, this thesis will investigate to which extent they can affect ECs chances to succeed.

A further step forward has been done with the Directive 2019/944 [2], concerning the electricity market. Its Art. 2 introduces the word *"Citizens"* to highlight the involvement of local people. *Citizens Energy Communities* (CECs) are a legal entity based on voluntary and open participation and effectively controlled by members or partners. Their main purpose is to offer environmental, economic or social benefits to its members or associates at community level, rather than generating financial profits. Finally, it can participate in the energy generation (from RES or other traditional sources), distribution, supply, consumption, aggregation and storage, as well as to energy efficiency services, charging services for electric vehicles, or provide other energy services to its members or associates. Both these directives are awaiting the transposition by the MSs.

As far as the Italian legislation is concerned, since the case study of this work is placed near Turin, ECs could be considered a sort of evolution of the so-called SSPC (*Sistemi Semplici di Produzione e Consumo*). SSPC [3] are electric systems, connected to the national grid, in which the transport of electricity to the consumption units is not configured as a transmission and/or distribution activity, but as an activity of energy self-supply. They are made by one producer and one end-user, represented by groups of companies or historical cooperatives or consortia, provided with a single grid connection point. For instance, self-production or Net Metering (also known as *"scambio sul posto"*) systems are SSPC [4]. It is worth noting that before February 2016 SSPC production system could not exceed 20 MW_{el} [5]. ECs could be understood as SSPC with more than one producer and end-user, with multiple grid connection points.
In 2017, the national authority (ARERA) published a document [6] in which the UVAM (*"Unitá Virtuali Abilitate Miste"*), a sort of aggregator that might be seen as a precursor of the ECs, are defined as (Art. 2):

1. A cluster of users provided with Production Units (PUs), consumption units (measurable separately) and storage units.

2. One or more PUs that are not already enabled for the MSD (*Mercato del Servizio di Dispacciamento*), which share their connection point to the grid with one or more consumption units.

Among the necessary constraints for being a UVAM stand out the followings (Art. 3):

1. Consumption units within the UVAM cannot purchase from the Single Buyer (*"Acquirente Unico", AU*);

2. The fraction of the self-consumed energy must be *at least* 50%;

3. The value of the *Maximum Power Enabled* (i.e. the maximum increase in input that the UVAM can in any condition make available to Terna) and that of the *Minimum Power Enabled* (i.e. the maximum decrease in input that the UVAM can in any condition make available to Terna) have specific thresholds according to the UVAM configuration.

If only one of these requirements fails, the aggregate decays from the UVAM state, thus being disabled by the transmission system operator (TERNA in Italy) from the MSD services.

Furthermore, the Piedmont region issued a regulation to promote the establishment of ECs [7], which is one of the first regional example of regulation about ECs, besides that of Apulia. It is born from the law n. 221 of the 28^{th} December 2015, which coined the term *Oil Free Zone* (Art. 71) [8] to promote the decarbonization substituting fossil fuels with RES. This document is fascinating since it establishes operative requirements for ECs, anticipating in some ways the receipt of European directives by the Italian state. The requirements (Art. 1) to be acknowledged as an EC are indeed quantitative rather than qualitative:

1. Members must belong to *nearby areas*, namely to the same portion of the grid in medium and low voltage;
2. Yearly electricity consumption *at least* equal to 0.5 GWh;
3. Fraction of self-consumed energy *at least* equal to 0.7 and, of this minimum share, at least half must be produced by RES locally available;
4. Presence of several prosumers.

The first aspect that comes to mind is the increase in the minimum threshold of the self-consumed energy with respect to the UVAM, 70% against 50%, suggesting an evolution of the aggregate. According to the Piedmont law, ECs are requested to compile yearly a document describing all the energy flows (final use and type), the RES percentage on electricity and heat production, alongside with the pollutants and CO_2 balance (Art. 2). Also, they have to explicitly indicate the actions they intend to take to reduce consumption and make the production more efficient (Art. 3).
Table 1 helps to visualize the main contents of the laws seen so far.
After this complete framework of the EC definitions, obligations and benefit, subsidies that may affect the EC market must be presented.

3.2 Electricity bill composition

The current electricity bill is in force since 1^{st} January 2016 and it is composed of four different parts [9]:

- **Energy**: It includes the amounts invoiced for the various activities carried out by the seller to supply electricity to the final customer. The total price charged on the bill is the sum of the prices for the following components: energy (PE), dispatching (PD), equalization (PPE), marketing (PCV), dispatching component (DispBT).
- **Transport and meter management**: It includes the amounts invoiced for the different activities that allow sellers to deliver electricity to final users. The total price includes the components of the transport, distribution and measurement tariff and the UC3 and UC6 tariff components. The former is to cover imbalances in systems equalizing the costs of transporting electricity on transmission and distribution networks and in integration mechanisms; the latter aims to cover recognized costs arising from quality service recoveries.

Date	Proponent	Community name	Main contents
2015 [6]	ARERA	*UVAM* Unitá Virtuali Abilitate Miste	·Minimum share of self-consumption (SC) is 50%; ·Constraints on the grid power imposed by TERNA.
2018 [1]	European Union	*RECs* Renewable Energy Communities	·Members exchange energy and participate in the electricity market; ·Governments cannot apply discriminatory fees on SC energy.
2018 [7]	Regione Piemonte	*CE* Comunitá Energetiche	·Minimum yearly electricity consumption is 0.5 GWh; ·Minimum share of SC is 70%; ·Obligation to draw up balances and strategic plans.
2019 [2]	European Union	*CECs* Citizens Energy Communities	·Aimed at creating benefits to local people, rather than financial profits; ·It can participate in the market and in several energy services.

Table 1: Main legislations about ECs.

- **System charges**: It includes the amounts invoiced to cover costs relating to activities of general interest for the electricity system, which are paid by all final customers of the electricity service. The total price includes, since 1^{st} January 2018, the voices: A_{SOS}, general charges relating to RES production and CIP 6/92, and A_{RIM}, remaining general expenses.
- **Tax**: It includes items related to excise duty and Value Added Tax (VAT). The first is applied to the total amount of energy consumed, while the second is on the total amount of the bill. The excise duty is paid, for domestic users, if the total yearly consumption is bigger than 1800 kWh on the exceeding $kWh's$.

Each price can be composed by three parts: a fixed fee (€/*pod*/*year*), an energy fee (€/kWh) and a power fee (€/*kW*/*year*). Table 2 shows the amount of each item for domestic users in the protected market [2] [3].
This information is relevant to carry out the economic assessment of ECs. The community could pay a percentage of the transport and system charges on the energy internally exchanged. More precisely, since the various production systems will be placed in different buildings, there will be two *types* of self-consumption:

[2]A single rate tariff has been considered.
[3]A consumption bigger than 1800 kWh/y has been considered.

Fee	Energy	Transport	System charges	Excise duty
Energy [€/kWh]	0.07133	0.00798	0.076557	0.0227
Fixed [€/pod/y]	48.0070	20.2800	-	-
Power [€/kW/y]	-	21.2934	-	-

Table 2: Electricity bill composition (1^{st} Jul 2019 - 30^{th} Sep 2019) [10].

- The *direct* self-consumption: members consume the energy produced with their plants.
- The *indirect* self-consumption: members consume the energy produced by other EC members, that has to pass through the public grid.

The second share (i.e. the increase in self-consumption that arises from an EC compared to a SSCs configuration) may be subjected to system and/or transport charges. In other words, members may have to pay a fee for every kWh exchanged: pertinent analyses will be provided showing how the payment of such taxes impacts on the economic results.

3.3 Possible incentives for Energy Communities

Another important aspect is the subsidies to support energy generation from RES and HEC (High-Efficiency Cogeneration). Besides, new technologies purchased to reduce fossil fuel consumption may benefit from tax incentives, being their cost deductible.

3.3.1 RES subsidies

The energy production from PV has received, over time, mainly three different forms of incentives:

- **Conto Energia (CE)**: Started with the D. Lgs 387/2003 receiving the EU Directive 2001/77, it consists of a financial contribution per kWh of energy produced by PV over a certain period (20 years). This mechanism is named *feed-in premium* since it provides a constant award to all the energy produced [Fig. 10] in addition to the energy sales price related to the share feed into the grid. From 2005 to 2013 in Italy there have been five *Conto Energia* programs [11], being the fifth ended due to the achievement of the maximum share of energy that could be fostered.
- **Green Certificates (GCs)**: GCs are negotiable assets corresponding to a certain quantity of CO_2 emitted. If a plant achieves a CO_2 saving due to the RES, it is granted with GCs that may be re-sold to other plants, forced but not able (for various reasons) to install RES; in Italy GCs were emitted and sold by the GSE (*Gestore dei Servizi Energetici*) and their value was around 0.2 €/kWh. From January 2013, GCs have been substituted by an auction system, but, due to the high number of issued GCs, they continued till the end of 2015, having been replaced by a *feed in premium* mechanism [12]. This subsidy can be applied to all RES, not only to PV systems. As a matter of fact, in 2011 almost 90% of wind capacity was supported through the GCs.
- **CIP 6**: This was the first incentive introduced in Italy in 1992. It is a *feed in tariff* mechanism, namely a policy to support the development and the diffusion of RES by offering long-term purchase agreements for the sale of produced electricity at a

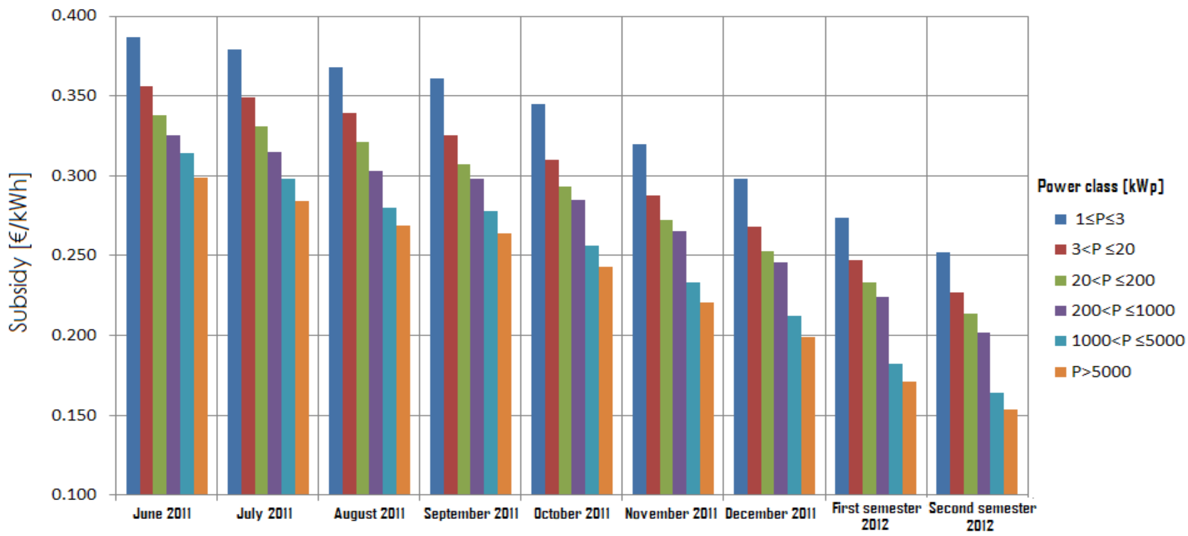

Figure 10: Subsidy for electricity produced by PV: fourth *Conto energia* [12].

fixed price [13]. The GSE undertakes to purchase the electricity at the price set by CIP 6 and then re-sell it on the market at the actual market price [12]. The component A_{SOS} seen before has been introduced for compensating possible price imbalances coming from this subsidy; in 2001 CIP 6 was substituted by GCs, but contracts previously activated have remained valid.

Actually there is another form of subsidy for RES, the *Tariffa Onnicomprensiva* (TO) for small not-solar plants (till 1 MW, 200 kW for wind). However, since only PV panels are installed in the case study of this work, please refer to [12] for more details.
However, on the 6^{th} June 2013 the GSE has announced that the threshold of 6.7 billion euros of indicative cumulative annual cost of PV incentives has been reached. Nowadays there is no more the possibility to take advantage of the subsidies described so far for EC as they are all ended.

The current RES regulatory framework is organized around the FER1 decree [14]; issued in June 2019, it could be very interesting for ECs because of the premium it provides for the self-consumption: if the energy consumed directly on site is greater than 40% of the net production, a premium of 0.01 €$/kWh$ should be granted for plants with a power output of up to 100 kW. It establishes also a constant tariff, depending on the size, at which the electricity produced can be sold for PV plants whose capacity is higher than 20 kW. In addition, PV small installations can enjoy a subsidy: there is the possibility to benefit from a 10-year deduction on IRPEF equal to 50% of the plant initial investment cost if:

1. The plant capacity is below 20 kW and the CAPEX is less than 96,000 €. If it exceeds this threshold, deductions are calculated on it.
2. The sale of the excess energy produced is not the main commercial activity;
3. The plant has been designed to serve the domestic dwelling.

Waiting for future regulations that will establish the subsidies to which communities could access, in this work various hypotheses are applied considering the current policy and

regulatory constraints. The total installed capacity could be bigger than 100 kW, thus it is not certain that EC will have access to the *feed in premium* on the self-consumed energy. Anyway, for ECs the issue is more complex because nowadays it is not known to which plants and to which self-consumption the threshold is referred to. As said before, the self-consumption could be direct or indirect, so the 40% limit could be about the first or the second; in this perspective, the reference PV capacity may not be the total within the community, but it may need to be seen user by user.
In this work, the presence of this further subsidy is considered for the EC, bearing in mind the previous considerations.

Furthermore, ARERA has defined new mechanisms for feeding and subsequently withdrawing the energy on the grid:

- *Net Metering* (NM): Valid since 1^{st} January 2009 [15], it is accessible for RES plant with capacity below 500 kW. The GSE provides a financial contribution to the plant owner, namely a refunding for expenditure incurred in purchasing energy from the grid.

- *Dedicated withdrawal*: Valid since 2007 [16], it was born as an alternative to the electricity market, it allows to sell the energy through simplified procedures. The GSE pays directly for the energy fed into the grid. Applicable to any PV size, it establishes a selling electricity price according to the $kWhs$ fed into the grid.

The question for ECs is always the same: how are they collocated in this framework? Will be such subsidies still valid for the community? Accessing the Net Metering mechanism could be very boastful for ECs, since it gives the possibility to buy energy in the night and sell it during the day at the national reference price (*"Prezzo Unico Nazionale", PUN*) which is lower in the night and higher during the day.
Waiting for precise regulations, in this thesis it is shown how different incentive terms affect ECs: the NM is firstly considered and then substituted by FER tariffs, as these mechanisms are not compatible (Art. 3, issue 8).

3.3.2 HEC subsidies

Among the technologies that will be installed in the EC, there will be also a CCHP (Combined Cooling Heating and Power) system, based on an internal combustion engine. In the framework of fossil fuel-saving, cogeneration plants are very interesting, since they recover the waste heat from power generation to meet heating and cooling (through an absorption chiller) needs. These devices, if respect some requirements, fall into the high-efficiency cogeneration (HEC) category, enjoying thus subsidies like RES.
Cogeneration plants are qualified as HEC if their global efficiency is above a threshold value established by the regulation, depending on the capacity P_{el} of the cogeneration unit. The D. Lgs 20/2007 [17], transposing the EU Directive 2004/08, enshrines that HEC qualification is given based on the PES (Primary Energy Saving) coefficient, which expresses the relative saving of primary energy achievable by a cogeneration plant compared to separate plants for the production of heat and electricity:

$$PES = \frac{\Delta E_c}{\frac{E_t}{\eta_t} + \frac{E_e}{\eta_e}} \tag{1}$$

where E_t and E_e are, on yearly basis, the thermal and electrical energy produced. Thus, being η_t and η_e are the efficiency in separated production mode, the denominator represents the primary energy consumption in separate mode. Please note that the yields have been defined by each MS, considering the technological *State of Art*; for Italy their values are established by the annexes IV and V of the D.Lgsl 20/2007. ΔE_c is defined by:

$$\Delta E_c = \left(\frac{E_t}{\eta_t} + \frac{E_e}{\eta_e}\right) - E_c \tag{2}$$

with $E_c = m_c \cdot H_i$ primary energy introduced in the plant; ΔE_c is thus the absolute primary energy saving of the cogeneration plant. The EU directive gives the HEC certification if:

- $PES \geq 0$, for $P_{el} < 1\,MW$;
- $PES \geq 0.1$, for $P_{el} \geq 1\,MW$.

Among the benefits enjoyed by these HEC plants there are:

- The exemption from the purchase of GCs for the energy produced by HEC;
- The reduction of the excise duty on natural gas;
- The access, if $P_{el} < 200\,kW$, to the procedures for the sale of electricity of *Net Metering* and *dedicated withdrawal*.
- The possibility to obtain TEE (*Titoli di Efficienza Energetica*), also called White Certificates (WCs), which may be re-sold on a market organized by the GME. This policy has brought to annual energy savings of 2.9 $Mtoe$ at the end of the first five years of operation (2005-2009) [18]. Their value is directly proportional to the *toe* saved, currently worth a WC 260 €/*toe* [19]; the number of WCs to which the cogeneration unit is entitled is given by:

  $$WC = SAV[MWh] \cdot 0.086 \cdot K \tag{3}$$

  where K is a harmonization coefficient, which varies according to the power of the cogeneration unit and the factor 0.086 converts MWh into *toe*. SAV represents the primary energy savings and it can be computed with eq, (2) using $\eta_e = \eta_{e,rif} = 0.46$ (average conventional efficiency of the Italian power generation plants) and $\eta_t = \eta_{t,rif} = 0.90$ (average conventional efficiency of the Italian thermal generation plants for hot water production) [20].

If possible plants installed in the EC were to respect all the HEC requirements, the community would take advantage from these subsidies.

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4 Systems modeling description

In this section, the mathematical models used for the simulations are presented. The EC has been physically defined choosing the type of buildings, their dimension, and specific use. A mix of residential and commercial (tertiary sector) buildings has been chosen. A methodology to determine the users' load profile is proposed, adapting the data from an American database published by the U.S. Department of Energy (DOE) for this work purpose.
Then, the equations used to model the technologies used to meet the demand are described. A specific focus is given to the optimization of the gas boiler-heat pump integration. Finally, the techno-economic equations used to compare the SSCs and EC scenarios are presented.

4.1 Creation of energy demand profiles

The EC case study of this work is composed of a residential reference building (a multi-family condominium), and by three commercial reference buildings: an office block, a supermarket, and a mall. For each one, the various energy profiles are known and used as input for the EC simulations.
The starting point is the DOE database available in [1], which contains the profiles of sixteen reference buildings for 841 American cities. To make a correct transposition aimed at obtaining significant profiles for the considered case study, it is necessary to know how these profiles have been generated.

4.1.1 DOE database description

The database developed by the DOE contains the profiles of heating, cooling, Domestic Hot Water (DHW) and electricity demands for commercial and residential users. Such profiles have been obtained by carrying out dynamic simulations of the buildings through the software EnergyPlus [2]. Please note that electricity consumption does not include cooling demand. The database is divided into two main parts, which are:

- **Commercial profiles** [3]: the DOE has defined 16 *archetypes* (or reference buildings) aimed at describing at least 2/3 of the U.S. commercial activities. Then he simulated each building in different American cities, using a climatic database inside EnergyPlus [4].

- **Residential profiles** [5]: the DOE has defined a typical building, following the indications provided by the Building America benchmark [6], called Base Load. Then, by changing some parameters, they took into account the possible variations from this model, both "positive" (Low Load) and "negative" (High Load). For climatic data, the same database previously introduced was used.

Given this subdivision, a clarification is essential. Actually, fifteen out of the sixteen archetypes of the first category are commercial buildings (so here there are the office, the supermarket and the mall), while the remaining one is instead a condominium. In the second group, there are dwellings with less than six housing units *and* less than four floors [5]. Therefore, all the profiles interesting for the case study belong to the first group, while the second part of the database is not considered.

The procedure adopted by the DOE [3] to generate these profiles follows three steps:

1. The first phase of the DOE was to define the 16 archetypes, trying to include the highest possible percentage of American commercial buildings. The reference document was the CBECS (Commercial Buildings Energy Consumption Survey) of 2003 [7], in which 5,215 buildings with their energy consumption and final uses were identified; analyzing the survey, the DOE defined a subset of 15 commercial archetypes (corresponding to 62% of the total square footage and 65% of energy consumption) to which he also added a residential user the so-called *"midrise apartment"*, reaching a total of 16 typical buildings.

2. In the second step, the buildings *zones* have been defined. In this phase, the localization is aimed simply at defining another parameter, the envelope insulation, and not at choosing the climatic data. The external temperature affects the U-value since where it is less cold building with low transmittance might be meaningless. The DOE starts from the 8 climatic zones defined by Briggs [8], defining, where he deemed the case, sub-zones, obtaining 16 zones.

   After these two phases, there are 16 different buildings with their dimensions [Fig. 11], each one with a proper U-value function according to the zone [Fig. 12].

Building Type	Floor Area		Aspect Ratio	No. of Floors	Floor-to-Floor Height		Floor-to-Ceiling Height		Glazing Fraction
	ft²	m²			ft	m	ft	m	
Small Office	5,500	511	1.5	1	10	3.05	10	3.05	0.21
Medium Office	53,628	4,982	1.5	3	13	3.96	9	2.74	0.33
Large Office	498,588	46,320	1.5	12*	13	3.96	9	2.74	0.38
Primary School	73,960	6,871	E-Shape	1	13	3.96	13	3.96	0.35
Secondary School	210,887	19,592	E-Shape	2	13	3.96	13	3.96	0.33
Stand-Alone Retail	24,962	2,294	1.3	1	20	6.10	20	6.10	0.07
Strip Mall	22,500	2,090	4.0	1	17	5.18	17	5.18	0.11
Supermarket	45,000	4,181	1.5	1	20	6.10	20	6.10	0.11
Quick Service Restaurant	2,500	232	1.0	1	10	3.05	10	3.05	0.14
Full Service Restaurant	5,500	511	1.0	1	10	3.05	10	3.05	0.17
Small Hotel	43,200	4,013	3.0	4	11** 9	3.35** 2.74	11** 9	3.35** 2.74	0.11
Large Hotel	122,120	11,345	3.8** 5.1	6	13** 10	3.96** 3.05	13** 10	3.96** 3.05	0.27
Hospital	241,351	22,422	1.3	5*	14	4.27	14	4.27	0.15
Outpatient Healthcare	40,946	3,804	1.4	3	10	3.05	10	3.05	0.19
Warehouse	52,045	4,835	2.2	1	28	8.53	28	8.53	0.006
Midrise Apartment	33,740	3,135	2.7	4	10	3.05	10	3.05	0.15

* Plus basement (not included in the table number)

** First floor

Figure 11: Reference buildings form [3].

3. The final phase consisted of developing the energy model for each building. This step requires some information taken by the DOE from different data sources; the EnergyPlus file has been divided into four macro-categories, each containing a series of input boxes to be filled with data from various sources, reported in Figure 13. The data of the program and form categories were taken from three different sources: AEDG (Advanced Energy Design Guide), PNNL (Pacific Northwest National Laboratory) and the previous CBECS. As far as the fabric and equipment are concerned, the standards proposed by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) were used.

Thus, using an input file so generated in different American cities (841 in total) scattered across the 16 climatic zones, the profiles of the energy *consumption* to meet the four energy needs are generated [Fig. 14]. Since *demand* profiles are worthy for this work, in the transposition, it will be needed to pass through the machines' performances.

Location	90.1-2004 Climate Zone	New Construction Btu/ $h \cdot ft^2 \cdot {}^oF$	New Construction $W/m^2 \cdot K$
Miami, FL	1A	0.124	0.704
Houston, TX	2A	0.124	0.704
Phoenix, AZ	2B	0.124	0.704
Atlanta, GA	3A	0.124	0.704
Los Angeles, CA	3B-CA	0.124	0.704
Las Vegas NV	3B-other	0.124	0.704
San Francisco, CA	3C	0.124	0.704
Baltimore, MD	4A	0.124	0.704
Albuquerque, NM	4B	0.124	0.704
Seattle, WA	4C	0.124	0.704
Chicago, IL	5A	0.084	0.477
Denver, CO	5B	0.084	0.477
Minneapolis, MN	6A	0.084	0.477
Helena, MT	6B	0.084	0.477
Duluth, MN	7	0.064	0.363
Fairbanks, AK	8	0.064	0.363

Figure 12: U-value for the 16 climatic zones [3].

Program	Form	Fabric	Equipment
Location	Number of floors	Exterior walls	Lighting
Total floor area	Aspect ratio	Roof	HVAC system types
Plug and process loads	Window fraction	Floors	Water heating equipment
Ventilation requirements	Window locations	Windows	Refrigeration
Occupancy	Shading	Interior partitions	Component efficiency
Space environmental conditions	Floor height	Internal mass	Control settings
Service hot water demand	Orientation	Infiltration	
Operating schedules			

Figure 13: Building energy model input categories [3].

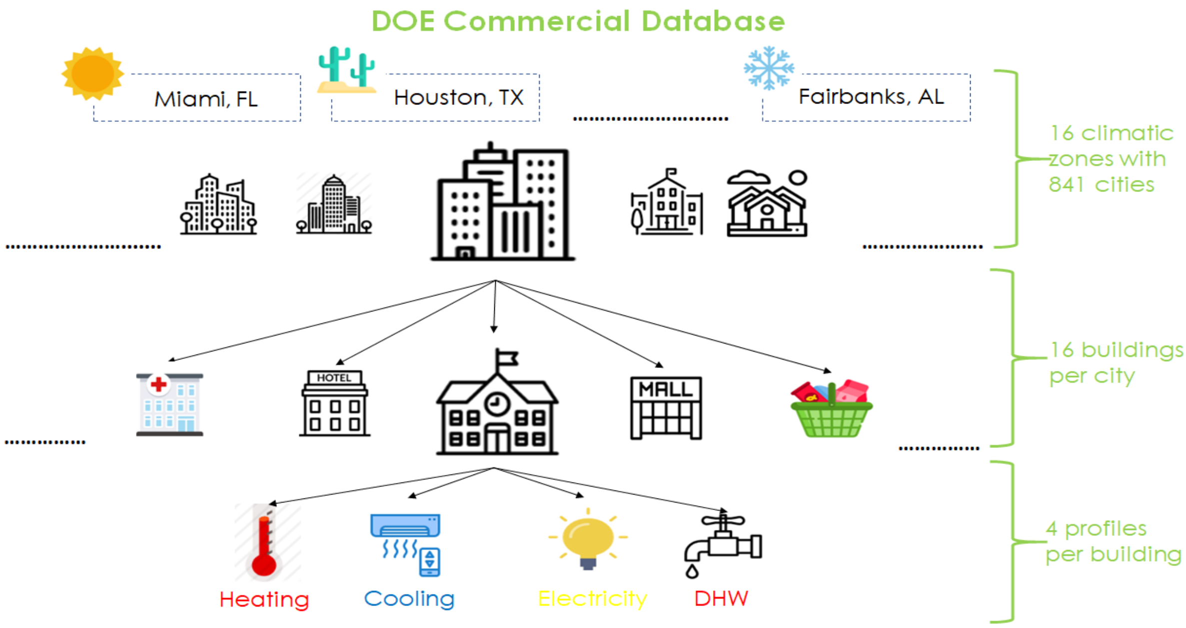

Figure 14: DOE Database scheme.

To sum up, the four users in the case study of this work have within the database 841 profiles for each type of energy need. In other words, before doing the actual transposition, it is necessary to select a reference city to have the starting profiles.

4.1.2 Profiles transposition: Reference city selection

It is expected that the more two zones are climatically similar, the more the load profiles shape will be analogous. Please note that this is true especially for heating and cooling demands, while the electricity one results obviously much less affected. In the DOE database, there are plenty of buildings in several American cities, thus the climate is the parameter taken under consideration.
The American city whose weather conditions are more similar to those of the province of Turin, where the EC is located, has been selected. Since it would be very time expensive to assess quantitatively and in detail 841 cities, at the beginning a qualitative analysis has been performed to eliminate some possibilities. Considering a city like Miami (FL) or Fairbanks (AL) would be unnecessary, being them very different in weather with respect to Turin.
According to the climatic classification provided by Köppen, Turin is classified as *Cfa*: the coldest month average temperature is between −3°C and 18°C, that of the hottest is more than 22°C and it rains every month [9]; therefore, only a subset of U.S. cities belonging to this zone is considered. Since the DOE database is based on the Briggs classification, it is useful to establish a connection between the two divisions [Fig. 15].

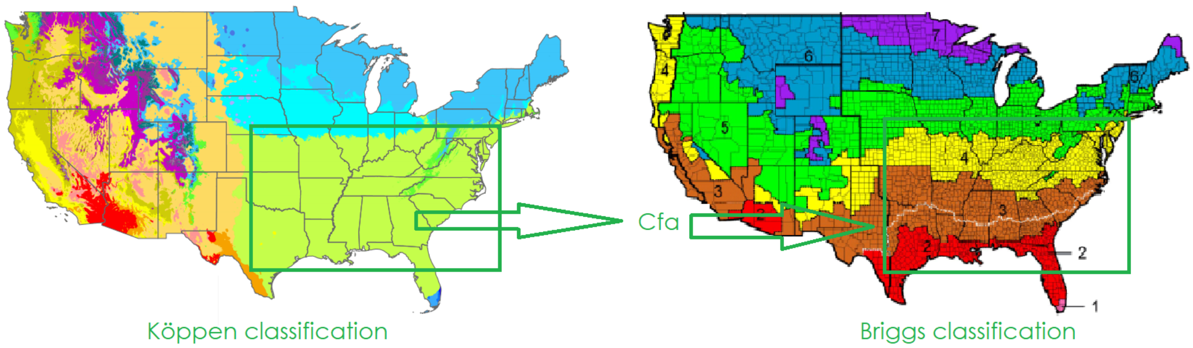

Figure 15: From Köppen to Briggs classification.

As it is shown, U.S. *Cfa* area can be identified with good approximation in the south-east Briggs zone 2,3 and 4, reducing the cities from 841 to 232. Nevertheless, being this number still too much, a list of 15 cities [3] dispersed in this area has been extrapolated; only such cities will be analyzed quantitatively to find the location from which load profiles can be created.

City	Zone	City	Zone	City	Zone
Atlanta, GA	3A	Indianapolis, IN	4B	Oklahoma City, OK	3A
Montgomery, AL	3A	Louisville, KY	3B	Jefferson, MO	4A
Little Rock, AR	3A	Nashville, TN	4A	New Orleans, LA	2B
Salt Lake City, UT	4C	Jackson, MS	3A	Charlotte, NC	3A
Houston, TX	2A	Lincoln, NE	4C	Columbia, SC	3A

Table 3: List of the 15 cities to be quantitatively assessed.

To select in this list the most similar city to Turin, some indicators must be defined. Heating Degree Days (HDD) and Cold Degree Days (CDD) measures how much the external temperature is different from a reference comfort value in winter and summer respectively. In other words, they are two climatic parameters strongly bonded with the heating and cooling demands. More precisely, they are defined as the sum, extended to a whole year, of the daily differences between the average daily temperature and the comfort one:

$$HDD = \sum_{i=1}^{365} max(T_{w,comf} - \bar{T}_i; 0) \tag{4}$$

$$CDD = \sum_{i=1}^{365} max(\bar{T}_i - T_{s,comf}; 0) \tag{5}$$

Being $\bar{T}_i$ the average temperature of the generic day i, $T_{w,comf}$ and $T_{s,comf}$ the internal winter and summer temperatures, set equal to 20°C and 24°C.
Therefore, with the weather database of PVGIS [10] which provides the external temperature hourly profile for every location, it is possible to evaluate HDD and CDD for every U.S. location and Turin with a simple algorithm. Finally, to validate the calculations, for Turin a check with the HDD value provided in the Italian legislation (DPR 1993/412) is reported.
Since the difference between Turin and a generic U.S. city has to be computed, the following parameter is defined:

$$\Delta_{HDD} = \frac{|HDD_{US} - HDD_{TO}|}{HDD_{TO}} \tag{6}$$

It measures the relative difference: the higher it is, the more the weather of the American location is different. The structure of eq. 6 is applied similarly to calculate the Δ_{CDD}.

To further refine the list of possible cities threshold values of 0.2 and 0.5 are established for HDD and CDD respectively. For such cities, a deeper comparison on monthly average temperatures and hourly profiles in the hottest (July) and coldest (January) month is necessary [see Section 5.1.1].
To sum up, at the end of this phase, the starting heating, cooling, electricity and DHW load profiles are known, having so the general profile shape.

4.1.3 Profiles transposition: Profiles scaling

The DOE database contains hourly *consumption* profiles expressed in kW; therefore, to obtain *demand* profiles for heating, cooling and DHW the yields of the devices have to be considered. The strategy used to create Italian profiles differs depending on the building type, distinguishing between residential and commercial, as the data availability is different.
The procedure aims at scaling the power profiles, without modifying the shape and the control logic. After the scaling, profiles will be expressed in W/m^3 to make easier comparisons with the results already available in the literature.

Residential User

The heating request depends on several factors, such as external temperature, building shape (S/V ratio), U-value, windows position, building orientation, etc. To create a

time expensive methodology considering all these elements is far from the objectives of this work, thus only the more important has been taken into account. Therefore, the profile has been scaled to external temperature (HDD) and U-value, assuming in the first approximation that the shape factor does not change among U.S. and Turin.
Nevertheless, the HDD normalization has been done not simply multiplying the U.S. profile by the ratio HDD_{TO}/HDD_{US}. On the contrary, using the DOE database, a function expressing the heating request as the parameter HDD vary is created. HDD and specific heating demand $[kWh/m^3]$ are known for the 16 climatic zones [Fig. 12]; hence, by interpolating these 16 points, it is possible to create a mathematical function $H = f(HDD)$. By applying it to Turin and the selected U.S. city, the scaling factor is obtained:

$$wf_{h,HDD} = \frac{H(HDD_{TO})}{H(HDD_{US})} \tag{7}$$

It is worth noting that to introduce a function also for the U-value factor would not have made sense. Such expression would have been created by interpolating again the specific heating demand for the 16 climatic zones with their U-value [Fig. 12] and, since heating needs are higher in colder zones where U-value are lower, the final result would have been that the lower the transmittance of a building, the higher its heating demand, which is logically a nonsensical statement. The absurd derives from the DOE streamlining to consider all the user of a climatic zone featured by the same U-value. Hence, the U-value weighting factor is simply defined as the ratio between the Italian and the American value:

$$wf_{h,U} = \frac{U_{TO}}{U_{US}} \tag{8}$$

This factor takes into account different materials used for building houses; for instance, in the U.S.A. wood is much more used compared to Italy, where bricks and concrete are the masterpieces. Moreover, the buildings simulated by the DOE have been modeled taking as reference new building standards (2004) while the large majority of Turin dwellings dates back to the 50s and 60s [11]. Both these factors cause a lower envelope efficiency (i.e. a weighting factor bigger than one) in Turin. U_{US} is calculated using the data provided by the DOE in [3], considering also the building dimensions [Fig. 11], being the final U-value the area-weighted average of the single roof and wall transmittances. The complete formula is:

$$U_{US} = \frac{2 \cdot U_{wall,US} \cdot h \cdot (a+b) \cdot NF + U_{roof,US} \cdot A_r}{2 \cdot h \cdot (a+b) \cdot NF + A_r} \tag{9}$$

Where NF is the number of floors, h is the height of a room, a and b are the length and the width of the building and A_r is the roof area. Given the data reported in Fig. 11, these dimensions are:

$$a = \frac{\sqrt{A_f}/NF}{AR} \tag{10}$$

$$b = a \cdot AR \tag{11}$$

$$A_r = \frac{A_f}{NF} \tag{12}$$

Where AR is the Aspect Ratio and A_f is the floor area; the last equation is valid if the roof is considered flat. The transmittance values are $U_{wall,US} = 0.704\, W/m^2/K$ and $U_{roof,US} =$

$0.193\,W/m^2/K$. With the hypothesis of the same dimensions, U_{TO} can still be computed with the (9), substituting $U_{wall,TO} = 1.40\,W/m^2/K$ and $U_{roof,TO} = 1.10\,W/m^2/K$ [12]. These values have been chosen to consider a house built in the period 1946-1975, since about 42% dwellings in the province of Turin date back to these years [11].
The hourly heating profile in W/m^3 for a condominium placed in Turin is given by:

$$p_{h,TO}(i) = \frac{P_{h,US}(i) \cdot wf_{h,U} \cdot wf_{h,HDD} \cdot \eta_b \cdot 10^3}{V} \tag{13}$$

where i indicates the generic hour and it ranges from 1 to 8760, V $[m^3]$ is the condominium volume, $P_{h,US}$ $[kW]$ represents the energy consumption of the simulated U.S. building and $\eta_b = 0.8$ [3] is the gas condensing boiler yield, which transforms kW of consumed gas into kW of heating needs.

The procedure adopted for the cooling profile is basically the same. Logically, the function that takes into account the external temperature is based on CDD:

$$wf_{c,CDD} = \frac{C(CDD_{TO})}{C(CDD_{US})} \tag{14}$$

In this case the U-value is not considered, since it has a not so relevant impact on cooling needs. The hourly W/m^3 profile is given by:

$$p_{c,TO}(i) = \frac{P_{c,US}(i) \cdot wf_{c,CDD} \cdot SEER \cdot 10^3}{V} \tag{15}$$

Please note that $P_{c,US}$ $[kW]$ represents the electricity consumption used for the cooling demand, so, to get the demand, a SEER (Seasonal Energy Efficiency Ratio) is introduced, assumed equal to 3.28 [3].

The methodology adopted to normalize electricity and DHW profiles is slightly different. The electricity demand is not scaled by factors affecting the request, but rather on the comparison with Italian standards consumption.
Indeed, the scaling is based on the consumption of the typical user provided by the national authority. The typical domestic user, a family of 2.7 people, consumes every year $E_{el,y} = 2,700\,kWh$ [13]. The weighting factor is defined as:

$$wf_{el} = \frac{E_{el,y} \cdot ND}{\sum_{i=1}^{8760} P_{el,US}(i)} \tag{16}$$

Where $ND = 28$ is the number of dwellings in the DOE condominium [9], while the denominator represents the total energy of the American building. The final profile is:

$$p_{el,TO}(i) = \frac{P_{el,US}(i) \cdot wf_{el} \cdot 10^3}{V} \tag{17}$$

Finally, in order to scale the Domestic Hot Water (DHW) profile, the legislation UNI 9182/14 about the design of domestic water systems establishes a consumption of $60\,lt/day/person$. Considering 3 people in every house, the total building yearly DHW demand $[kWh]$ can be computed with:

$$E_{DHW,y} = 3 \cdot ND \cdot 60 \cdot 365 \cdot c_p \cdot (T_{use} - T_{mains}) \tag{18}$$

Where $c_p = 0.0012\,kWh/lt/K$ is the water specific heat, $T_{use} = 45°C$ is the set point value and $T_{mains} = 15°C$ is the tap water temperature. Thus, by proceeding in the same way as for electricity, the weighting factor and the final profile are:

$$wf_{DHW} = \frac{E_{DHW,y}}{\sum_{i=1}^{8760} P_{DHW,US}(i)} \tag{19}$$

$$p_{DHW,TO}(i) = \frac{P_{DHW,US}(i) \cdot wf_{DHW} \cdot \eta_b \cdot 10^3}{V} \tag{20}$$

The hourly load profiles for the condominium can be obtained with this procedure.

Commercial Users

The procedure for the office, supermarket, and mall profiles presents some differences. Firstly, DHW consumption has been neglected, since the DOE did not even calculate it. Secondly, due to the lacking of a precise indication for electricity consumption and scarcity of significant data in the literature, the DOE profile has been directly taken without being scaled. Anyway, when the results will be presented and discussed, some comparisons with the profiles available in the existing literature are reported to support these choices.
Only two profiles have been scaled. For heating, the eq. (7), (8) and (13) are still valid and the same is true for cooling with the (14) and the (15). The only difference is in the U-value: for U.S. buildings the eq. (9) works again and the result does not change, depending it only on the climatic zone, while $U_{TO} = 1.6\ W/m^2/K$ has been taken from a study on the non-residential building stock [14].

4.2 EC building modeling

In this paragraph, the geometric features of the four buildings are described. Such data are essential, besides to determine the final loads, also to understand the size of the PV that could be installed, since it is bounded by the roof surface.

As far as the condominium is concerned, it has been considered a typical building of six floors ($N_f = 6$), each one with two dwellings ($ND = 12$). Every dwelling is $h = 3\,m$ high with a gross floor area $A_f = 120\,m^2$. So the total volume to be satisfied is given by:

$$V = N_d \cdot A_f \cdot h \tag{21}$$

And the total roof surface available for PV is:

$$A_r = 2 \cdot A_f \tag{22}$$

To have an idea of the building shape, the factor S/V can be evaluated. Assuming square-plan houses, it is equal to:

$$\frac{S}{V} = \frac{2 \cdot [2 \cdot A_f + 3 \cdot \sqrt{A_f} \cdot h \cdot N_f]}{V} \tag{23}$$

The result is $S/V = 0.38$. Table 4 sums up the data of all buildings
The last column of the table shows the ratio between the roof area and the building volume and it is a geometric indicator that gives an idea of the self-sufficiency (i.e. the ratio between the energy locally consumed and that required in a year). Indeed, A_r describes how many PV panels can be installed, while V gives an idea of the load.

Building	N_f $[-]$	V $[m^3]$	A_r $[m^2]$	A_r/V $[m^{-1}]$
Condominium	6	4320	240	0.055
Office	12	19000	800	0.042
Supermarket	1	3714	780	0.210
Mall	2	5976	1500	0.251

Table 4: Geometric features of the buildings.

4.3 Technologies modeling

Suitable technologies must be inserted to meet the demand. At the beginning, buildings are hypothesized outfitted with old devices without producing electricity: Business As Usual (BAU) scenario. Starting from this situation, a retrofit has been implemented: new and more efficient technologies have been installed in the buildings which have become prosumers. Associating every machinery with a specific building is essential, as in the SSCs configuration each one operates separately. A picture of the EC, showing instead how the users collectively act, is reported in Fig. 16.
For each user, the retrofit is performed as follows, schematized in Fig.17:

- **Condominium**: The BAU scenario consists of a traditional configuration with a gas boiler and an electrically-driven air conditioning system. While maintaining both these devices, a rooftop PV and a HP have been added to promote the electrification of the building final energy uses.

- **Office**: In the BAU, the situation is the same as the condominium; however, here the pre-existing cooling system has been eliminated, being a reversible HP installed for both heating and cooling. The gas boiler has been kept, while PV panels have been added.

- **Supermarket**: This is the building where fewer interventions take place. PV has been installed, but the gas boiler and the old cooling system are still active.

- **Mall**: Here a complete change in technologies has taken place. Both old heating and cooling system have been replaced by a CCHP (Combined Cooling Heating and Power), consisting of an internal combustion engine coupled with an absorption chiller to recover the waste heat also in summer: this device could obtain the HEC classification. Finally, PV has been placed also in this building.

In the next pages, the modeling equations of each technology are explained. It is worth underlining that the condominium and the office heating demand are simultaneously meet through the old boiler and the new HP (see Fig. 17); therefore an optimization algorithm to maximizes the HP capacity factor has been developed to model such integration.

4.3.1 Photovoltaic panels (PV)

PV modeling did not present any particular innovation on the modeling side. The formula through which the output AC power can be evaluated is:

$$P_{PV}(i) = A_{PV} \cdot \eta_{PV}(i) \cdot G_T(i) \cdot \eta_{inv} \tag{24}$$

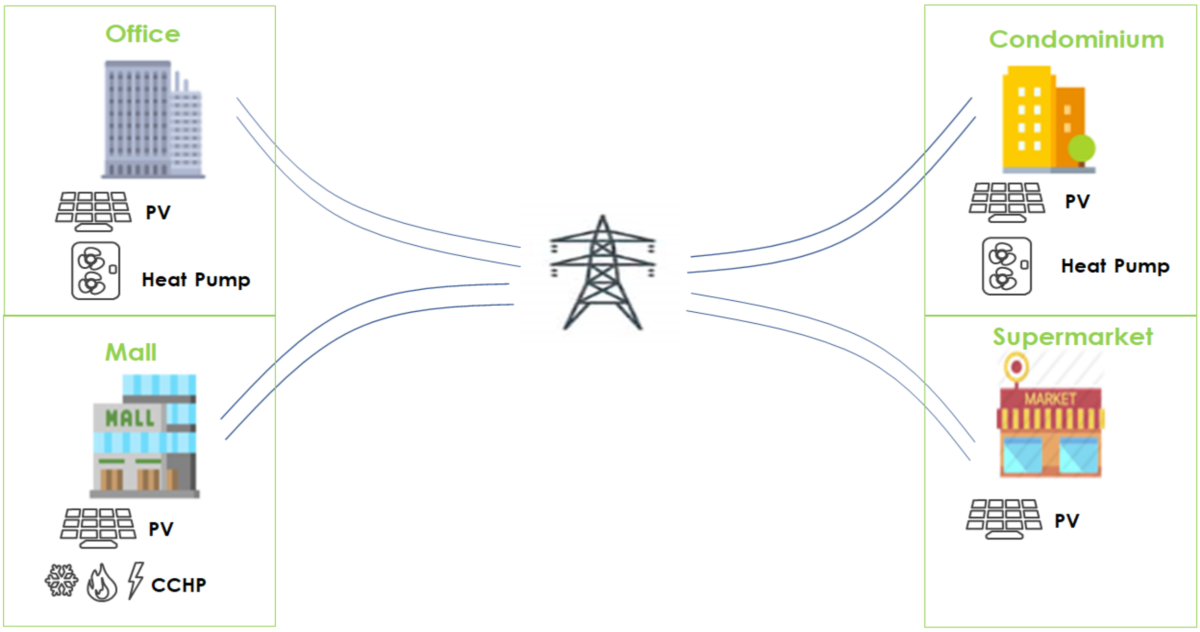

Figure 16: EC configuration highlighting the new technologies

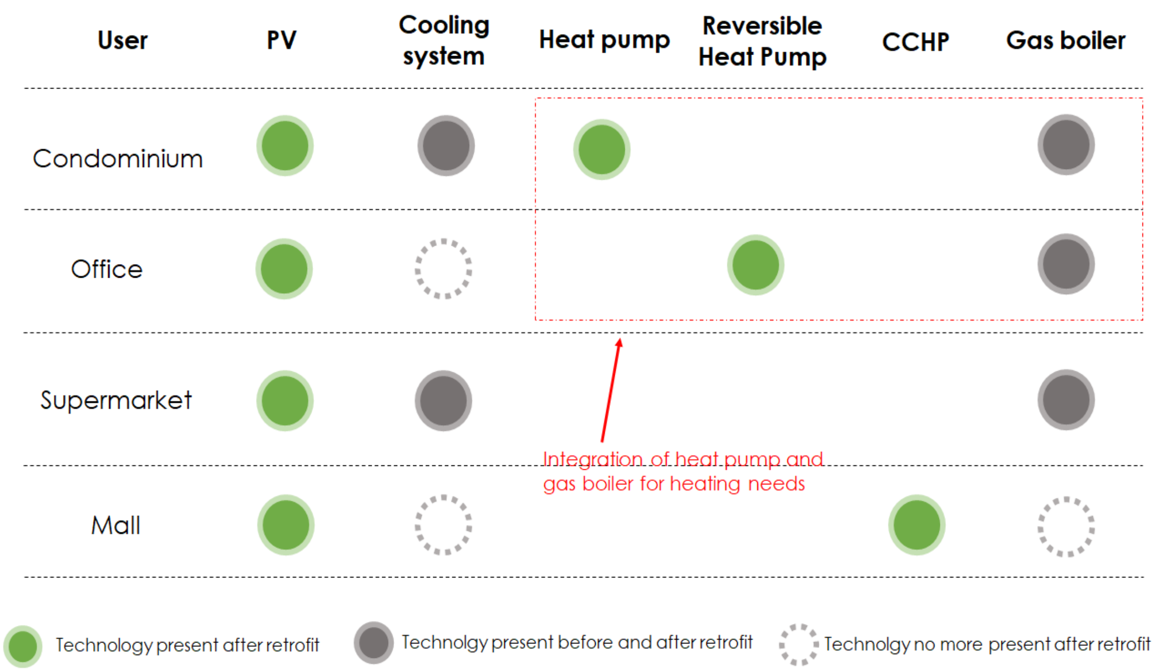

Figure 17: Retrofit in each EC user

A_{PV} is the total surface, a parameter that will be subjected to a final sensitivity analysis. η_{PV} is the panel efficiency, η_{inv} (equal to 0.9) is the inverter efficiency allowing the conversion from DC to AC power and G_T is the total perpendicular incident solar radiation per unit area.

The solar-to-power efficiency η_{PV} is function of several variables, such as the intensity of the solar radiation, the cell temperature and the angle formed by the Sun with respect to the zenith [15]. In this case, only the first parameter is considered, following the indications provided by the company *LG Electronics* in [16]. They suggest a yield of 20.8% at 1000 W/m^2 which decreases by 4.5% if the radiation passes from 1000 W/m^2 to 200 W/m^2. A linear interpolation has been made between these two points, thus the efficiency expression is:

$$\eta_{PV}(G_T(i)) = 0.1986 + 1.175 \cdot 10^{-5} \cdot (G_T(i) - 200) \tag{25}$$

Therefore, knowing the incident radiation G_T hour by hour allows to compute the electricity produced by the PV. Such profile depends mainly on three angles: the latitude Φ (45.11° for Turin), the tilt β and the orientation γ of the arrays. There are several models through which $G_T(i)$ can be extracted [17]; for this work, the one proposed by ASHRAE [18] has been implemented. The formula is:

$$G_T(i) = G_{bn}(i) \cdot \cos\theta(i) + G_d(i) \cdot F_{c-s} + \rho \cdot G_h(i) \cdot F_{c-g} \tag{26}$$

where $G_{bn}(i)$, $G_d(i)$ and $G_h(i)$ are the beam normal, diffuse and total horizontal radiation whose profiles are provided by PVGIS weather database [10]; $\rho = 0.2$ is the ground albedo factor, F_{c-s} and F_{c-g} are the PV-sky and PV-ground view factors respectively:

$$F_{c-s} = \frac{1+\cos\beta}{2} \tag{27}$$

$$F_{c-g} = \frac{1-\cos\beta}{2} \tag{28}$$

And $\theta(i)$ considers the relative position of the Sun respect to the panel, given by:

$$\cos\theta(i) = \cos\theta_z(i) \cdot \cos\beta + \sin\theta_z(i) \cdot \sin\beta \cdot \cos(\gamma_s(i) - \gamma) \tag{29}$$

$\theta_z(i)$ is the angle the Sun forms with the zenith and $\gamma_s(i)$ describes the angle formed between the direction and the projection of the sun on the horizontal plane:

$$\cos\theta_z(i) = \cos\Phi \cdot \cos\delta(i) \cdot \cos\omega(i) + \sin\Phi \cdot \sin\delta(i) \tag{30}$$

$$\sin\gamma_s(i) = \frac{\cos\delta(i) \cdot \sin\omega(i)}{\sin\theta_z(i)} \tag{31}$$

Where $\delta(i)$ is the angle between Earth-Sun line and Earth Equator plane and it varies with the day of the year n:

$$\delta(i) = 23.45°\left(360\frac{284+n}{365}\right) \tag{32}$$

$\omega(i)$ is the angular displacement of the Sun from the local meridian, given by:

$$\omega(i) = (ST - 12)15° \tag{33}$$

ST is the solar time of the location; it may be computed starting from the local time LT with the approximate formula:

$$ST = LT - \frac{L_{loc} - L_{ref}}{15°} - DST \tag{34}$$

With $L_{loc} = 7.67°$ as the local longitude, $L_{ref} = 15°$ as the longitude of the meridian for the local time and DST (Daylight Saving Time) equal to one when in force and zero otherwise.
By implementing eqq. from (26) to (34) in MATLAB, it is possible to create a function $G_T = f(\beta, \gamma)$ that accepts in input the tilt and the orientation (with respect to the south, positive towards west) of the panel, returning in output the perpendicular radiation profile

$[W/m^2]$. This function is very helpful for performing subsequent analyses much faster. The whole code has been written to obtain as final results the PV angles that optimize the EC economic performances by minimizing the yearly expenditures in the electricity bills [see Section 5.2.1].

4.3.2 Heat pump (HP)

Heat pumps (HP) are electrically-driven devices used to extract heat from a low-temperature source (external air in this case), transferring it to a higher temperature. In the retrofit, they have been installed to produce hot water for satisfying the condominium and office heating demand, being also used in the latter for cooling needs (reversible HP). The modeling of such a device has been the most complex, due to the integration with an already existing gas condensing boiler. As a matter of fact, design a heating system relying only on an HP is rarely the best solution [19], since it may suffer mostly two operating conditions which are the reason for a low COP (Coefficient of Performances):

- When the external temperature is too low; this implies a high difference between the hot and the cold source, forcing the HP to work with low efficiencies.
- When the load partialization is too high. Without the boiler, the nominal capacity of the HP would be chosen based on the peak demand. In this way, the HP would work for long periods in off-design conditions causing low efficiencies.

Therefore, the retrofit couples an HP with the existing gas boiler, being it the best solution. In this framework, the control logic that drives everything is rooted on the definition of a COP_{lim}. When the electricity is withdraw form the grid (not self-produced by the PV system or not in enough amount) the COP of the HP is computed knowing the temperature of the two sources and the partialization factor. If it is above a threshold value, namely COP_{lim}, the HP is switched on, alone or along with the boiler, otherwise it remains off. Since the capacity has to be chosen by following an economic optimization, the criterion that has driven this definition has been purely economic: the HP is switched off every time using the gas boiler becomes more convenient. In practice, this can be easily visualized by computing the hourly operational cost of both devices, given by:

$$C_b(i) = \frac{P_h(i)}{\eta_b \cdot LHV} \cdot c_{gas} \tag{35}$$

$$C_{HP}(i) = \frac{P_h(i)}{COP(i)} \cdot c_{el} \tag{36}$$

Where c_{gas} and c_{el} are the natural gas and electricity costs, while LHV is the lower heating value of the fuel. The HP is no more convenient when:

$$C_{HP}(i) \leq C_b(i) \rightarrow COP(i) \leq \frac{c_{el}}{c_{gas}} \eta_b \cdot LHV = COP_{lim} \tag{37}$$

To assess the COP, HP performance curves are necessary, and they have been defined by interpolating the data extrapolated from [20]. Fig. 18 shows the nominal COP as the outside air temperature changes, parameterized in the water supply temperature, while Fig. 19 represents the COP percentage reduction f due to the partialization CR_{HP}:

$$CR_{HP}(i) = \frac{P_h(i)}{P_{th,max}(i)} \tag{38}$$

Where $P_h(i)$ is the heating demand and $P_{th,max}(i)$ is the maximum thermal power deliverable by the HP, provided again by [20] [Fig. 20], according to the temperature of the sources.

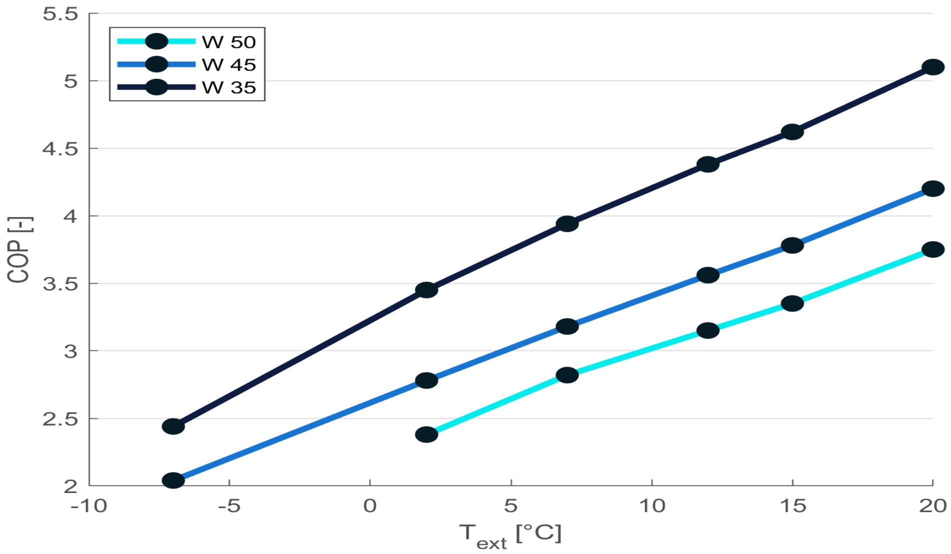

Figure 18: Nominal COP as the temperature sources vary.

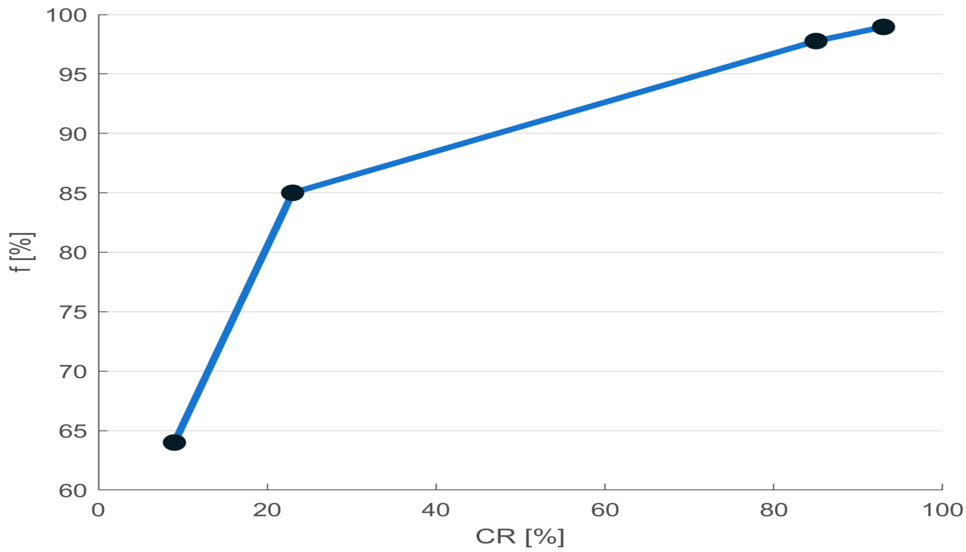

Figure 19: Percentage reduction of the nominal COP due to partialization.

The hot water supply temperature can be evaluated starting from the external temperature through a climate curve, namely a control system that establishes such temperature according to the signal of an external thermostat. The chosen curve has the expression:

$$T_w(i)[°C] = 24 - \frac{50-24}{28}(T_{ext}(i)[°C] - 20) \tag{39}$$

Therefore, knowing the external temperature profile, it is possible to obtain the supply temperature one. With these data, using interpolation equations provided in the DM 26/06/2015, the nominal COP can be evaluated. More precisely, to interpolate between the hot source temperatures $T_{h,1}$[°C] and $T_{h,2}$[°C] in which the COPs are known, fixed

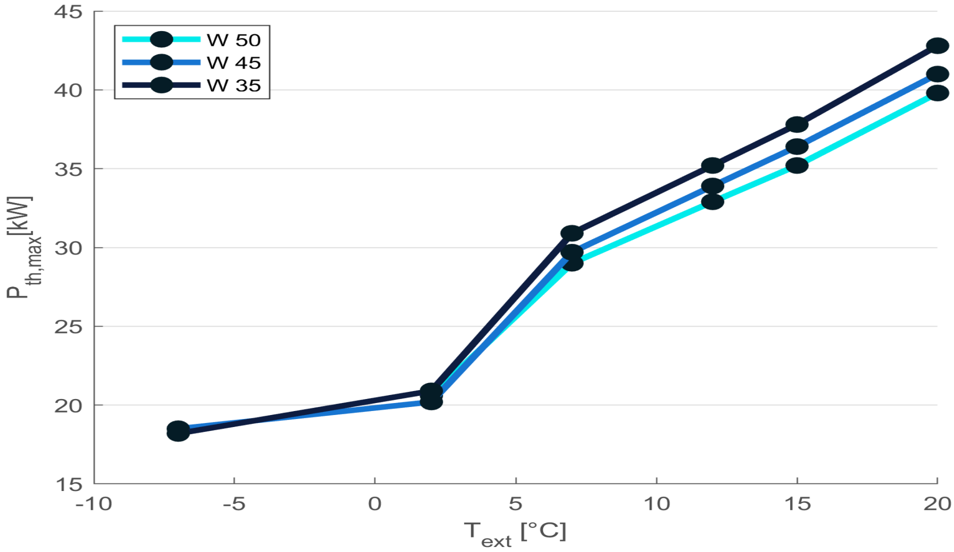

Figure 20: Maximum thermal power deliverable by the HP.

that of the cold source T_c[°C], the following equations have been applied and the COP_{nom} at T_c and T_h [21]:

$$\eta_{II,1} = \frac{COP_1}{\frac{T_{h,1} + 273.15}{T_{h,1} - T_c(i)}} \tag{40}$$

$$\eta_{II,2} = \frac{COP_2}{\frac{T_{h,2} + 273.15}{T_{h,2} - T_c(i)}} \tag{41}$$

$$\eta_{II}(i) = \eta_{II,1} + (\eta_{II,2} - \eta_{II,1}) \cdot \frac{T_h(i) - T_{h,1}}{T_{h,2} - T_{h,1}} \tag{42}$$

$$COP_{nom} = \eta_{II}(i) \cdot \frac{T_h(i) + 273.15}{T_h(i) - T_c(i)} \tag{43}$$

Hence, the $COP_{nom}(i)$ and $P_{th,max}(i)$ are evaluated. Then, with eq. (38) and Fig. 19, $CR_{HP}(i)$ and $f_{HP}(i)$ are computed. Thus, the real $COP(i)$ is:

$$COP(i) = f_{HP}(i) \cdot COP_{nom}(i) \tag{44}$$

The HP efficiency is known every hour of the year. With these definitions, the algorithm can start and two cases may happen:

- *The $COP(i)$ is below the threshold*: if PV panels are not producing electricity, the boiler fully meets the demand. Instead, if they can feed the HP, it is switched on to enhance the self-consumed energy and it can work alone or in cooperation with the boiler.

- *The $COP(i)$ is above the threshold*: it is more convenient to use the HP. If the coefficient $CR_{HP}(i)$ is equal to one, it means that the HP works in the nominal condition integrated with the boiler, while, if $CR_{HP}(i)$ is smaller, the HP can work alone.

The final algorithm [Fig. 21] result is the hourly scheduling of the HP $P_{h,HP}(i)$. The capacity factor of the device is thus computed as:

$$F_{HP} = \frac{\sum_{i=1}^{8760} P_{h,HP}(i)}{\sum_{i=1}^{8760} P_h(i)} \tag{45}$$

Running the algorithm with different HP sizes, at the end the one with the highest F_{HP} (or the highest $\sum_{i=1}^{8760} P_{h,HP}(i)$) has been installed, since it will work the greatest number of hours and, due to the chosen control logic, it is also the most convenient choice.

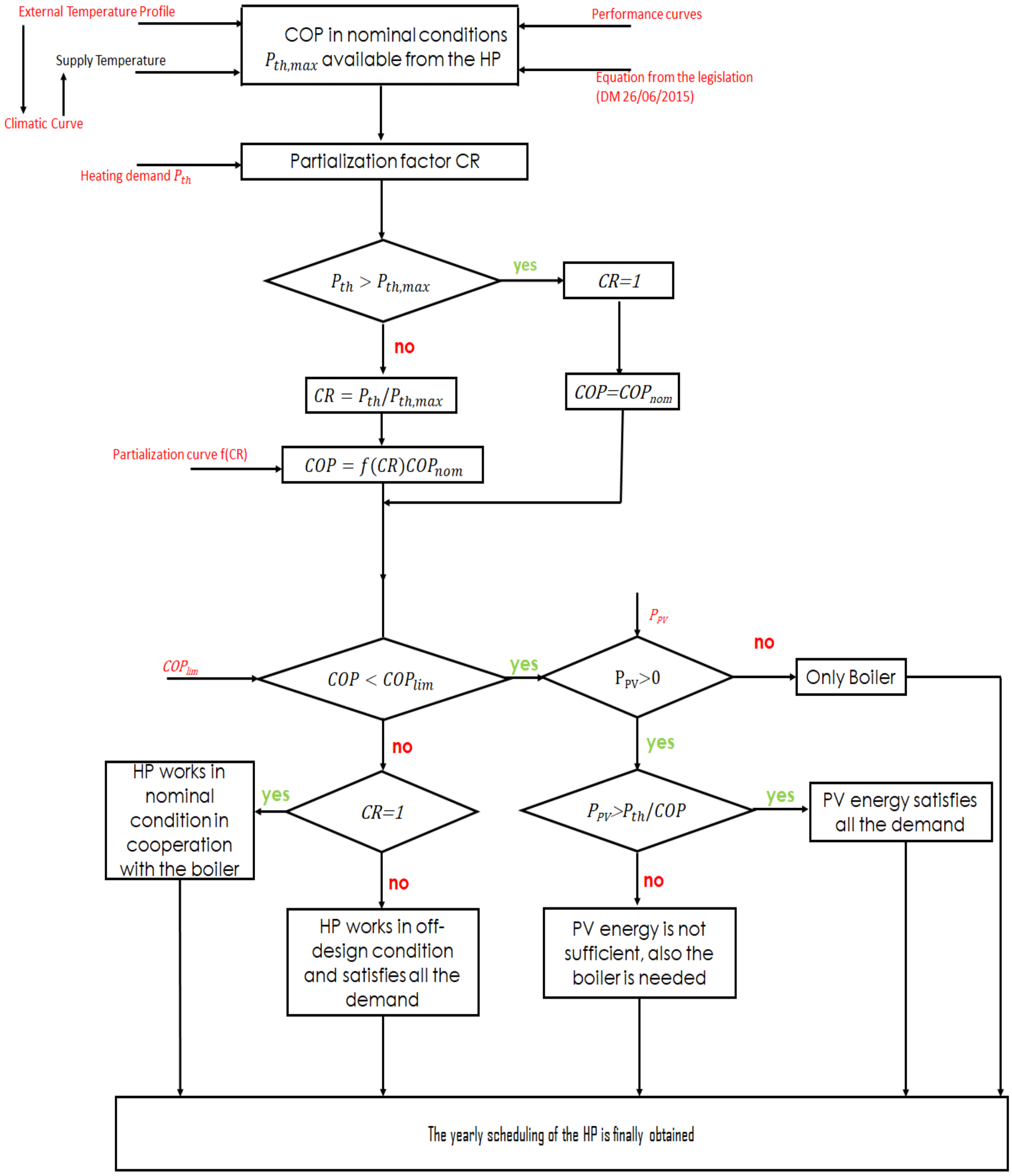

Figure 21: Optimization HP algorithm flow chart

It is important to remember that in the office the HP has to meet also the cooling needs, being it reversible. For this optimization, the algorithm needs an additional constraint: since the HP is the only technology aimed at satisfying the cooling demand, its cooling capacity must be higher than the cooling peak demand $P_{c,max}$. The mathematical expression of such constraint is:

$$P_{c,max,HP} \geq P_{c,max} \tag{46}$$

Where $P_{c,max,HP}$ is the HP cooling capacity, usually slightly smaller than its size (i.e. the maximum deliverable power in heating mode).

4.3.3 CCHP system

The CCHP system is based on a gas-fed internal combustion engine that produces electricity and hot water using the hot exhaust gas and the engine cooling system. Such hot water in winter can be directly used for heating purposes, while in summer, so as not to lose the cogeneration effect, it can feed an absorption chiller, to convert the heat into chilled water for cooling needs.

The scheduling of the CCHP system is quite simple: it has been designed to do *thermal demand following* in every moment. Based on the mall demand, it satisfies always the heating and cooling loads; the amount of gas to be burnt and the power output is thus determined accordingly.
The gas-to-electricity yield η_e has been considered a function of the external temperature and the partialization. As a matter of fact, according to the ideal gas law, when the temperature rises the density decreases, forcing the engine cylinders to work with a lower amount of air mass, producing less power. Therefore, knowing the external temperature, it is possible to evaluate the efficiency in design condition $\eta_{e,nom}$ and then, multiplying it by a factor that depends on partialization, the actual efficiency η_e is computed.
The thermal efficiency depends only on partialization, being it constant and equal to $\eta_{th,nom} = 0.471$ in design condition. The absorption chiller efficiency has been considered always equal to an average value of $\eta_{ch} = 0.74$ [22].
The following curves represent the efficiency reduction factor f due to partialization [Fig. 22] and the nominal value of the electrical efficiency as T_{ext} varies [Fig. 23] [23].

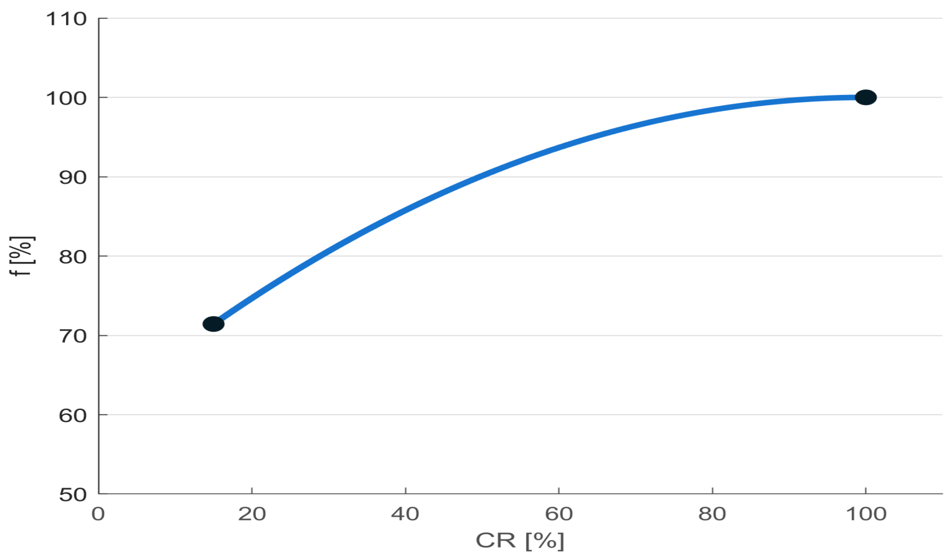

Figure 22: Efficiency reduction factor in off-design conditions.

The power output of the CCHP system can be evaluated by using the following equations. Firstly, the partialization factor is needed:

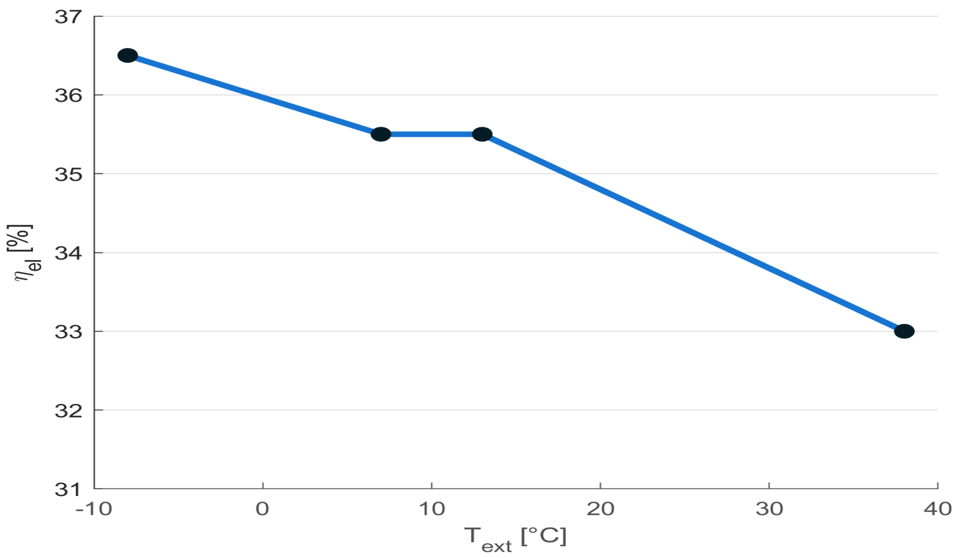

Figure 23: Nominal value of η_e as T_{ext} varies.

$$CR_{CCHP}(i) = \frac{P_h(i)}{P_{h,max}} \tag{47}$$

Where $P_{h,max}$ is the yearly peak of the CCHP thermal production, while P_h corresponds to:

- The heating load in winter;
- the thermal power input in the absorption chiller in summer, namely the cooling demand multiplied by the chiller yield.

So it is possible to evaluate the thermal and electrical yield:

$$\eta_{th}(i) = f(CR_{CCHP}(i)) \cdot \eta_{th,nom} \tag{48}$$

$$\eta_e(i) = \eta_{e,nom}(T_{ext}(i)) \cdot f(CR_{CCHP}(i)) \tag{49}$$

The hourly natural gas power entering the CCHP system is:

$$P_{fuel}(i) = \frac{P_h(i)}{\eta_{th}(i)} \tag{50}$$

And finally the power electrical output is:

$$P_{CCHP}(i) = P_{fuel}(i) \cdot \eta_e(i) \tag{51}$$

4.4 Power flow modeling and energy KPIs

After the retrofit, in the SSCs configuration, each building is characterized with five different power profiles; being j the generic user, there are: the requested power $P_{req,j}(i)$, the produced power $P_{prod,j}(i)$, the self-consumed power $P_{self,j}(i)$, the fed into the grid power $P_{exp,j}(i)$ and the withdrawn power $P_{imp,j}(i)$.
With these profiles, it is possible to define the following Key Performance Indicators (KPIs) to assess how each building works alone:

- *Self-Sufficiency* (SS): the ratio between the self-consumed and the requested energy. It describes the user capability to be independent of outside (it may be also called *autarky*):

$$SS_j = \frac{\sum_{i=1}^{8760} P_{self,j}(i)}{\sum_{i=1}^{8760} P_{req,j}(i)} = \frac{E_{self,j}}{E_{req,j}} \tag{52}$$

- *Self-Consumption* (SC): the ratio between the self-consumed and the produced energy. It indicates the capability to consume locally the available power, it is always smaller than one:

$$SC_j = \frac{\sum_{i=1}^{8760} P_{self,j}(i)}{\sum_{i=1}^{8760} P_{prod,j}(i)} = \frac{E_{self,j}}{E_{prod,j}} \tag{53}$$

In order to have a unique value for the SSCs scenario to compare with the EC, a single indicator is defined by doing a weighted average on the requested energy for SS and on the produced one for SC respectively:

$$SS = \frac{\sum_{j=1}^{4} SS_j \cdot E_{req,j}}{\sum_{j=1}^{4} E_{req,j}} \tag{54}$$

$$SC = \frac{\sum_{j=1}^{4} SC_j \cdot E_{prod,j}}{\sum_{j=1}^{4} E_{prod,j}} \tag{55}$$

With the evaluation of these numbers, the simulation of the buildings in the SA configuration has been completed. The algorithm to create an EC is logically based on the idea to enhance the self-consumed energy by aiding the exchange among its members. Thus, if it exists at the same time a user that is importing and another which instead is exporting power, the second can feed the first, avoiding the interaction with the external grid, increasing self-consumption and saving finally more money. More precisely, the algorithm is structured as follows.
In every hour of the year i, if both $P_{imp}(i) = \sum_{j=1}^{4} P_{imp,j}(i)$ and $P_{exp}(i) = \sum_{j=1}^{4} P_{exp,j}(i)$ are bigger than zero, there is the possibility to implement an internal exchange and two cases may arise:

- $P_{imp}(i) > P_{exp}(i)$, therefore:

$$P_{self,EC}(i) = P_{self}(i) + P_{exp}(i) \tag{56}$$

$$P_{imp,EC}(i) = P_{imp}(i) - P_{exp}(i) \tag{57}$$

$$P_{exp,EC}(i) = 0 \tag{58}$$

- $P_{exp}(i) > P_{imp}(i)$, therefore:

$$P_{self,EC}(i) = P_{self}(i) + P_{imp}(i) \tag{59}$$

$$P_{exp,EC}(i) = P_{exp}(i) - P_{imp}(i) \tag{60}$$

$$P_{imp,EC}(i) = 0 \tag{61}$$

The self-consumed power takes advantage from either the power withdrawn or the fed one. At the end, five new profiles are obtained for the EC: $P_{req,EC}(i)$, $P_{prod,EC}(i)$, $P_{self,EC}(i)$, $P_{exp,EC}(i)$ and $P_{imp,EC}(i)$. By applying again eqq. (52) and (53) it is possible to evaluate SS and SC also for the EC, making the comparison with the SSCs values. Fig. 24 shows a scheme of the algorithm just described.

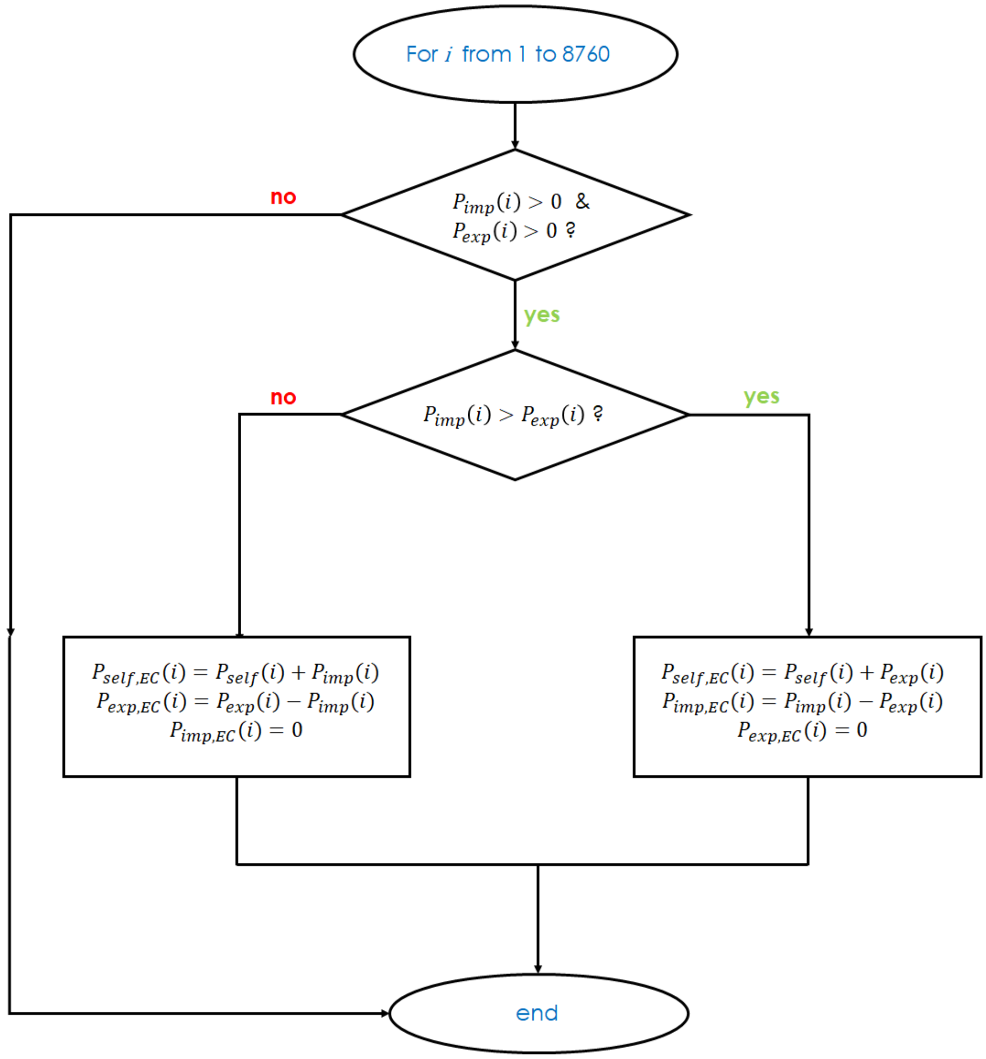

Figure 24: Flow chart of the EC algorithm

It is worth noting that the relative difference of SS and SC in the two configurations will be the same, as they are bonded by the *Production-Load* ratio P/L [24]:

$$P/L = \frac{SS}{SC} = \frac{E_{self}/E_{req}}{E_{self}/E_{prod}} = \frac{E_{prod}}{E_{req}} \tag{62}$$

Such a ratio remains constant since no changes are expected in the total yearly load and production.

4.5 Economic KPIs

With data coming from the simulations, the economic assessment can be carried out. The SSCs-EC comparison has been done in different economic scenarios, but the equations reported here are valid in each one. This paragraph describes firstly how the yearly bills expenditures have been computed before (the BAU scenario) and after (SSCs and EC configurations) the retrofit. Thus, the saved money of the two improved system can be compared. Then, a cash flow analysis has been performed to evaluate the investment as a whole.

4.5.1 Yearly bills expenditure definition

The equations used in the three scenarios (BAU, SSCs and EC) to compute the yearly bills expenditure are the following:

- **BAU scenario**: All the users do not produce energy, so every year they paid a certain amount of money directly proportional to the gas C^0_{gas} and the electricity C^0_{el} they withdraw. Before the retrofit, gas boilers to satisfy heating demand and traditional electrically-driven cooling system are installed. Therefore, the expenses incurred by the general user j are:

$$C^0_{j,gas} = \frac{\sum_{i=1}^{8760} P_{h,j}(i)}{LHV \cdot \eta_b} \cdot c_{gas} \tag{63}$$

$$C^0_{j,el} = \left[\frac{\sum_{i=1}^{8760} P_{c,j}(i)}{SEER} + \sum_{i=1}^{8760} P_{el,j}(i) \right] \cdot c_{ee} \tag{64}$$

  $\eta_b = 0.88$ and $SEER = 3.28$ are again the average devices efficiency.

- **SA scenario**: As far as the gas is concerned, the equation to be used depends on the specific user since different devices have been installed.

  Where HPs (i.e. condominium and office) are present, being $P_{h,HP,j}(i)$ the instantaneous heating demand fraction met by them, the gas expenditures C^{SSCs}_{gas} are reduced according to the following expression:

$$C^{SSCs}_{j,gas} = \frac{\sum_{i=1}^{8760} P_{h,j}(i) - \sum_{i=1}^{8760} P_{h,HP,j}(i)}{LHV \cdot \eta_b} \cdot c_{gas} \tag{65}$$

  In the mall, instead, the gas is used to feed the CCHP system:

$$C^{SSCs}_{j,gas} = \frac{\sum_{i=1}^{8760} E_{fuel}(i)}{\eta_b \cdot LHV} \cdot c_{gas} \tag{66}$$

  Finally, the supermarket retrofit has been performed in such a way the gas consumption has not been modified, thus:

$$C^{SSCs}_{j,gas} = C^0_{j,gas} \tag{67}$$

  Regarding the electricity expenditures C^{SSCs}_{el}, the equation is the same for all the users:

$$C_{j,el}^{SSCs} = \left[\sum_{i=1}^{8760} P_{req,j}(i) - \sum_{i=1}^{8760} P_{self,j}(i) \right] \cdot c_{ee} - Sales \tag{68}$$

The term *Sales* represents the monetary contribution related to the sold energy. Since a full understanding of it is crucial for the final results, a detailed description has been reported in Section 4.5.2.

- **EC scenario**: There are no reasons why gas expenditure C_{gas}^{EC} should change, as each building is independent of others with respect to this energy carrier, therefore:

$$C_{gas}^{EC} = \sum_{j=1}^{4} C_{gas,j}^{EC} = \sum_{j=1}^{4} C_{gas,j}^{SSCs} \tag{69}$$

The electricity expenditures C_{el}^{EC} are computed with an expression similar to the (68), but with an additional term:

$$C_{el}^{EC} = \sum_{i=1}^{365} P_{with,EC}(i) \cdot c_{ee} - Sales + AC \tag{70}$$

The new term AC refers to the possibility for the EC to pay Additional Charges on the internally exchanged energy passing through the public grid:

$$AC = p \cdot \sum_{i=1}^{365} P_{self-ind,EC}(i) \cdot (c_{el,tr} + c_{el,sys}) \tag{71}$$

Where $P_{self-ind,EC}(i)$ is indeed the indirect self-consumption or, in other words, the additional contribution to the energy internally consumed deriving from the sharing. $c_{el,tr}$ and $c_{el,sys}$ are the transport and the system charges [see Section 3.2], while p is a coefficient indicating the percentage that must be paid. Currently, it is unknown what future policies will establish, hence p will be varied to show ancillary charges impact, ranging it from 0 to 1.

It is worth noting that expenditures could be also negative, representing, in this case, revenues for the user/community. Doing this *three-step* procedure allows to define the following KPIs for the comparison, namely the savings achieved by the improved configurations:

$$SSCs_{sav} = \sum_{j=1}^{4} (C_j^0 - C_j^{SSCs}) \tag{72}$$

$$EC_{sav} = \sum_{j=1}^{4} (C_j^0 - C_j^{EC}) \tag{73}$$

Thus, the *further* yearly earnings given by the EC are the difference between these indicators.

4.5.2 Sales definition

The SSCs prosumers and the EC have two mechanisms to sell energy: Net Metering (NM) and FER constant tariffs.

The *Net Metering* mechanism rules the interaction of a producer with the public grid. It provides a refunding to the user on the energy he withdraws depending on the one fed into the grid. According to [25], the term $Sales = NM$ of eqq. (68) and (70) is given by:

$$NM = min(O_E; C_{Ei}) + CU_{sf} \cdot E_s + Exc \tag{74}$$

Where:

- O_E [€] is the charge incurred by the user for the purchase of the electricity withdrawn; it is equal to the product between the amount of electricity withdrawn and the hourly Single National Prices (*Prezzo Unico Nazionale* PUN):

$$O_{E,j} = \sum_{i=1}^{8760} P_{with,j}(i) \cdot PUN(i) \tag{75}$$

- C_{Ei} [€] is the counter-value of the electricity fed into the grid determined on the basis of the hourly area prices (*prezzi zonali* PZ, the north area for this case study) formed on the Day Ahead Market (*Mercato del Giorno Prima*, MGP):

$$C_{Ei,j} = \sum_{i=1}^{8760} P_{grid,j}(i) \cdot PZ(i) \tag{76}$$

Both the $PUN(i)$ and the $PZ(i)$ are taken from the 2018 GME historical library [26]. To limit price fluctuations and make a more consistent analysis, a typical day is defined and considered for the whole year: it has been generated by doing the 365-day average of each hourly price; the trend of both prices in the typical day is shown in Fig. 25.

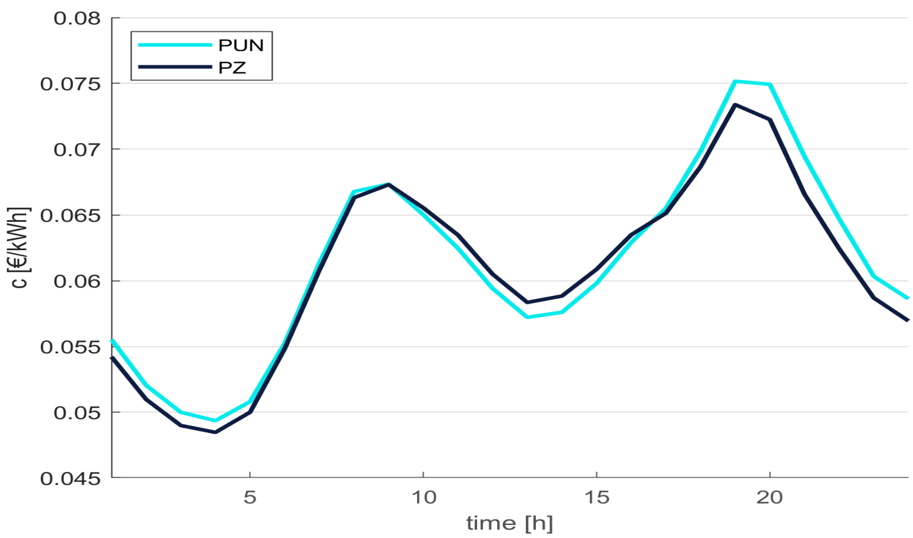

Figure 25: Trend of PUN and PZ in the typical day

Considering PV, it is now possible to understand why the Net Metering is so favorable: users buy during the night, when the price is smaller compared to the day, the period in which they sell.

- CU_{sf} [€/kWh] is the annual flat-rate exchange unit fee. For RES palnt with installed capacity bigger than 20 kW:

$$CU_{sf} = CU_{sf,grid} + min(CU_{sf,sys}; yearly\ \ threshold) \tag{77}$$

While where there is (only or also) a HEC plant:

$$CU_{sf} = CU_{sf,grid} \tag{78}$$

The 2018 values of CU_{sf} coefficient for various users is reported on the authority website [27]. For further details and explanations, please refer to [25] and to Annex B.

- E_s [kWh] is the amount of the electricity exchanged and equal to the yearly minimum between the energy fed and withdrawn:

$$E_{s,j} = min\left(\sum_{i=1}^{8760} P_{grid,j}(i); \sum_{i=1}^{8760} P_{with,j}(i)\right) \tag{79}$$

- Exc [€] is a payment activated if the term $C_{Ei,j}$ is greater than O_E, since the GSE refunds the difference to the user:

$$Exc_j = min(C_{Ei,j} - O_{E,j}; 0) \tag{80}$$

By implementing these equations for the general user j and the energy community as a whole, it is possible to evaluate the term $Sales = NM$ in eqq. (68) and (70).

If, instead, the users choose to subscribe the FER tariffs, the term $Sales = FER$ is simply:

$$FER = \sum_{i=1}^{8760} P_{grid}(i) \cdot c_{FER} + premium \tag{81}$$

Where c_{FER} [€/kWh] is the 20 years constant selling price, depending on PV capacity, and $premium$ is the award recognized if the SC fraction is greater than 40%:

$$premium = \sum_{i=1}^{8760} P_{self}(i) \cdot c_{premium} \tag{82}$$

With $c_{premium} = 0.01$ €/kWh.

4.5.3 Cash flow analysis

To compare the SSCs and EC investment a cash flow analysis is necessary. To this aim, a powerful indicator is the Net Present Value (NPV); by definition, it is given by:

$$NPV = -I + \sum_{k=1}^{n} \frac{B_t(k)}{(1+i)^k} \tag{83}$$

Where $n = 20\, years$ is the lifetime of the devices and $i = 5\%$ is the interest rate of the investment. I represents the total initial investment cost and it is given by the sum of the single technologies costs:

$$I = I_{PV} + I_{HP} + I_{CHP} + I_{chiller} \tag{84}$$

The specific cost [€$/kW$] of each technology has been taken from the catalog by the Danish Energy Agency (DEA) [28]. They provide the unit cost of investment i with the operation and maintenance one $c_{O\&M}$ in different years: 2020 values have been considered in this work.
Finally, $B_t(k)$ are the revenues in the year k. More precisely, the following expression has been used:

$$B_t(k)^{EC} = EC_{sav} - C_{O\&M} + C_{inc} \cdot inc(k) \tag{85}$$

The EC income due to energy saving is the first term, supposed constant throughout the year, defined in Section 4.5.1, $C_{O\&M}$ is the maintenance cost and C_{inc} is the yearly percentage of the initial expenditure that may be repaid in 10-year installments. $inc(k)$ is a binary variable necessary to activate and deactivate subsidies: it is equal to one in the first ten years ($1 \leq k \leq 10$) and zero otherwise. If incentives are not considered, it is logically always equal to zero. Eq. (85) works obviously in the same way for the SSCs configuration.
Besides the NPV, there are other two helpful economic KPIs when dealing with a cash flow analysis:

- Pay Back Time (PBT): Time needed to recover the initial investment cost; eq.(83) is set to zero and solved with respect to n.
- Internal Rate of Return (IRR): The interest rate that makes NPV equal to zero after 20 years; eq.(83) is set to zero and solved with respect to i.

Using all the equations reported in this section, from the profile generation to the economic model, it is possible to simulate and assess the EC and the SSCs scenarios. The next chapter goes to present all the results.

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5 Results and discussions

This section aims at introducing and explaining in detail the results obtained by implementing the model previously described. In the first paragraph [Section 5.1], load profiles of each user, coming from the scaling of American ones, are introduced following the normalization procedure; to assess the proposed methodology, a benchmark with the existing literature, as the theme has been already widely tackled, is provided. Then [Sections 5.2-5.3], the findings of the energy simulation are shown: SS and SC for each user, highlighting the relative increase of the latter in the EC configuration. Economic evaluation in terms of bill expenditures and cash flow analysis are finally reported [Section 5.4], changing the economic scenario under which the comparison has been performed. The last part of the chapter [Section 5.5] is dedicated to a sensitivity analysis to verify the EC behavior when changing the PV installed capacity.
The discussion of the obtained results aims primarily at showing the possible economic improvements registered between the EC and the SSCs scenario. More precisely, the parallel comparison in different economic scenarios provides with a wide glimpse on how and what energy policies could facilitate ECs deployment, waiting indeed for the RED II Italian transposition.

5.1 Users' load profiles

In this first part, the load profiles obtained with the methodology described in Section 4.1 are shown. The process has been done in two steps:

- Establishing the profiles shape by selecting the most climatically similar city to Turin.
- Scaling the American load profiles, making them consistent with Italian climate and habits.

At the end, specific profiles $[W/m^3]$ for each user are got and, to validate the results, a benchmark with values found in the literature is provided.

5.1.1 Step 1: Reference city definition

By applying eq. (6) to the 15 cities reported in Table 3, Fig.26 can be obtained, where each point indicates a city, identified by the initials of the State in which it is located.
The closer a point is to the origin of the axes, the greater the climatic similarity between Turin and the respective city. The bottom-left dial identifies the threshold values previously established; it is worth noting that it has been chosen to accept smaller errors on HDD. As a matter of fact, the heating consumption for Turin is much bigger than the cooling one and having a city with similar heating needs is surely more important to carry out a realistic energy simulation. In other words, a higher *relative* error on CDD are tolerable because they bring to acceptable *absolute* error on the final cooling profile shape, as it is almost one order of magnitude smaller than the one for heating.
Two cities are in the dial: Jefferson (MO) and Salt Lake City (UT). Evaluating the distance from the origin with the following expression:

$$\Delta = \sqrt{\Delta_{HDD}^2 + \Delta_{CDD}^2} \tag{86}$$

Salt Lake City results affected by a smaller value: 0.278 against 0.395. Nevertheless, Jefferson seems particularly suitable for its small error on HDD, to support what has been

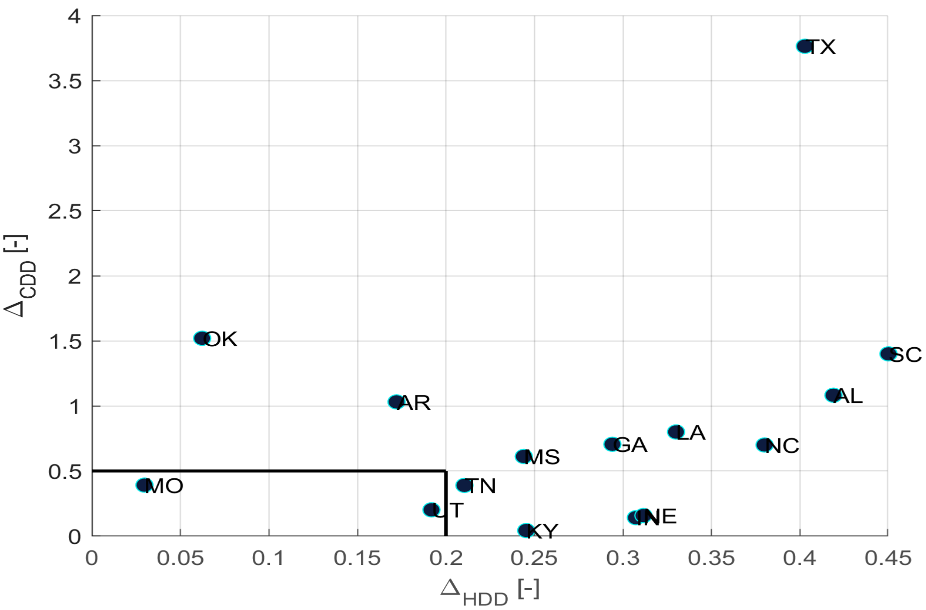

Figure 26: Relative difference in HDD and CDD between the American cities and Turin.

previously observed. To make the best choice, further climatic analyses are necessary. Fig. 27 shows the hourly temperature profiles of the two cities and Turin for the hottest (July) and the coldest (January) month, while Fig. 28 reports a comparison of the average monthly temperatures
Jefferson winter temperatures are more similar to Turin ones, confirming the smaller error on HDD, while the same is true in July for Salt Lake City; to assess quantitatively the differences, the following indicator is introduced:

$$\Delta T_k = \frac{\sum_{i=1}^{nh} |T_{TO,k}(i) - T_{AM,k}(i)|}{nh} \tag{87}$$

It is basically the average temperature difference in the k^{th} month between Turin and the two American cities, being nh the number of hours in that month, and it can be graphically seen in Fig. 28. Table 5 sums up the comparison, allowing to select the final town based also on the temperature variations sampled over smaller periods.

Parameter	**Turin**	**Jefferson**	**Salt Lake City**
HDD [°C]	2657	2736	3166
CDD [°C]	245	341	294
Δ_{HDD} [−]	0	0.0297	0.192
Δ_{CDD} [−]	0	0.392	0.202
ΔT_{jan} [°C]	0	4.88	6.12
ΔT_{jul} [°C]	0	4.08	3.33
$T_{mean,y}$ [°C]	13.6	13.7	11.9
$Height$ [m]	239	192	1288

Table 5: Final comparison between the cities.

Computed Turin climatic parameters are consistent with the one provided by the legislation, since the DPR 412/1993 [1] indicates 2617 HDD while the standard UNI 10349 [2] suggests a yearly average temperature of 12.7 °C.

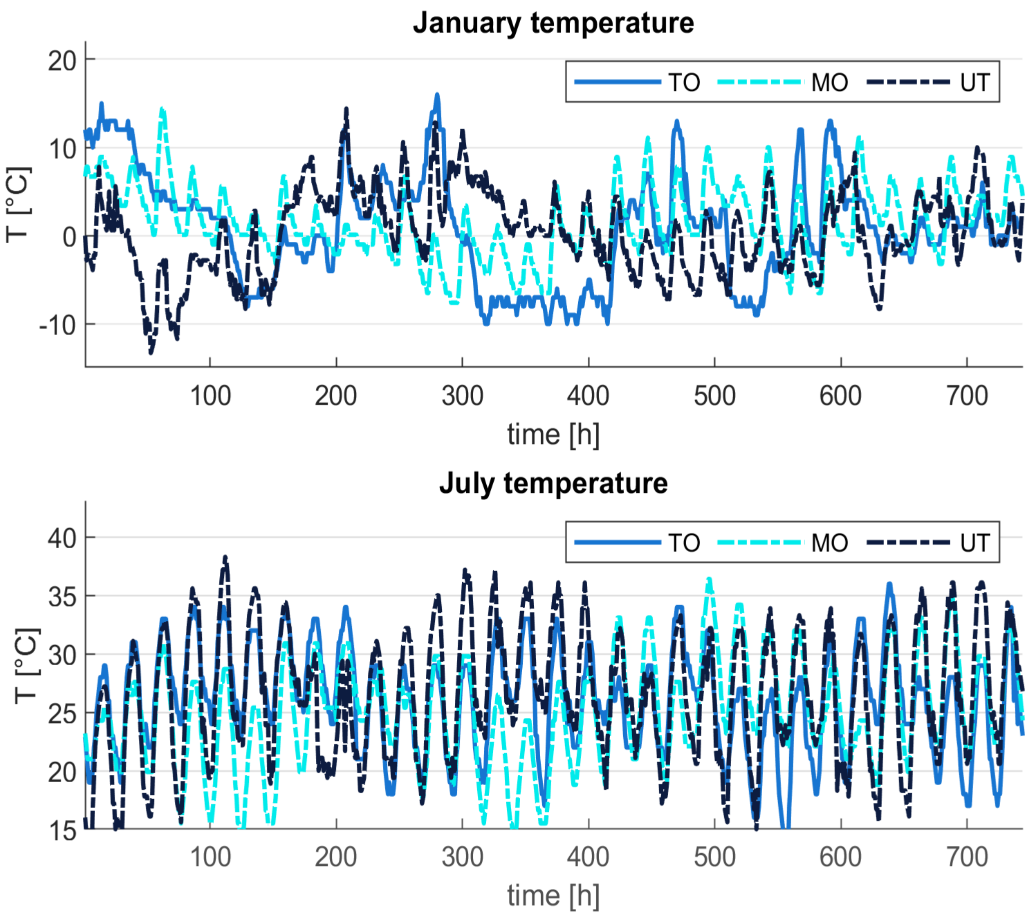

Figure 27: Comparison on January and July temperature.

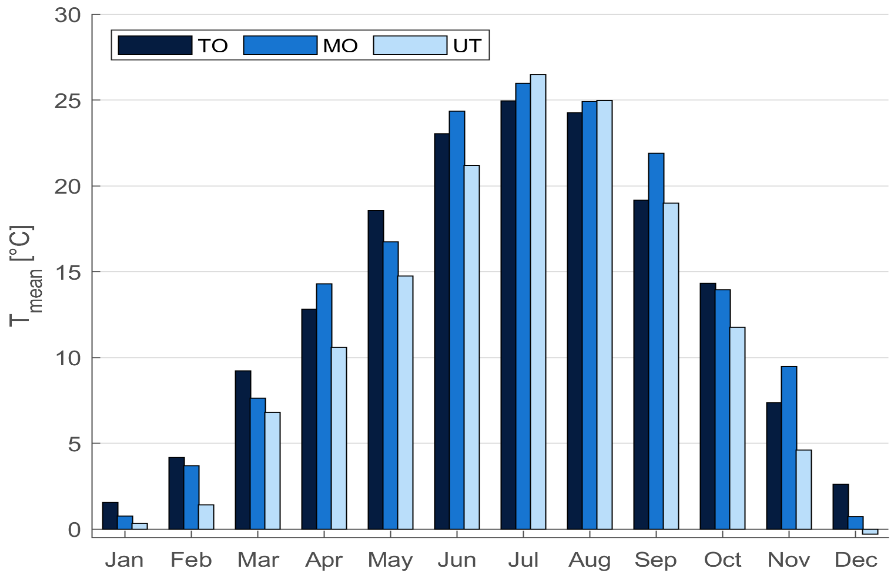

Figure 28: Comparison on average monthly temperatures.

The findings so achieved confirm that Jefferson (MO) seems the best choice. This city not only is very similar to Turin during the heating season, when loads are much higher compared to summer (HDD are indeed 2657/245 = 10.84 times greater than CDD) but it presents also a yearly average temperature basically identical. On the other hand, Salt Lake City (UT) is affected by too harsh winter mainly due to its higher altitude above sea level. This last parameter further reinforces the choice made, since it is fair to assume that Turin and Jefferson are characterized by similar micro-climatic phenomena, undergoing for instance similar atmospheric pressures.

5.1.2 Step 2: Profile scaling

The first step to obtain the scaling factors introduced in Section 4.1.3 is to find the functions $H(HDD)$ and $C(CDD)$ expressing heating and cooling specific needs $[kWh/m^3]$ as HDD and CDD vary. Points available from the DOE database for the 16 climatic zones have been interpolated with second and first order polynomials respectively. Functions resulting from this interpolation are obviously different for each user. In Figg. 29-30 the condominium results are shown, while fitting coefficients of all buildings, with their R^2 value, have been reported in Table 6.

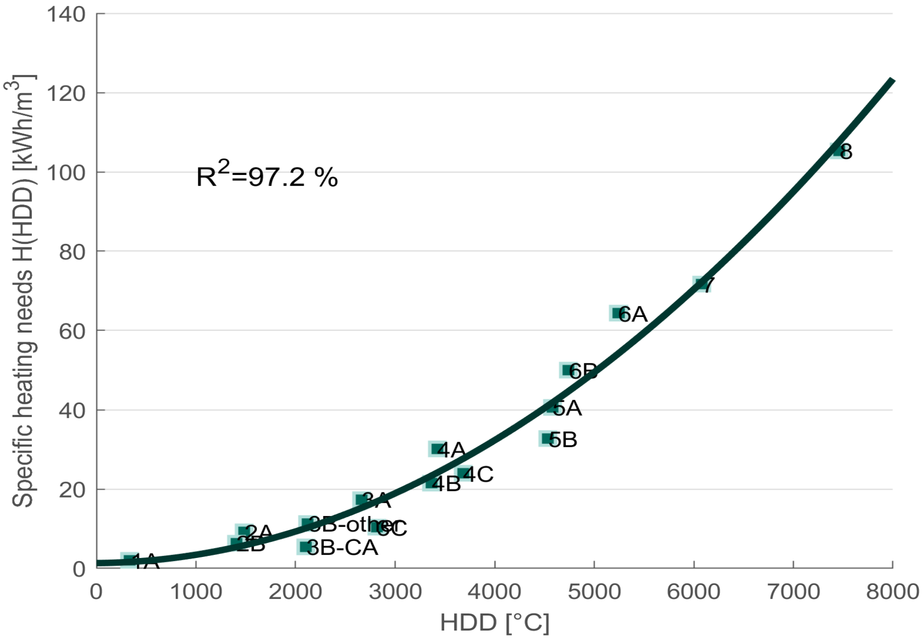

Figure 29: Residential user: curve fitting of heating specific needs.

User	Heating				Cooling		
	a $[10^{-6}]$	b $[10^{-4}]$	c	R^2	a $[10^{-2}]$	b	R^2
Condominium	1.88	2.26	1.33	97.2	1.96	5.70	77.1
Office	1.03	1.89	97.3	3.78	8.67	7.71	77.2
Supermarket	1.95	2.21	1.15	97.2	2.56	4.17	77.2
Mall	2.72	3.26	1.17	97.3	2.83	4.27	77.1

Table 6: Fitting coefficients of heating and cooling curves for all the users.

Different functions for different users imply that each one will have its own weighting factors when it comes to do the scaling. These results reinforce the idea of avoiding a single weighting factor, expressed as the ratio of American and Turin HDD or CDD: it would have been not so representative of the various users types. The higher a coefficient,

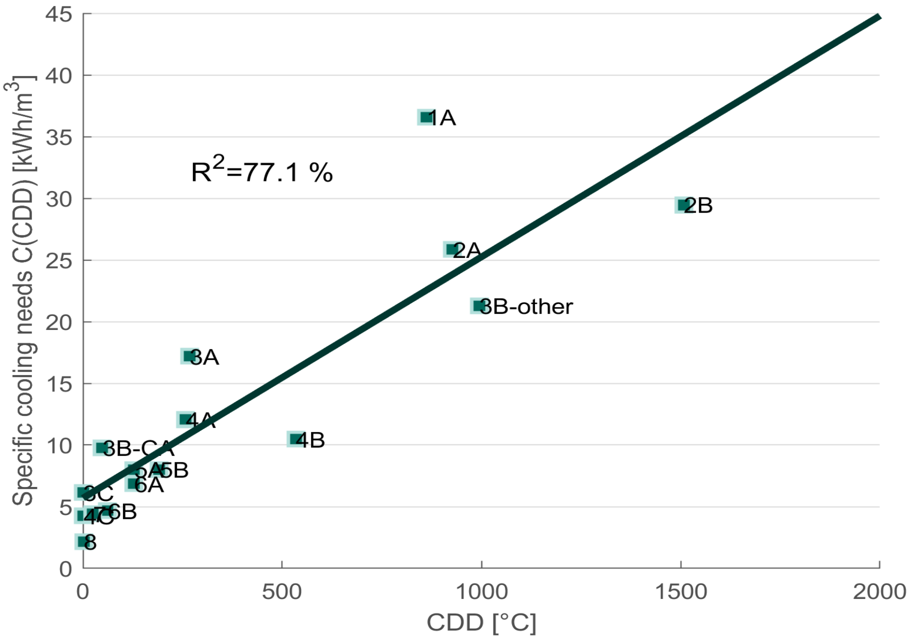

Figure 30: Residential user: curve fitting of cooling specific needs.

the greater is the specific heating/cooling consumption for that user; this difference can be credited to various reasons such as shape factor S/V, occupancy and possible presence of particular internal loads, deriving from the activity to be performed. In this perspective, Table 6 gives for instance an idea of how much the tertiary sector is more energy-intensive in cooling than the residential one.

All the elements to compute the weighting are known and their values are reported in Table 7.

User	wf_h	wf_c	wf_{el}	wf_{DHW}
Condominium	2.34	0.84	0.37	0.89
Office	2.46	0.80	1	-
Supermarket	2.51	0.83	1	-
Mall	2.53	0.79	1	-

Table 7: Weighting factor of all needs for the various users.

Heating weighting factors are so high due to the smaller envelope efficiency of Turin buildings [Section 4.1.3]. American U-values are much lower because buildings are supposed to be built in 2004 with totally different standards compared to those of the construction period (50s-70s) of the Turin ones. On the other hand, cooling factors smaller than one are explained by Turin cooler summers, as CDD values pointed to. For commercial users, no DHW profiles have been considered and no scaling has been applied to electricity consumption: this approximation [see Section 5.1.3] still leads to consistent results. Finally, the residential electricity weighting factors is confirmed also by data gathered by the DOE; an average Italian dwelling consumes yearly $2,700\ kWh$ [3], while an American household needs $27 \cdot 10^6\ Btu = 7,913\ kWh$ [4]. Therefore, also according to eq. (16), it is fair to expect that $wf_{el} = 2,700/7,913 = 0.34$, not far from the value found. Such a large difference in electricity consumption can be attributed to the lower American electricity

cost: in Missouri the price is slightly higher than half of the Italy one, being it only 0.1163 $/kWh$ [5].
Now all the data to generate the hourly load profile are known and final results can be presented.

5.1.3 Profile definition and verification

To avoid a bulky section, full load profiles (8760 values) for each user, with a zoom on a winter and summer typical days, are reported in Annex A. Here [Figg. from 31 to 34] the yearly load trends are shown with the average daily monthly demand; Table 8 sums up the total specific demand.

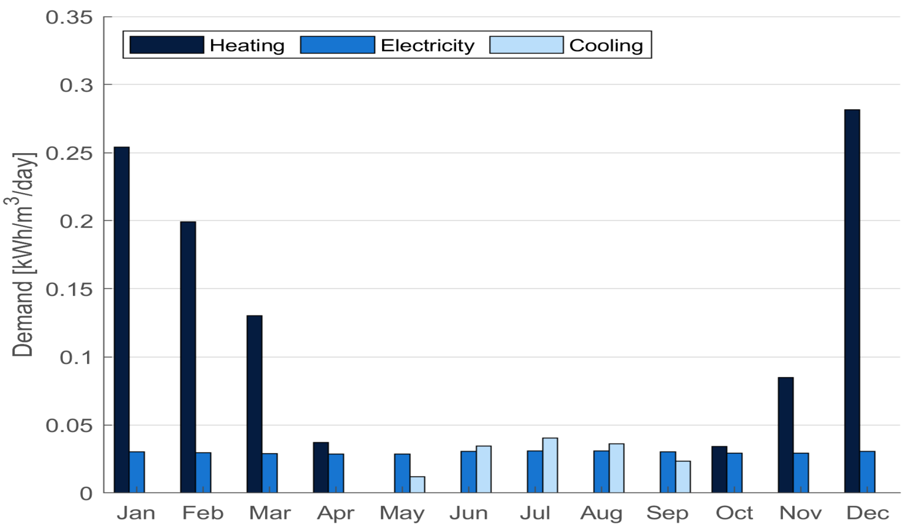

Figure 31: Condominium: yearly load trends.

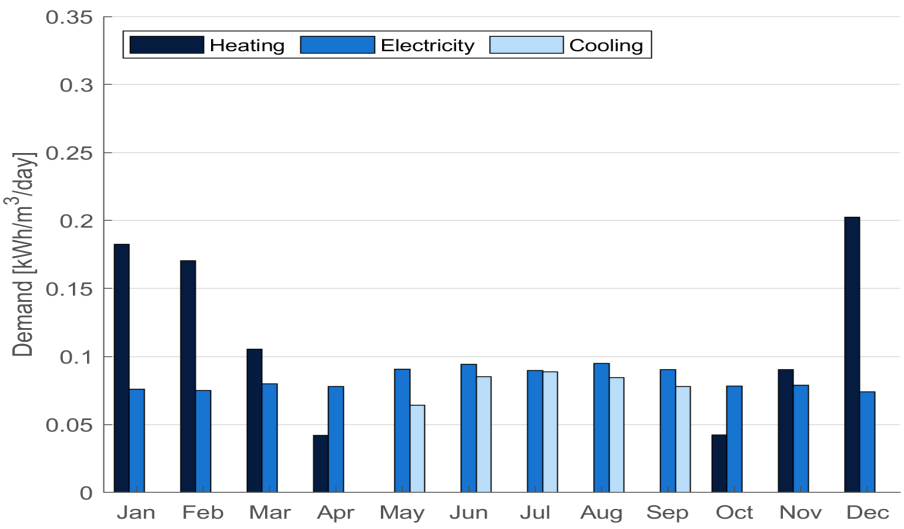

Figure 32: Office: yearly load trends.

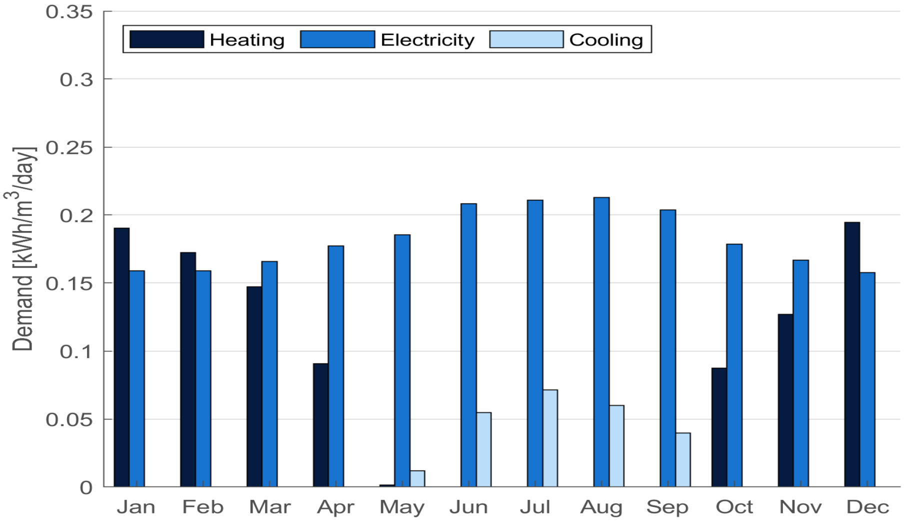

Figure 33: Supermarket: yearly load trends.

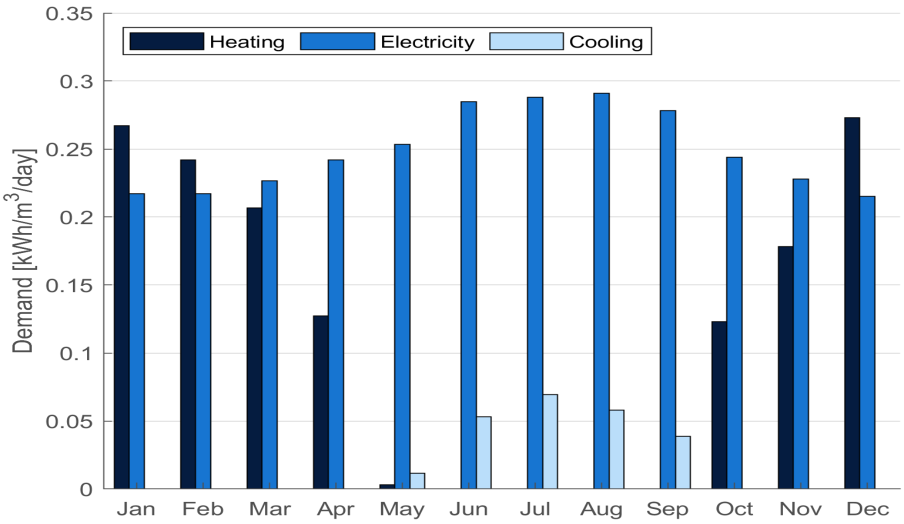

Figure 34: Mall: yearly load trends.

User	Heating	Cooling	Electricity	DHW
Condominium	30.9 [57.4%]	4.5 [8.4 %]	10.9 [20.3 %]	7.5 [13.9 %]
Office	25.2 [37.2 %]	12.2 [18.0 %]	30.4 [44.8 %]	-
Supermarket	30.6 [29.3 %]	7.3 [7.0 %]	66.5 [63.7 %]	-
Mall	43.0 [31.0 %]	7.1 [5.0 %]	90.9 [64.0 %]	-

Table 8: Yearly specific needs $[kWh/m^3]$ for the various users.

Numbers clearly shows that the mall is the most energy-intensive building, especially regarding the electricity consumption. Such high values can be attributed to the several loads within it: apart from the shop and hall lighting, also freezers and refrigerators of two small supermarkets are present, together with four lifts and two escalators. The cooling demand is minimum in the condominium, since residential space are usually empty, except weekends, during the hottest hour of the day when people are at work, while the contrary stands logically for commercial buildings. In particular, the high cooling request for the office can be explained with the presence of further internal loads (computers, machinery, high occupancy $people/m^2$) , which justify the high demand already in the month of May. To complement the remarks, it is important to say that the office has been supposed closed on Sunday and during public holidays (Christmas, Easter, etc.), while the other two activities are always open. Anyway, for a complete description of the user activities and scheduling, as well as if interested in the impact of the various electrical appliances, please refer to [6]-[7].

Now that results are available, a brief benchmark with other works is necessary to validate the methodology.
Firstly, similar plots have been developed by Macchi et al. [8] and results are consistent with those listed above. Regarding the residential user, for the specific heating demand of a condominium built in the 60s placed in Italian climatic zone E, [9] suggests a value of 99.2 kWh/m^2; given the dwelling height of 3 m the number reported in Table 8 is acceptable. In this perspective, also the work by D'Amico et al. [10] is worth to be mentioned; they developed functions tying the specific heating demand with HDD and S/V. Finally, a powerful benchmark regarding the shares of the various consumption for households is the report about the Italian energy efficiency policy [11] [Fig. 35].

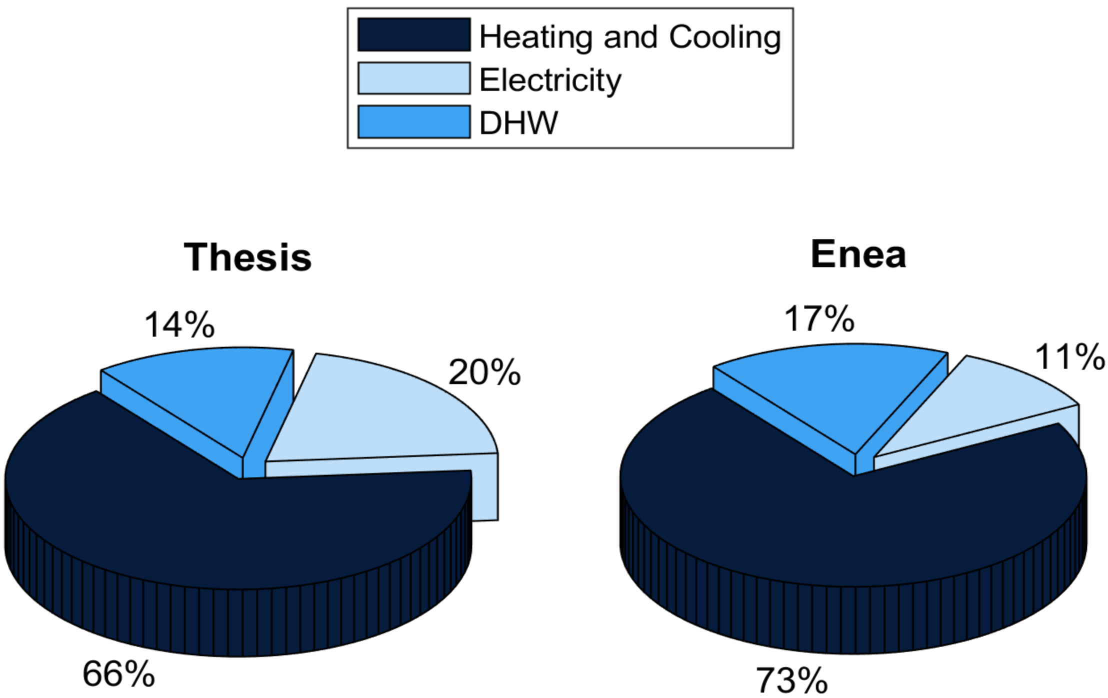

Figure 35: Condominium: comparison of the obtained results with the one provided by [11].

In [11] heating and cooling demands have been joined, since they strongly depends on external temperatures and defining two unique values for Italy would have been not so meaningful. The greater discrepancy is registered about the share of electricity consumption. In this case, probably the reason of such difference comes from the different location: in this thesis, the user is a condominium placed in Turin, while [11] refers to the whole Italy.
As far as the office is concerned, a detailed statistical analysis on energy yearly specific needs has been carried out by Enea and Assoimmobiliare [12]. The bar chart in Fig. 36

gives an idea about the distance between their results and those of this work.

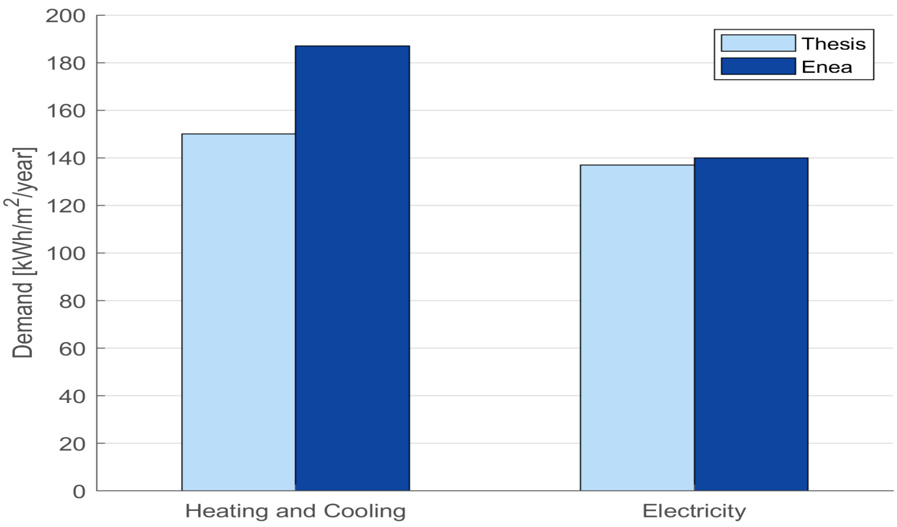

Figure 36: Office: comparison of results obtained with the one provided by [12].

Electricity consumption is almost perfectly matched, while a discrepancy of about 40 kWh/m^2 can be observed in the thermal demand. Nevertheless, such benchmark values have to be understood as a sort of *rule of thumb*, due to the great variety of the considered sample. Moreover, also the impact of both needs on the total energy request is similar between the two works.

To conclude, the methodology defined to transpose load profiles has brought to consistent data regarding the energy demand of the users. Undeniably, as it has been discussed, there are differences with some publications in the literature, which implemented more accurate methodology [8]-[13]-[14], and some scholars may argue that hourly profiles might be a little loose [15]-[16], especially when it comes to electricity needs. Nevertheless, the choice to exploit the DOE database seemed to be the best from the beginning, especially because of the high data availability provided about the commercial sector. Anyway, it is far from the objectives of this work to make a long and complete study about profiles; on the contrary, it is sufficient to have realistic values to conduct a reliable assessment of the SSCs-EC comparison.

5.1.4 Community total load profile: hints on the grid impact

Before closing the profile section, it is worth having an idea of how the union of commercial and residential users, on which an EC is based, can be important to reduce the load peaks, avoiding large energy imports from the external grid and increasing the internal self-consumption [Fig. 37].
Considering the electricity demand, the generic profile of a residential user presents two peaks, one in the morning and the other in the evening, when indeed people are at home, being lower and flat during the day. On the other hand, the typical load of a commercial user is higher and quite flat in the middle of the working day. The sum of the two, which is logically the EC demand, is therefore a globally steady profile. Such type of request implies several advantages, among which the most important are certainly:

- Easy to size production plants because of the absence of sudden peaks;

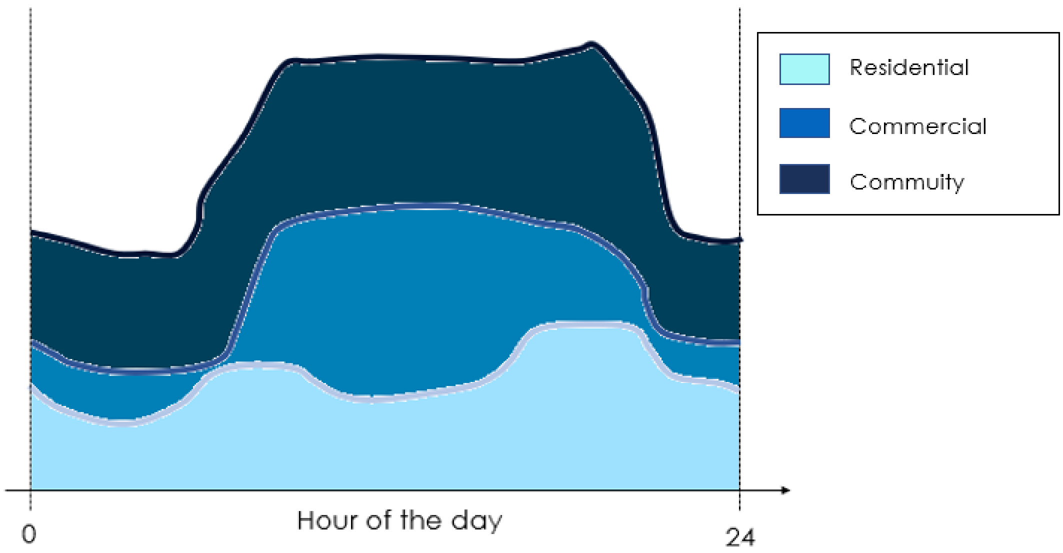

Figure 37: Load leveling by aggregation of different users.

- Avoid stressing the external grid with electricity demand peaks too high compared to the base-load.

These effects are further important when buildings *electrification* is performed; installing devices such as HPs, able to translate heating and cooling needs into electrical ones makes more impacting this phenomenon. In other words, beyond all subsequent evaluations, the community has an initial inherent benefit that simply springs from the load combination.

5.2 Single buildings technical assessment

Through the equations described in sections 4.3 and 4.4, the energy assessment of the EC can be carried out. Firstly, the results of each building are reported separately as they operate isolated; this allows also to understand how the capacity of each technology has been found. More precisely, the output coming from the HP optimization algorithm and the CCHP simulation are discussed.
Then, SS and SC have been computed in the SSCs and the EC configurations, with the main purpose of evaluating the enhancement of the second KPI. The analysis of the SSCs system is essential to understand what buildings will import-from/export-towards other users in the EC scenario.

5.2.1 PV optimal tilt and azimuth angle

The PV capacities (results available in Tab. 9) have been established accordingly to the roof available in each building [Tab. 4]: considering a pertinent clearance factor, 70% of each roof is occupied. Settled the surface, the MATLAB code is run with different values for the tilt β and the orientation γ, aiming at finding the combination that minimizes the yearly expenditures. Please note that for computing the expenditures in this optimization the EC has been hypothesized with the NT mechanism and no additional taxes have been considered for the energy internally exchanged. Fig. 38 shows the results of the optimization.
Numerical findings indicates a tilt angle $\beta = 33°$ and an azimuth angle $\gamma = 6°$. These numbers are, for instance, in line with those indicated by [17]: the tilt should be smaller than the latitude to capture more solar radiation in summer (i.e. when the Sun is higher)

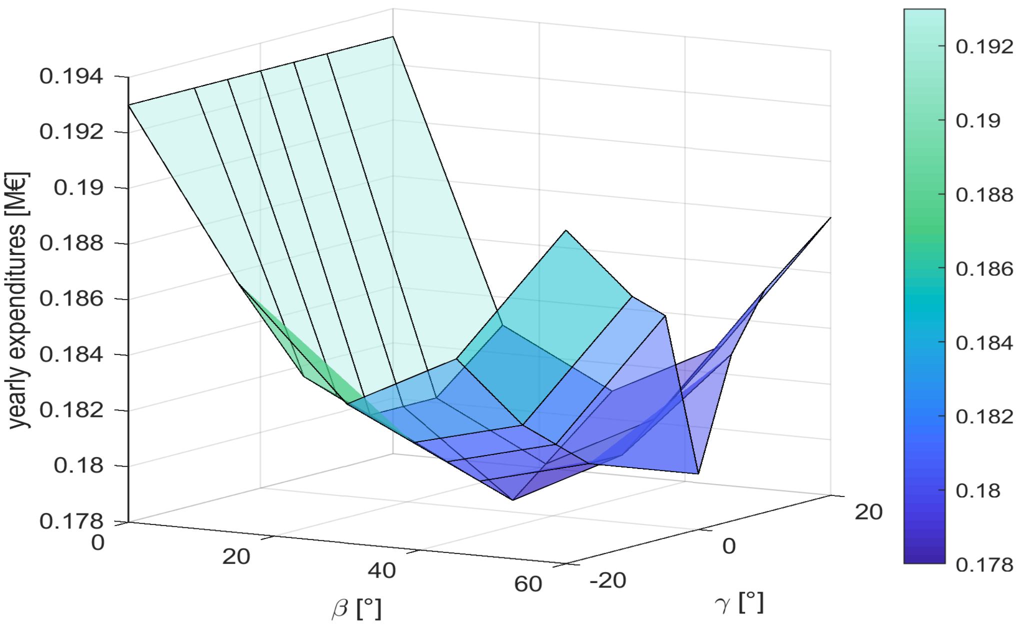

Figure 38: Optimization of PV tilt and orientation.

while the orientation is expected to be logically around 0°, even if slightly higher values match better with the load. The demand is bigger in the afternoon and west-oriented PV panels are better to produce more power when required, enhancing so the SC. The graph shows that mounting the PV in the correct position can bring to save up to $20,000$ € every year.

5.2.2 Condominium: HP integration optimization

The residential user retrofit consists in the installation of PV panels and of an HP to support the already existing gas condensing boiler during heating seasons [Fig. 17]. The HP optimization algorithm results are visible in Fig. 39: the left axis shows the heat delivered by various HPs in the whole heating season. As expected, such a curve presents a maximum, which identifies the optimum capacity that leads to the lowest heating bill. This parametric optimization led to choose an HP whose thermal nominal capacity is $32.2\,kW$. Capacities below the optimum would limit the HP maximum power, making it not able to meet a high percentage of the heating demand; on the other hand, too big HPs are forced to work for long periods in off-design conditions, making the COP too low and the boiler more economically convenient. Indeed, it is important to remember that the HP coming from this algorithm has been optimized in such a way the heating bills have been minimized. Fig. 39 shows also the electricity consumption (right axis) corresponding to the various sizes; its monotonous increasing trend is the confirmation that bigger HPs work with lower efficiency: even if they satisfy less demand, and thus produce less useful power, they consume more electricity.
The daily scheduling of HP integration aimed at meeting the heating request is reported in Fig. 40.
In these plots, two different days are represented to understand what happens depending on the COP values, readable on the right axis. The 15^{th} of December the external temperatures are such that, when there is the request, the COP is always higher than the threshold value, therefore the HP is always switched on. Nevertheless, during the morning peak, when the demand is maximum, the HP power is not enough to satisfy

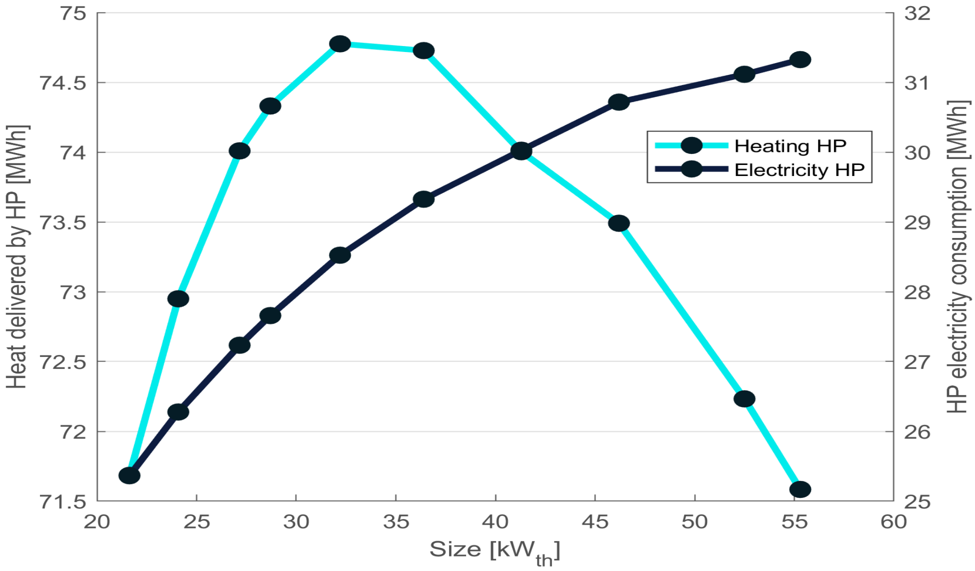

Figure 39: Condominium: HP optimization algorithm results.

alone the whole request and also the gas condensing boiler must be activated: in the plot this can be easily seen the from the lack of overlapping of the demand curve with that of the thermal power delivered by the HP.
In the other day (15^{th} of February), there are time slots during which the COP is below the threshold, so the HP *could* be switched off. More precisely, during the first and the last hours of the day (7-8 and 19-21), due to the absence of solar radiation, the PV does not produce power, there is not free electricity and the more convenient solution is to use only the boiler. In the other periods (8-13 and 18-19), although the COP is too low, there is free power available from PV and the HP exploits it to satisfy part of the demand, working alongside the boiler. Therefore, Fig. 40 helps to visualize all the possible working conditions of the new condominium heating system.

To sum up, the condominium has been subjected to an electrification process, consisting in the installation of an electrically-driven HP and PV arrays, through which it has become a *prosumer*. By changing heating system, natural gas consumption has been significantly reduced, while the possibility to satisfy heating needs with electricity enhances the building SC. Considering the new electricity demand profile, including heating and cooling, as well as PV production periods, it is possible to draw the daily trend of all the power profiles introduced in Section 4.4: the demand P_{req}, the production P_{prod}, the self-consumption P_{self}, the exports P_{exp} and the imports P_{imp}. Figg. 41 and 42 show the trend of these profiles in two significant days.
Obviously, due to the grid energy balance, the following relationships have always to be satisfied:

$$P_{req}(i) = P_{with}(i) + P_{self}(i) \tag{88}$$

$$P_{prod}(i) = P_{grid}(i) + P_{self}(i) \tag{89}$$

The requested power is the sum of the self-consumed and withdrawn ones, while the produced electricity may be either self-consumed or fed into the grid.
During winter, the electricity request is logically much higher, since, as it has been already widely discussed, the heating demand far outweighs that of cooling. Moreover, PV

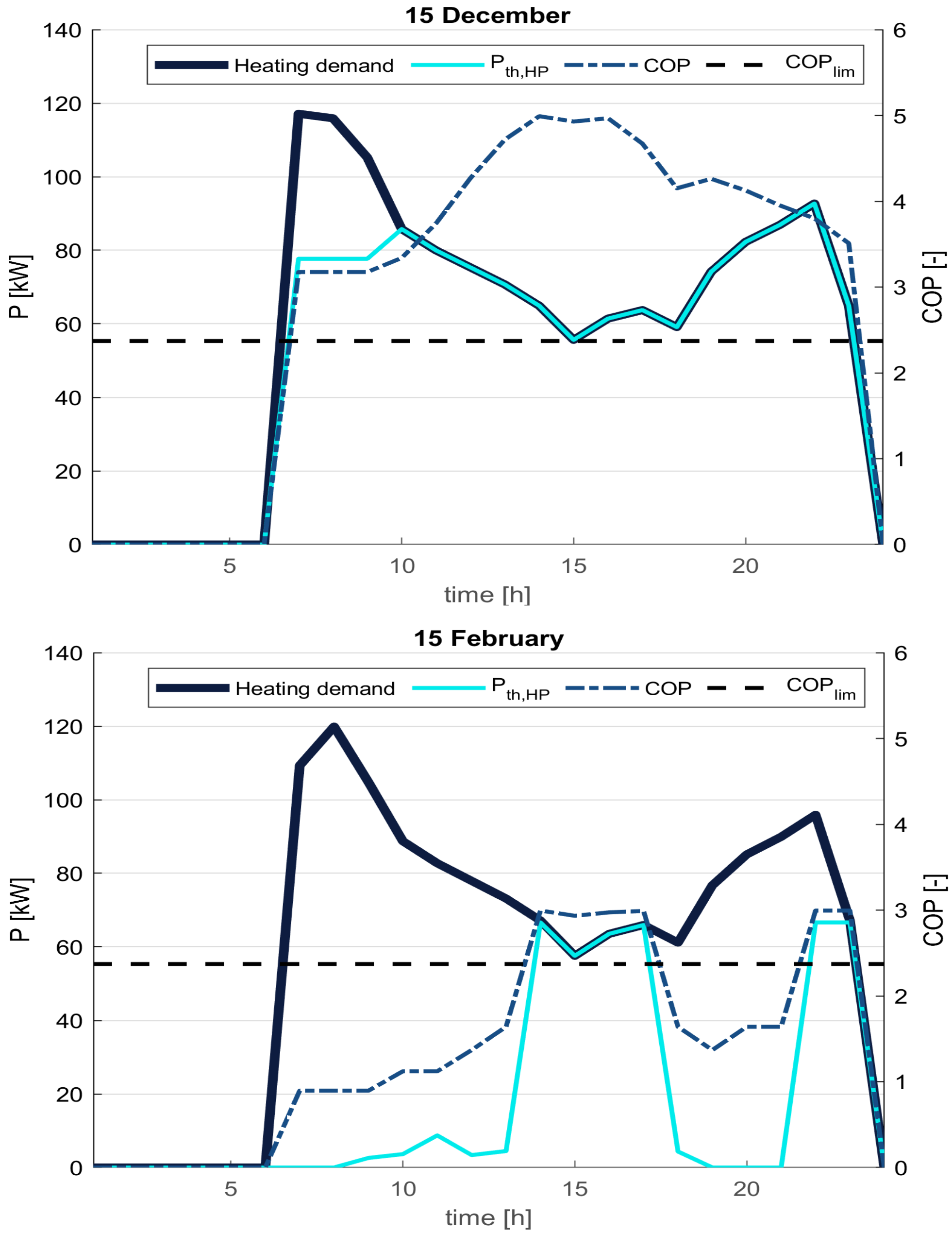

Figure 40: Heating scheduling of two different days in the optimized HP configuration.

productivity is lower due to the smaller solar radiation. Both these phenomena cause high withdrawals from the grid while very few energy can be exported: SS is globally lower in winter. In summer the opposite is true: longer days and lower requests are well-highlighted by the width bell-shaped production curve and by the similar export path. Finally, it is worth noting that winter helps to increase the on-site consumption, precisely because there is the matching between production and demand, while SC is smaller during summer.

5.2.3 Office: Reversible HP integration optimization

The office presents an energy-efficiency process very similar to that of the condominium. PV panels are installed on the roof to make it a *prosumer*, while a reversible HP is inserted to produce both hot and cold water and meet all the thermal needs. The HP capacity

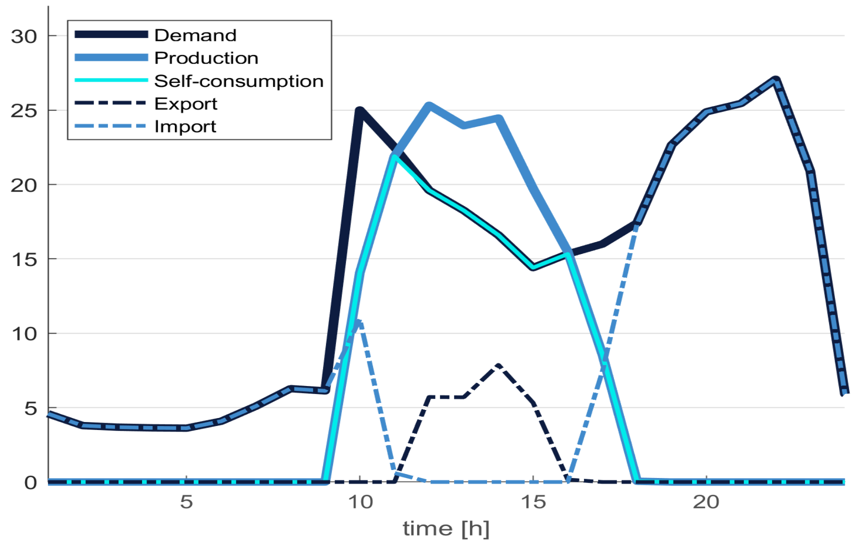

Figure 41: Condominium power profiles in a winter day (31^{th} January).

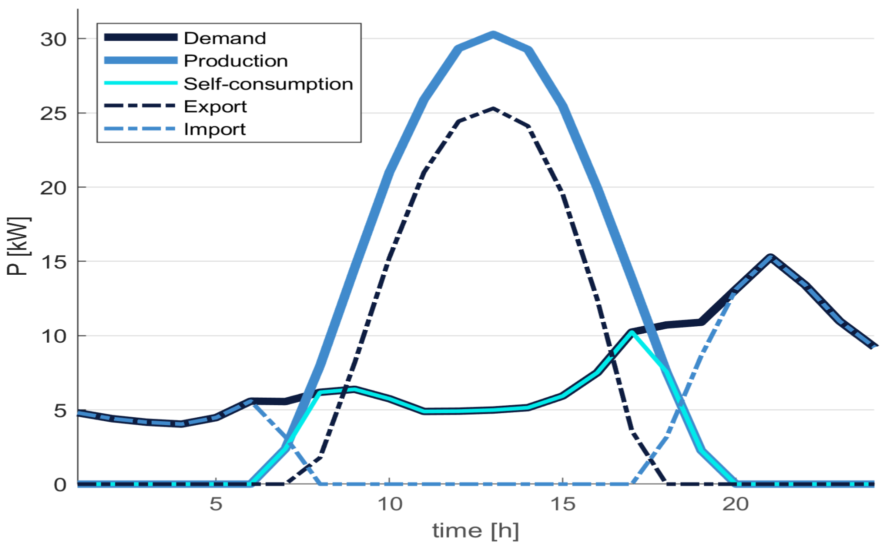

Figure 42: Condominium power profiles in a summer day (15^{th} July).

has been selected with the same optimization algorithm based on minimizing heating expenditures, whose results are shown in Fig. 43.

In this case, the best HP capacity is 92 kW. Such HP satisfies the 58.3% of the heating demand, while the condominium optimization has brought to a capacity factor equal to 56.2%: therefore, even if these users are different in profile shape and total load, the HP that minimizes the heating season expenditures meets in both cases about $55 - 60\%$ of the request.

The same HP so selected is reversible and it is used also in *cooling mode*. At the beginning of the cooling season, in May, the operating procedure for switching mode is carried out, based on the commutation of a 4-way reversing valve (4WV) [18]. When the operation is performed, the HP compressor is stopped and the Electronic Expansion Valve (EEV) is completely opened to equalize the pressure; then, the 4WV switches the connections and the flow is reversed [19] [Fig. 44]. The compressor and the EEV, through its opening degree, are in charge of regulating the refrigerant mass flow-rate and thus they establish

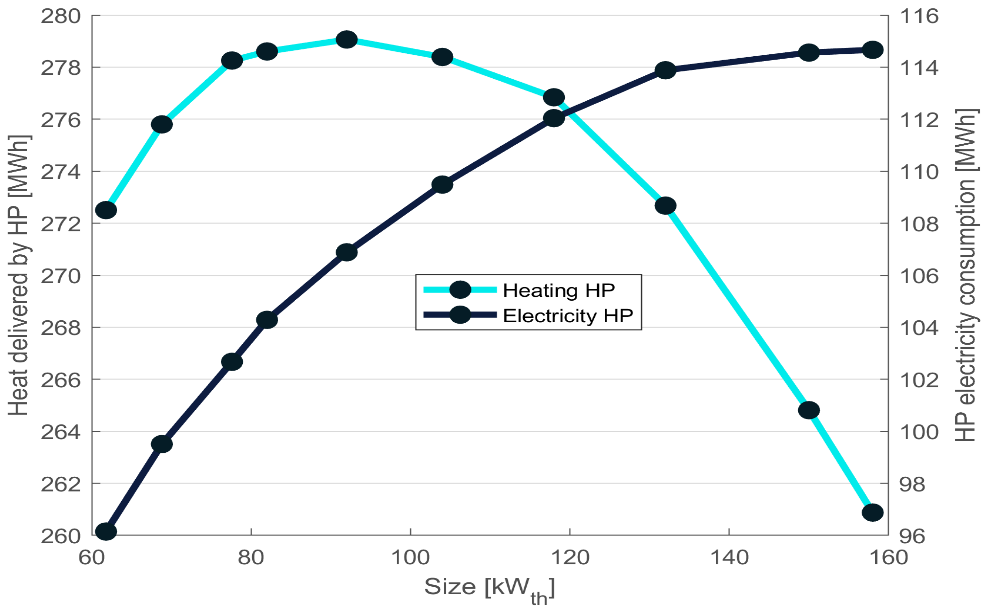

Figure 43: Office: HP optimization algorithm results.

the heating/cooling output power.

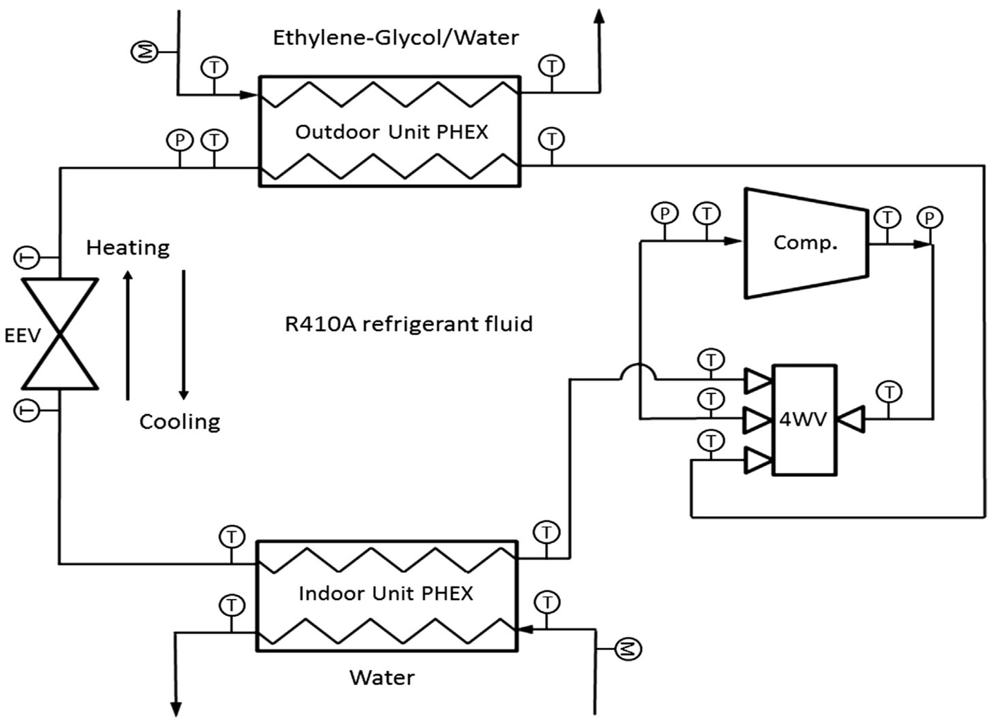

Figure 44: Reversible HP scheme [19].

In *cooling mode* the maximum delivered power, corresponding to the demand peak since no other technology has been developed for this purpose, is 80 kW. Since this value is below the HP capacity established with the algorithm, the previous result can be accepted, being it compatible to satisfy in every moment cooling needs.

Now the electricity demand of the office is fully known, thus it is possible to see its power profiles in two representative days of the year [Figg. 45-46].

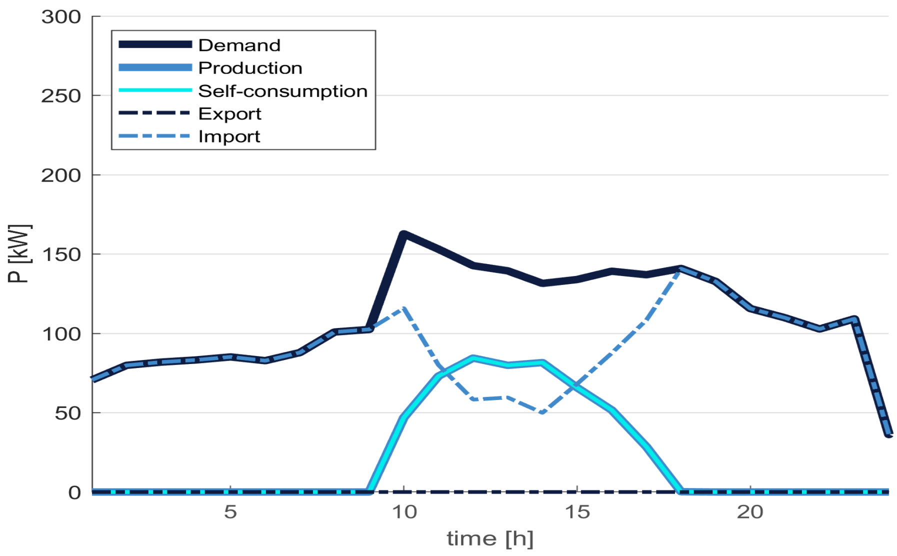

Figure 45: Office power profiles in a winter day (31^{th} January).

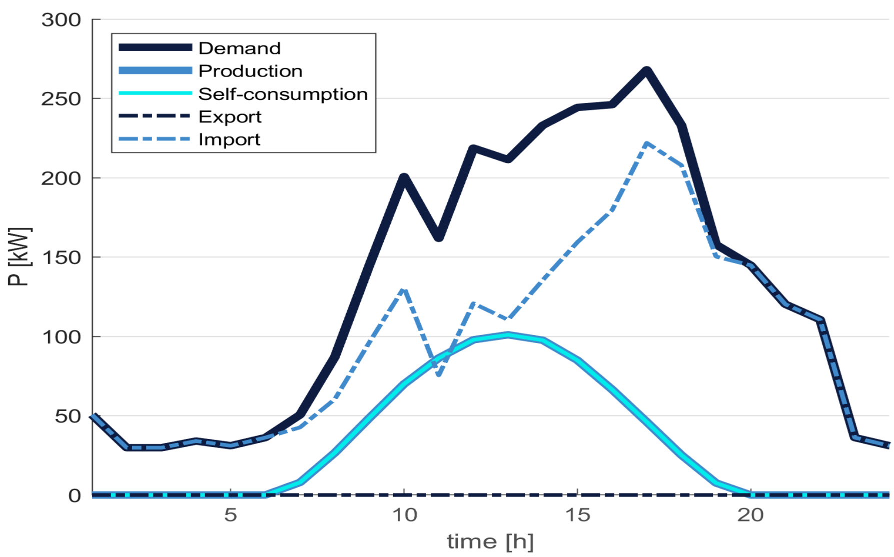

Figure 46: Office power profiles in a summer day (15^{th} July).

The global situation presents some differences compared to the residential user. Firstly, the demand is higher in summer, especially thanks to the electricity contribution and to the greater weight that the cooling demand compared to the heating one assumes. Secondly, and even more important, in both days all the energy produced is directly consumed, leading to an SC fraction close to one and very small values of exported energy. As it has been anticipated in section 4.2, these findings are due to the low ratio of the geometric parameter A_r/V [Table 4], which indicates high loads with respect to the production: the roof is too small and so it is the PV capacity, as it happens in buildings with prevalent vertical development. Therefore, the energy can not be exported, while the demand is primarily meet with withdrawals, suggesting low SS values.

5.2.4 Supermarket

The supermarket is the user in which the least number of interventions take place: only PV panels are installed from the BAU scenario. Figg. 47-48 reports the power profiles on the usual two representative days.

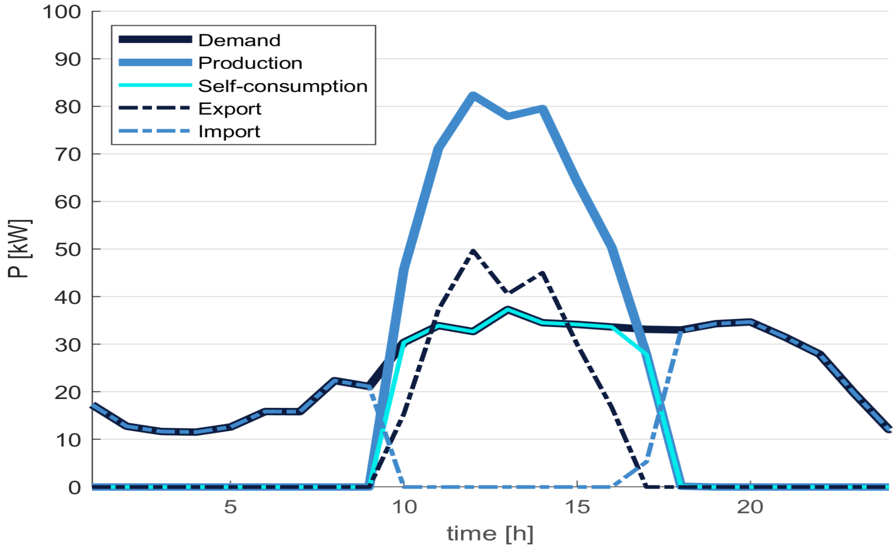

Figure 47: Supermarket power profiles in a winter day (31^{th} January).

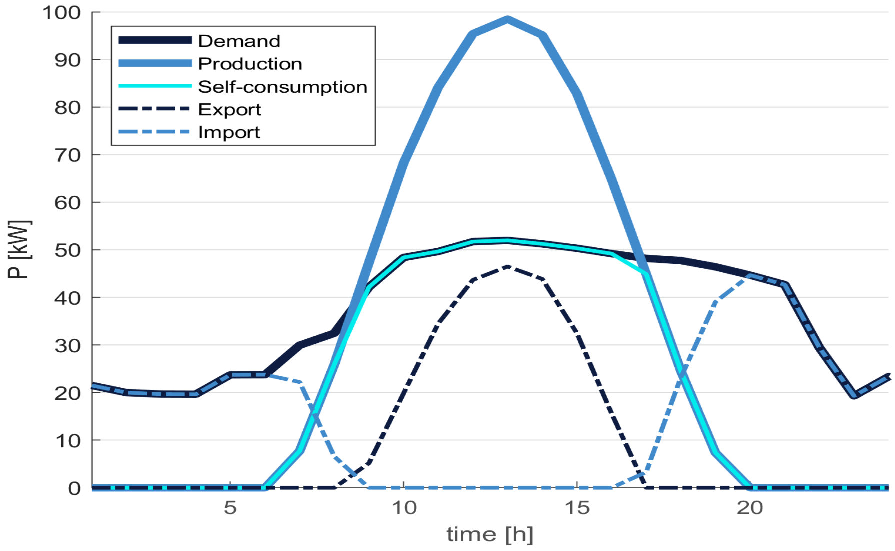

Figure 48: Supermarket power profiles in a summer day (15^{th} July).

As expected, the winter demand is lower, primarily because no electricity is required for heating the building. In both cases, the demand during the sunny hours is satisfied almost totally by PV panels, which produce even an appreciable amount of exported energy, suggesting high SS and quite low SC values: the supermarket is expected to be a *lending-energy* building inside the community.

5.2.5 Mall: CHP assessment and verification

The mall retrofit is featured by the installation of two electricity production units: PV panels and CCHP system. Remembering that the size of the CCHP has been established with the *thermal following* control logic (i.e. the system satisfies in every moment the thermal, heating or cooling, demand), a verification to check if the device falls under the definition of HCE is necessary. To facilitate the understanding of the CCHP scheduling, Fig. 49 shows the day when the system works in design conditions.

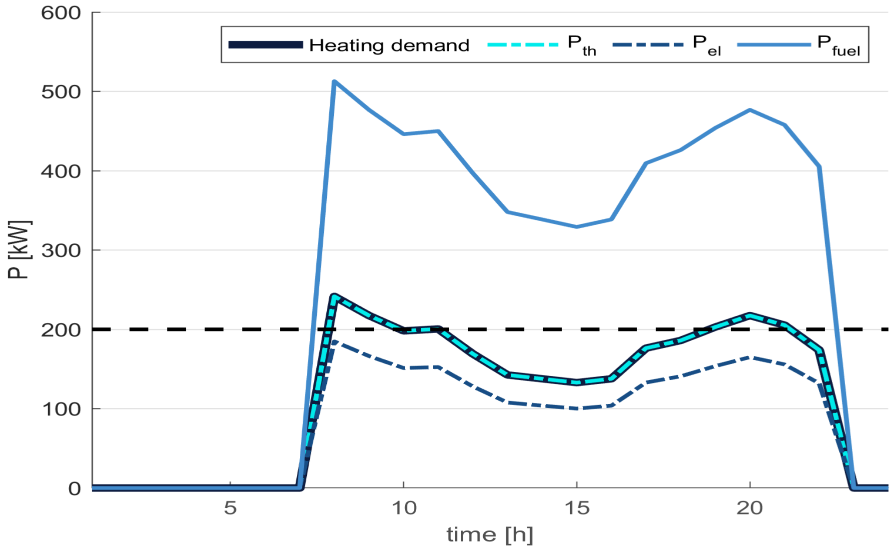

Figure 49: CCHP scheduling during the maximum day load (9^{th} December).

The thermal power output of the CCHP is exactly equal to the heating demand. The nominal capacity of the engine can be considered equal to 190 kW_{el}; it presents a yearly fuel savings equal to $\Delta E_c = 21.3\ MWh$ and a Primary Energy Savings factor of $PES = 2.48\%$ [Section 3.3.2]. Therefore, according to the D.Lgs 20/2007, the device can be awarded by the HEC certificate, having the rights to own White Certificates (WCs) and to purchase natural gas without duties. Besides, being its capacity below 200 kW, it can access to the favorable NM mechanism.

Such a type of regulation forces the power produced by the CCHP to be greater during the winter season, since in this period the thermal needs of the building are higher. Thus, unlike all other users where only PV panels are in force, here the energy produced could be major in winter than in summer.

Knowing that the production curve arises from two contributions, the winter and summer profiles are drawn also for the mall [Figg. 50-51].

As anticipated, the winter production seems higher, thanks to the late evening peak; since no solar radiation is present, it is only due to the CCHP contribution. Like in the supermarket, there is a surplus of energy produced that is fed into the grid, confirming what has been predicted when analyzing the building shape [Table 4]: these two buildings are expected to have high SS, as it is suggested by the withdrawn power equal to zero during days. On the other hand, SC is expected to much lower than the office due to huge exports.

In conclusion, consequently to their shape and to the technologies installed, the EC is composed of four *prosumers* with different power profiles. More precisely, there are users affected by large power exports to be used by other members: these buildings are those that *pay the bill for everyone*. On the other hand, an EC makes sense if there are also users featured by the opposite situation, needing energy to avoid withdrawals. Therefore, users having different needs and availability are the basis to make a *load-production* sharing strategy effective.

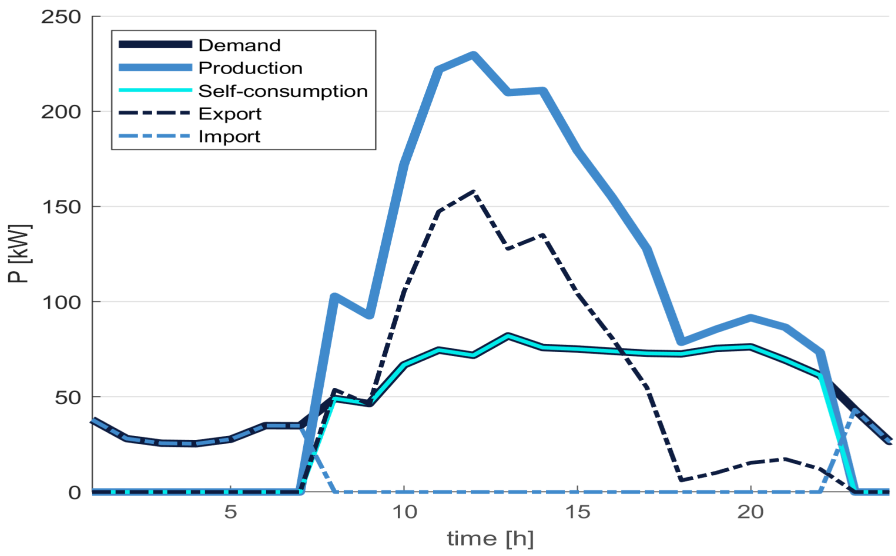

Figure 50: Mall power profiles in a winter day (31^{th} January).

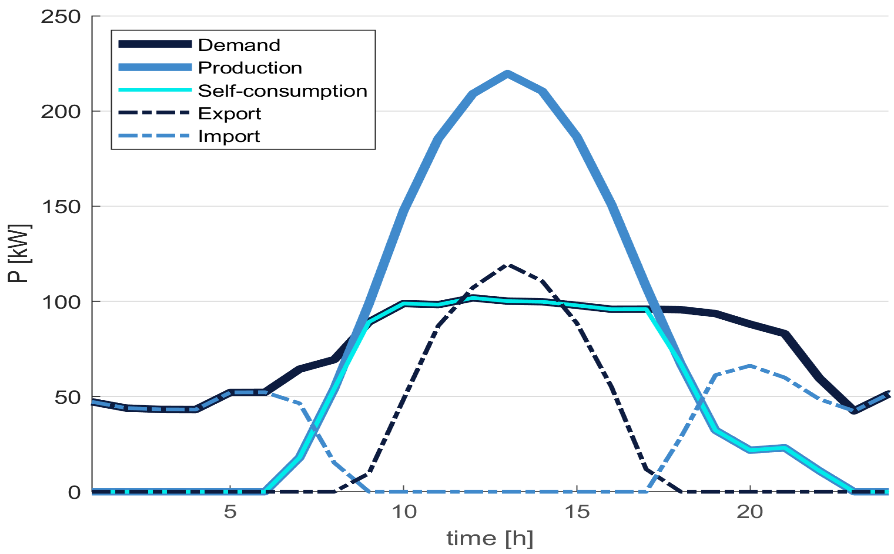

Figure 51: Mall power profiles in a summer day (15^{th} July).

5.3 Scenarios energy KPI

After this presentation of the single buildings, the two scenarios can be compared from a technical point of view.

5.3.1 Single Self-Consumers configuration results

To evaluate to which extent the energy sharing is a benefit, the SSCs configuration needs to be analyzed: Table 9 reports the capacity of the new technologies, while Table 10 sums up the yearly needs and availabilities of each user. The demand is expressed in kWh_{el} and it has been divided into the three needs to be satisfied.
Table 10 confirms what has been previously suggested by the profiles. The mall presents the highest energy surplus, while the office is the building that picks up more electricity, therefore in the EC scenario, there will be a power flux between these two users. The *total* row gives an idea of the amount of energy which passes through the grid; it is important

User	PV	HP	CHP	Absorption Chiller
Condominium	30	32	-	-
Office	99	92	-	-
Supermarket	98	-	-	-
Mall	190	-	190	75

Table 9: New technologies capacity [kW].

User	Electrical Demand			Production		SC	Exp.	Imp.
	Heating	Cooling	Electricity	RES	not RES			
Condominium	28.5	6.2	47.0	46.0	-	25.1	20.8	56.6
Office	106.9	45.2	651.3	153.2	-	148.6	4.6	654.8
Supermarket	-	8.6	247.0	149.4	-	100.7	48.6	155.0
Mall	-	-	543.1	287.2	235.7	332.0	190.9	211.0
TOTAL	135.4	60.0	1488.4	635.8	235.7	606.4	285.0	1077.4

Table 10: Energy balance of each user [MWh]. **SC**=Self-Consumed; **Exp.**=Fed into the grid; **Imp.**=Withdrawn.

to understand that ECs exploiting public networks cannot change these flows. In other words, in the grid it will transit always the same power, the only difference is the shorter path through which it must transit to satisfy a request.
The bar plot of Fig. 52 represents the two energy KPIs, SS and SC, for all the buildings.

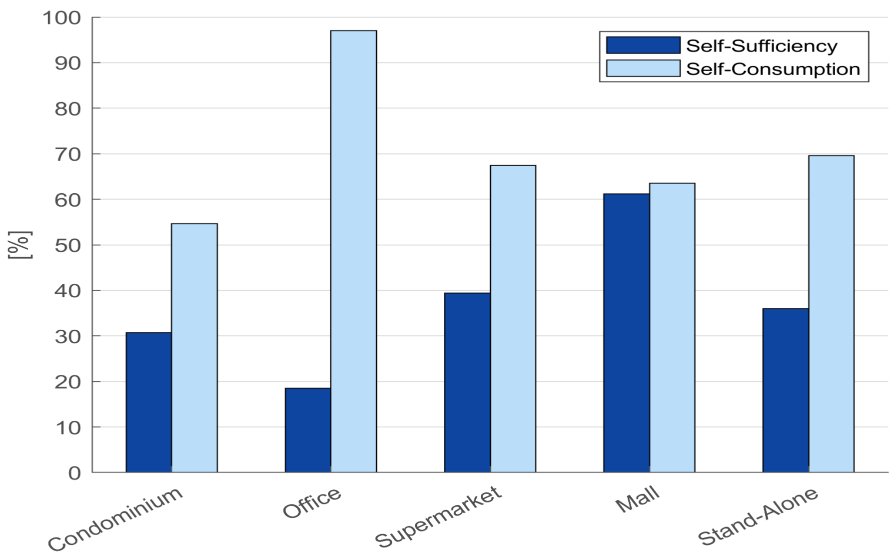

Figure 52: Self-Sufficiency and Self-Consumption in each user.

The global values have been defined as a weighted average of the four buildings and they are the numbers to compare with the following EC results. The aggregate consumes directly on-site the 70% of the produced energy. Moreover, it satisfies about 35% of its demand exploiting electricity generated by itself, indicating that the *Production-Load* ratio is about 50%. Finally, from an economic point of view, considering that SC is the best way to foster the investment done for becoming a *prosumer*, currently a full savings can be encountered only on 3.5 out of 10 $kWh's$ requested.

5.3.2 EC configuration results

To correctly address the EC results, a brief analysis of the interaction of the total load and the total production is necessary. Both these profiles are logically the sum of the four different contributions [Figg. 53-54] and analyzing their daily matching is essential to understand where the SC enhancement comes from.

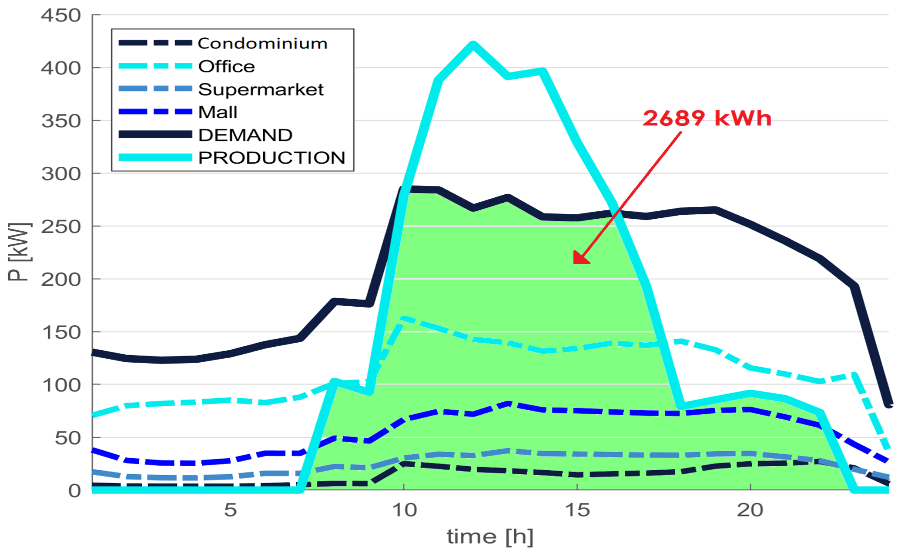

Figure 53: EC demand and production profiles in a winter day (31^{th} January).

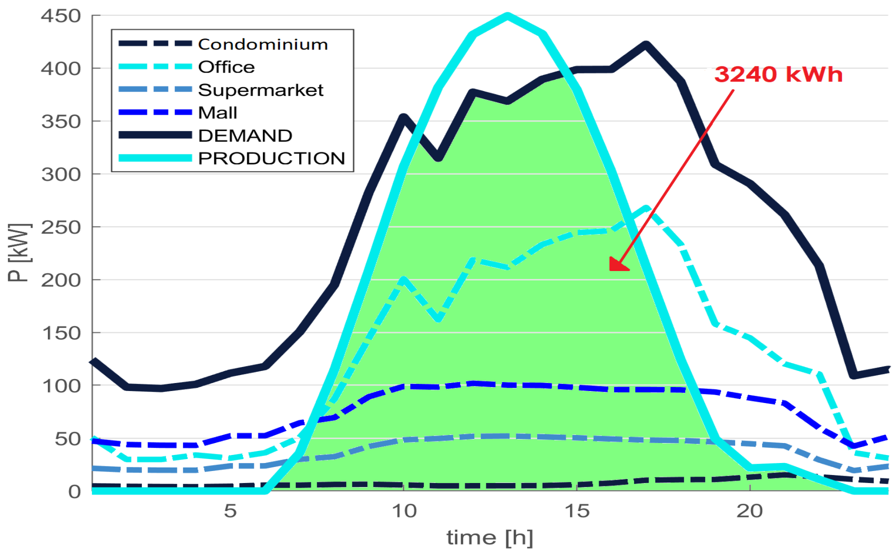

Figure 54: EC demand and production profiles in a summer day (15^{th} July).

In these plots, it is possible to see separately the load of the four buildings, which contribute to determine the total demand curve. They represent also the production curve, for visualizing the share of self-consumed energy, represented by the area highlighted in green. As already said, it is important to stress that an amount of this energy, even if it is classified as consumed on-site, passes through the public grid. First of all, the load combination flattening effect, discussed qualitatively in Section 5.1.4, has been confirmed: especially in winter, where the afternoon peak demand is absent, the load is quite steady all day. The interaction between commercial and residential users can be appreciated more in summer: PV production excesses during day, when dwellings are empty, can feed other users. The higher electricity request during summer is the main reason for a bigger amount of energy consumed within the community, about 20% more than on a typical winter day in which the PV productivity is quite high (i.e. there is enough solar radiation).

A further step of the comparison is provided by directly studying the power profiles of the two scenarios. The following plots [Figg. 55-56] highlight the increase of SC on the usual two representative days.

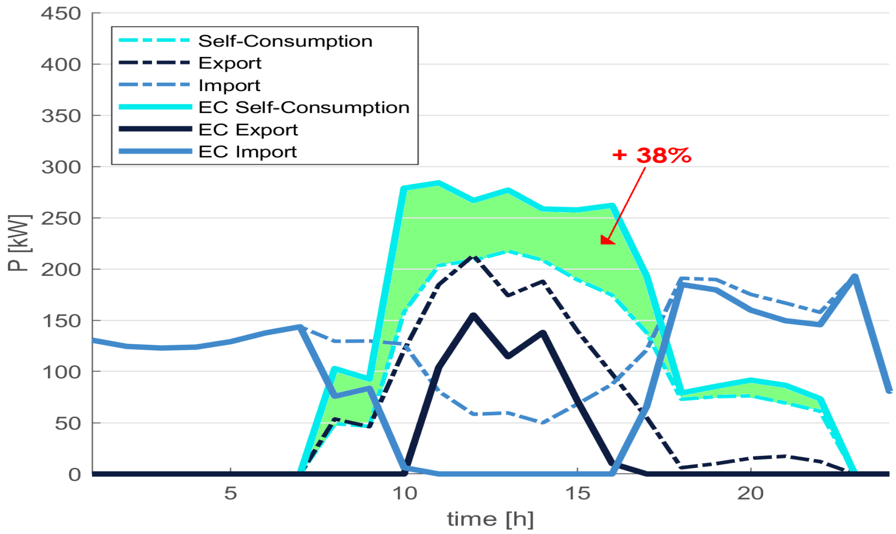

Figure 55: EC power profiles in a winter day (31^{th} January).

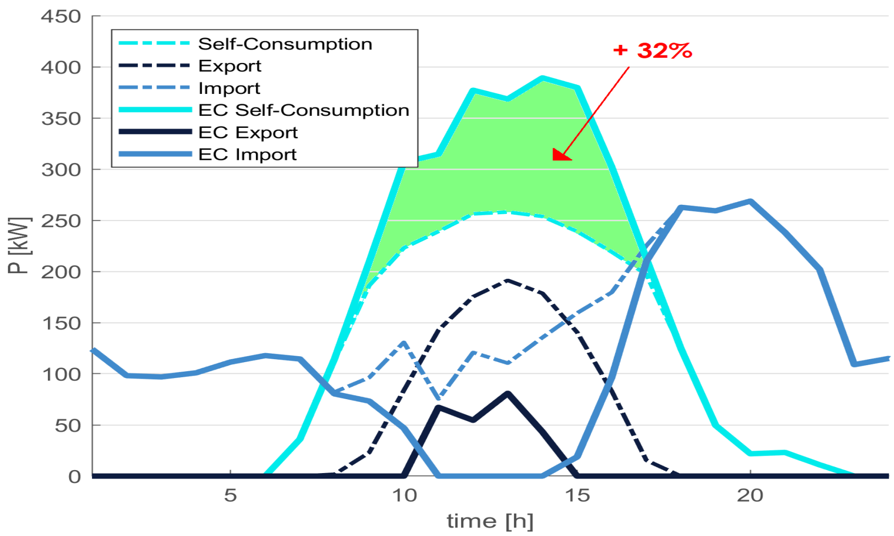

Figure 56: EC power profiles in a summer day (15^{th} July).

In these plots, the dot-dashed lines represent the power profiles of the SSCs scenario, that simply arises from the sum of the four separate buildings. The first thing that stands out

is the contemporaneity of power withdrawn from and fed to the grid: accordingly to the algorithm explained in Section 4.4 there is the possibility to enhance the SC, making sure that the building(s) that is picking up takes advantage of the overproduction user(s). In both days, being the PV productivity high, it is the withdrawn power that goes to zero while the SC increases by the corresponding amount. Logically, there will be days of low productivity in which the opposite happens, where no power is exported: the EC cancels out the contemporaneity of import and export profiles.
In both days the relative enhancement of the self-consumption is higher than the yearly mean value, because the demand matches well with the production.

The bar chart of Fig. 57 makes a monthly comparison, to understand when the improvement is more pronounced. First of all, every month presents an SC fraction bigger than 80%, with a global average yearly increase of 25.77%; during winter, the rise is more marked because of the mall. As a matter of fact, in the SSCs scenario, it exported the huge production excesses coming from the higher CCHP power output during heating seasons, which badly matched the limited electricity demand, which instead is larger in summer. In the EC configuration, this overproduction can be directed towards other users, as the office. Such a phenomenon is even more pronounced when solar radiation is low. Considering a very cold winter day, the CCHP production is high to cope with the large heating requirements while the one from PV is almost negligible. If the mall is disconnected from the other users, this power is fed into the grid while other buildings are forced to withdraw: this translates into a very huge relative increase of the self-consumption in the EC mode, which reaches in some cases (e.g. 14^{th} January) the 90%. That is why in winter large enhancement are encountered.

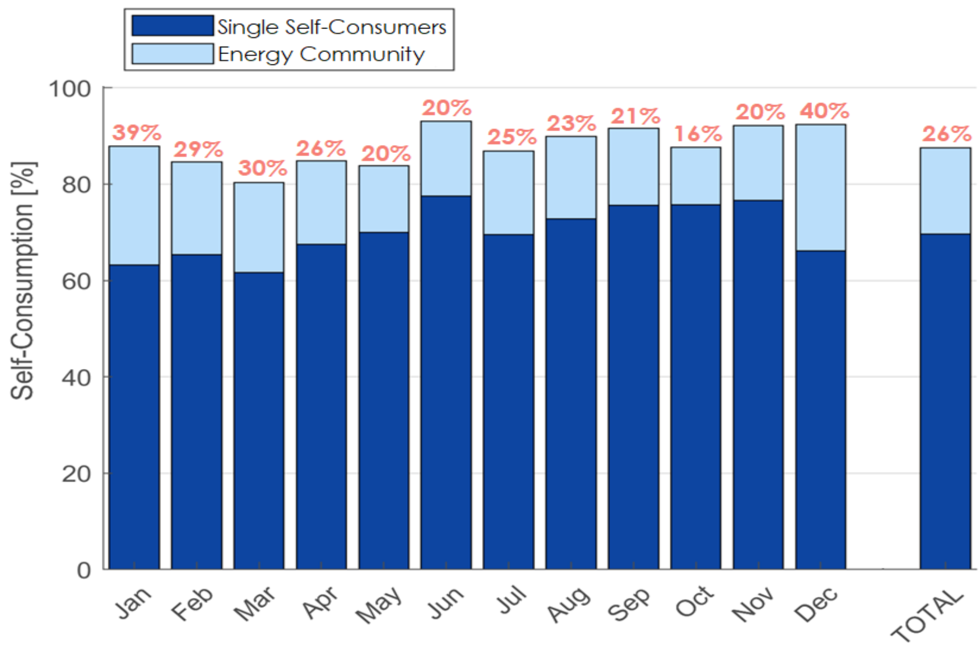

Figure 57: *SC* in the two configurations: the increase in EC mode is highlighted.

Nevertheless, it is worth noting that summer weights more on the total SC, being it the weighted average on the produced energy. Therefore, the final number is more affected by what happens in the seasons where a large productivity is registered. To conclude the energy assessment of the EC, Table 11 resumes the main results of the two configurations, reporting also the KPIs.

Scenario	E_{self} $[MWh]$	E_{exp} $[MWh]$	E_{imp} $[MWh]$	SS [%]	SC [%]
Single Self-Consumers	606	264	1077	36.0	69.6
Energy Community	762	108	921	45.3	87.5

Table 11: Final comparison: Single Self-Consumers vs. Energy Community.

It is worth noting that the demand and the productivity are always the same. As a result, the sum of self-consumed and imported, as well as that of self-consumed and exported, must be constant in both scenarios and consistent with the values of Table 10. On the other hand, as a consequence of self-consumed energy increase, both SS and SC increase by 26%.

To conclude and as a premise to the next section, the EC configuration involves two effects:

- An enhancement of the self-consumed energy equal to 156 $MWh's$. This has been already widely addressed and it is the main objective of the community, indeed the reason why it was born.
- A reduction of the energy exchanged with the *external* grid. The same 156 $MWh's$ are no longer fed or withdrawn to/from the grid.

Both these aspects have to be seen also from an economic point of view. The 156 $MWh's$ no more imported represent a full saving, since before they were bought while now the cooperation makes them free (as long as any additional charges are paid for the use of public grid, through which they pass). On the other hand, these 156 $MWh's$ are also no more sold and this represents an economic loss for users.
As it will be demonstrated, the first effect prevails on the second, making ECs an economically convenient choice. Nevertheless, if heavy taxes are paid on the *indirect* self-consumption, this advantage might become very little, making the community less attractive for citizens and entrepreneurs. In other words, politicians will play a key role in designing a suitable regulatory framework in which energy sharing can be a feasible solution. With this foreword, the economic comparison EC-SSCs, the *core* of the thesis, can start.

5.4 Economic assessment of the community

In this section, the economic comparison is simulated below different economic scenarios, trying to find if there are legislative conditions that would favor. In each one, the additional charges applied on the energy internally exchanged, that has to pass through the public grid, have been varied. The final aim is to compare the yearly electricity bills [Section 4.5.1], seeing how each item (energy, transport charges etc.) weights, and the whole investment in 20 years, with NPV, PBT and IRR as indicators [Section 4.5.3].

5.4.1 1^{st} economic scenario: definition

The first framework analyzed is the one where trades with the external grid are regulated by the Net Metering (NM) mechanism. Table 12 shows the various aspects of this framework, such as what tax deductions are applied and electricity market conditions.
The cost of the energy item $c_{ee,en}$, that contributes with other voices [Section 3.1] to establish the final electricity price, has been taken from the ARERA database [20], doing

Feature	Mechanism or Fares
Grid exchange	NM ~~FER~~
Tax deductions	~~PV $< 20\,kW$ (50% on a max. expenditure of $96,000$ €)~~ HP (50% on a max. expenditure of $100,000$ €) CHP (65% on a max. expenditure of $100,000$ €)
Market	Protected ($c_{ee,en} = 0.0841$ €$/kWh$) ~~Free~~

Table 12: 1^{st} economic scenario definition.

a mean of the prices in the different consumption bands and hypothesizing all users connected in low voltage. Data about applicable deductions on new technologies CAPEX (share and maximum expenditures) are provided by ENEA [21].

The PV capacity overcomes the limit for enjoying tax deductions [Table 9]; however, as generic analysis about ECs, this topic deserves a little insight. The current Italian legislation [22] establishes deductions for PV plants whose capacity is smaller than 20 kW, provided that they are placed to serve only the dwelling. On the other hand, when introducing the EC utterance, the RED II (art. 22, issue 2) [23] talks about production unit *"owned"* by the community and therefore, by definition, aimed at serving also other users. For what concerns this work, surely no user in the SSCs configuration can benefit PV incentives and, given the previous speculation, they are neither included for the EC. As far as the natural gas is concerned, its cost has been considered equal to $c_{gas} = 0.7651$ €$/Sm^3$. Then, the gas feeding the CCHP system is bought at $c_{gas,CCHP} = 0.6008$ €$/Sm^3$ [25], according to the excise duty exemption coming from the HEC accreditation.

5.4.2 1^{st} economic scenario: bills analysis

Doing a bills analysis means to quantify the savings achieved through the retrofit. Table 13 shows the yearly expenditures of each user before and after the retrofit. It shows basically the total yearly savings achieved by the SSCs configuration, summed up in the *total* row. The last column highlights the NM contribution, that after [see Section 5.4.4] is compared with another selling mechanism.
Calculations prove a global 32% saving on the electrical bill, while the total gas expenditures increase, as a result of the CCHP installation, by 10%. Directly on the bill 102.3 k€ are saved, to which the contribution of the NT should be added, leading to a total yearly net earning of 113.5 k€. Logically, the refund is higher in users where grid exports are higher, indeed where SS is too.

To assess the final results of the HP optimization algorithm, the bills of the condominium and the office must be analyzed. In both cases, the saving associated with the gas reduction request is around $55\% - 60\%$, while the addition of a new electrically-driven device increases the condominium expenditures. Instead, it is worth noting that office electricity bills have slightly decreased. This difference between the users may be attributed

User	Scenario	Gas	Electricity				
			Energy	Transp.	System	Duty	NM
Condominium	BAU	11.2	4.5	2.1	2.6	1.4	-
	SSCs	4.9	4.8	2.2	2.8	1.5	-0.9
	Savings	6.3	-0.3	-0.1	-0.2	-0.1	0.9
		(56%)	(-6.7%)	(-6.7%)	(-6.7%)	(-6.7%)	-
Office	BAU	40.4	58.6	27.3	34.5	18.2	-
	SSCs	16.8	55.0	25.7	32.4	17.1	-0.2
	Savings	23.6	3.6	1.6	2.1	1.1	0.2
		(58%)	(6.1%)	(6.1%)	(6.1%)	(6.1%)	-
Supermarket	BAU	9.6	21.5	10.0	12.7	6.7	-
	SSCs	9.6	13.0	6.1	7.6	4.1	-2.1
	Savings	0.0	8.5	3.9	5.1	2.6	2.1
		(0%)	(40%)	(40%)	(40%)	(40%)	-
Mall	BAU	21.7	49.2	22.9	29.0	15.3	-
	SSCs	60.2	17.7	8.3	10.4	5.5	-8.0
	Savings	-38.5	31.5	14.6	18.6	9.8	8.0
		(-177%)	(64%)	(64%)	(64%)	(64%)	-
TOTAL	BAU	82.9	133.8	62.3	78.8	41.6	-
	SSCs	91.5	90.5	42.3	53.2	28.2	-11.2
	Savings	-8.6	43.3	20.0	25.6	13.4	11.2
		(-10%)	(32%)	(32%)	(32%)	(32%)	-

Table 13: Yearly bills comparison before and after the retrofit [k€].

to the reversible HP (cooling production is made with a more efficient device) and to a better matching between PV production and electricity demand. To conclude, before the HP installation, the specific expenditure to meet one kWh of heating demand was 0.0844 €$/kWh$, while the optimization algorithm (thanks also to the free energy from PV) has brought to a value of 0.0594 €$/kWh$.

Starting from this data, the EC-SSCs comparison is reported in Table 14, emphasizing the expenditure and the NM term in the two scenarios. The comparison is made only on electricity bills, since there are no differences in the natural gas ones.

Scenario	Electricity				
	Energy	Transp.	System	Duty	NM
Single Self-Consumers	90.5	42.3	53.2	28.2	-11.2
Energy Community	77.5	36.1	45.6	24.1	-4.6
Savings	13.0	6.2	7.6	4.1	-6.6
	(15%)	(15%)	(15%)	(15%)	(-59%)

Table 14: EC and SSCs electricity bills [k€].

Numbers in red have been found without considering any additional charges on the energy

internally exchanged; in the following pages, it is shown also the impact of such parameter. In this very favorable scenario, the energy sharing causes an *additional* 15% saving, but the refunding coming from the Net Metering has been reduced by 59%.
Remembering the numbers of the previous section, the 156 $MWh's$ no more withdrawn reduce the electricity bill (in exact proportion to the full cost of energy, since taxes are absent) of 30.9 $k€$; but, since they are also no more exported, 6.6 $k€$ are lost: the total yearly savings starting from the BAU scenario are 137.8 $k€$. The yearly electrical expenditure is 178.7 $k€$, shortened by 12% with respect to the SSCs scenario. The bar chart of Fig. 58 helps to understand these data graphically.

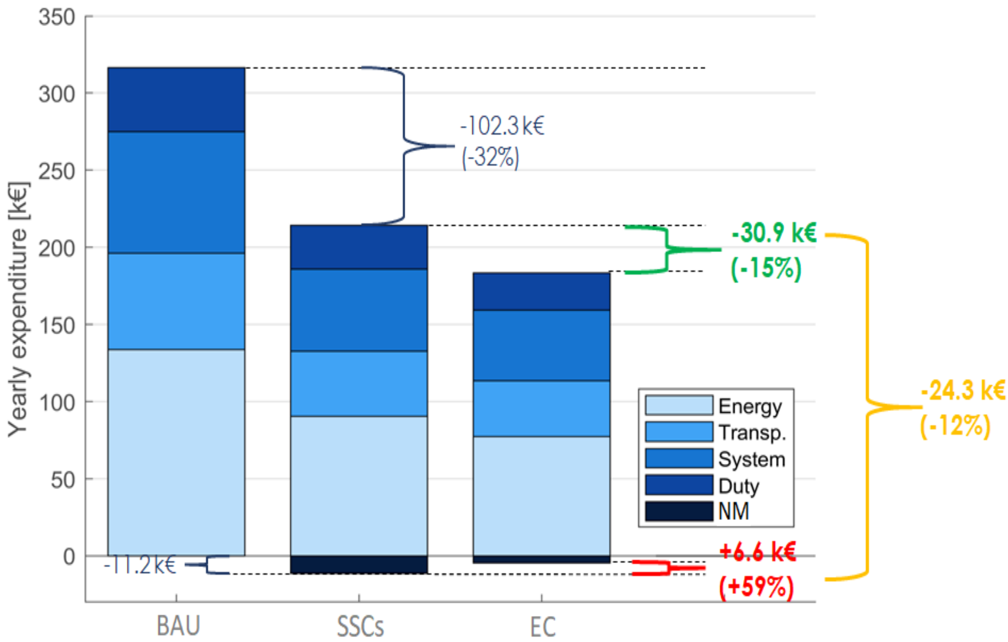

Figure 58: 1^{st} economic scenario: EC and SSCs electricity bills.

The EC positive effect may drop if system and/or transport charges have to be paid on the *indirect* self-consumption, as it would no longer represent a full saving concerning the energy price, but only the energy and the excise duty items would be entirely preserved. To go deeper into the issue, Fig. 59 shows how the EC relative savings, with respect to the SSCs scenario, decrease as the percentage of additional charges to be paid increase.

It is easy to observe that high taxes can make ECs much less attractive for investors and citizens. Even if lower yearly expenditures are always registered compared to the SSCs scenario, too little profit might not be worth the effort of building the community (setting up the legal entity, getting the various members to agree, establishing internal rules, etc.), pushing people towards the SSCs possibility. Nevertheless, the European Directive [23] affirms that Member States do not have to hinder EC constitution, thus the regulations cannot be too disadvantageous and a scenario in which full charges are paid is very unlikely. On the other hand, also the total absence of taxes on the energy passing through the public grid is unrealistic, as it belongs to the Government and ECs are expected to pay for its exploitation. Waiting for more precise regulations and reminding Section 3.1, the comments that may be done on additional charges are the following:

- *Transport Charges*: they include the cost of the transport, measurement, distribution and the UC3, UC6 tariff components. Since buildings have been supposed to

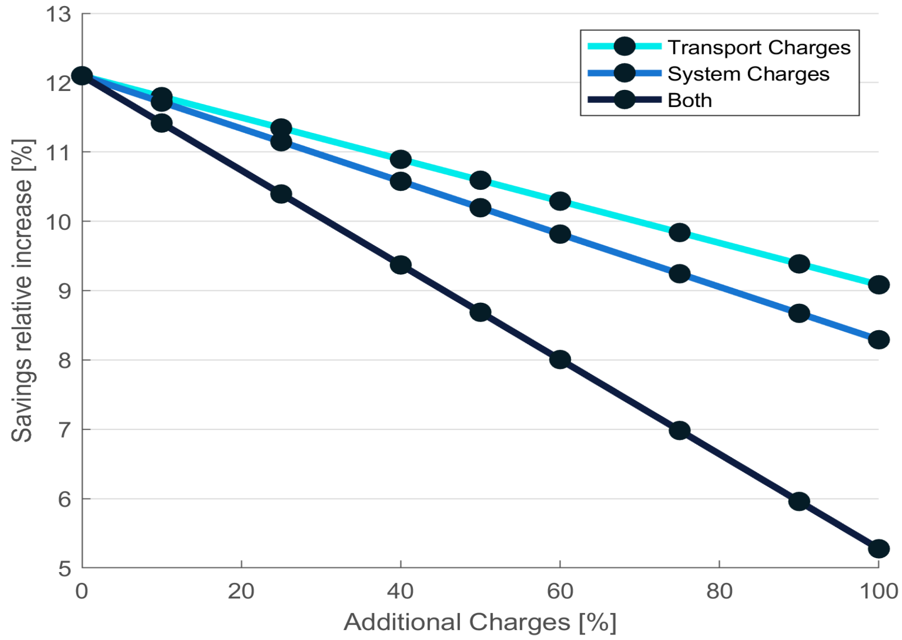

Figure 59: Impact of additional charges on EC further saving respect to SSCs scenario.

be *close* to each other and belonging to a zone served by the same secondary electrical substation, energy exchanged runs for a short path in the public grid and thus transport charges will be probably not entirely poured.

- *System Charges*: they include the cost for encouraging RES production and other generic charges concerning the whole national electric system. Since the money gained by the public authority through such taxes cannot be diminished, it is expected that they will be (almost) entirely paid [24].

Based on these speculations, only a percentage of the total additional charges would be paid, making the EC relative net gain around $6\% - 9\%$; anyway, these are only predictions deriving from *what is included* in the taxes. A favorable regulatory framework, that makes ECs truly economically attractive, is therefore necessary for their spread.

5.4.3 1^{st} economic scenario: cash flow analysis

To close the economic assessment and prove the EC feasibility, a cash flow analysis must be performed. Considering the initial investment cost and a period of 20 years, the investment as a whole has been evaluated for the two configurations. In the SSCs one, the NPVs of the four users have been individually computed only for this 1^{st} economic scenario, showing the single contributions to the total. Also for the cash flow, the EC KPIs increase from the SSCs has been studied as the magnitude of additional charges varies.
Fig. 60 shows the cash flow of the four users in time, while Table 15 sums up the economic KPIs of the SSCs configuration.
The *total* row simply arises from the sum of the four investments (NPV path is reported in Fig. 61) and it is the benchmark when it comes to compare the EC scenario. The most profitable investments are surely those done by the condominium, the office and the supermarket as their final NPV is almost three times the CAPEX. On the other hand, the mall has registered the worst performance, showing that costs incurred for purchasing

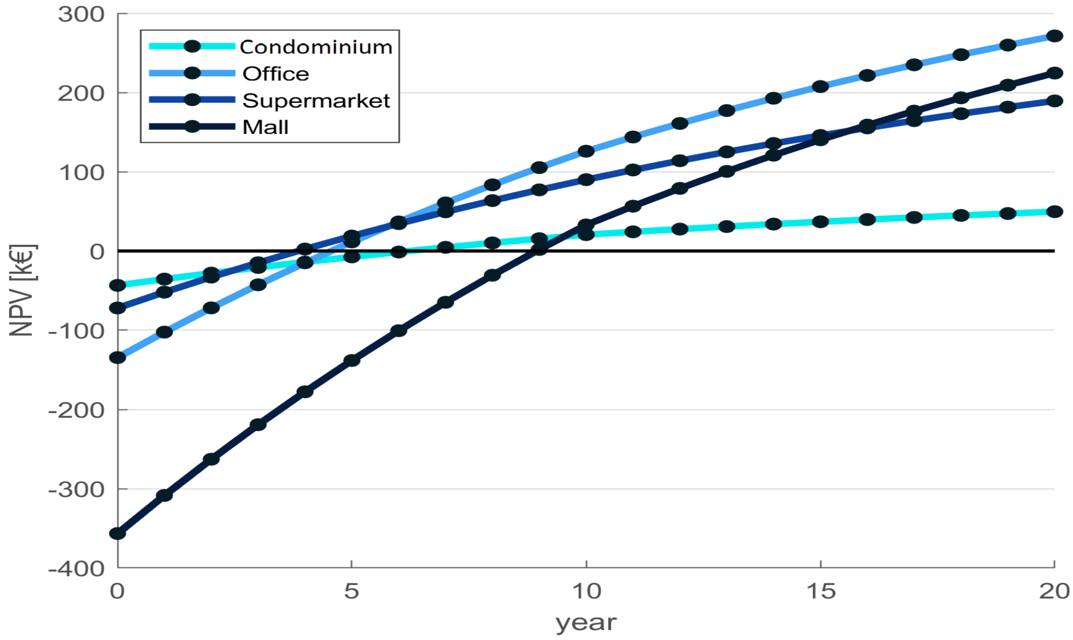

Figure 60: NPV in time of the four users.

User	**CAPEX** [k€]	**NPV** [k€]	**PBT** [y]	**IRR** [%]
Condominium	43	50	6-7	17.6
Office	135	271	4-5	24.6
Supermarket	72	189	3-4	29.0
Mall	357	225	8-9	12.1
TOTAL	607	735	6-7	17.6

Table 15: Single Self-Consumers cash flow analysis results.

the CCHP system might be not worthy of the reduction of the expenditures it implies. The global result indicates a positive cash flow, with an IRR greater than three times the established interest rate.

Fig. 61 and Table 16 resume the final comparison between the SSCs and EC configurations in this first economic scenario, without considering any extra charges.

Scenario	**CAPEX** [k€]	**NPV** [k€]	**PBT** [y]	**IRR** [%]
Single Self-Consumers	607	735	6-7	17.6
Energy Community	607	1033	5-6	21.9
Increase	-	+40.5%	-	+24.4%

Table 16: 1^{st} economic scenario: SSCs and EC economic KPIs comparison.

The higher yearly savings previously observed for the EC have led to a final net earning of about 300 k€, while the IRR has increased by 4.3 percentage points. These numbers suggest that ECs are valid alternatives to SSCs systems because they ensure not negligible additional profits, justifying any efforts made to establish them. However, this is the result in the upbeat scenario, where no additional charges are requested but the presence

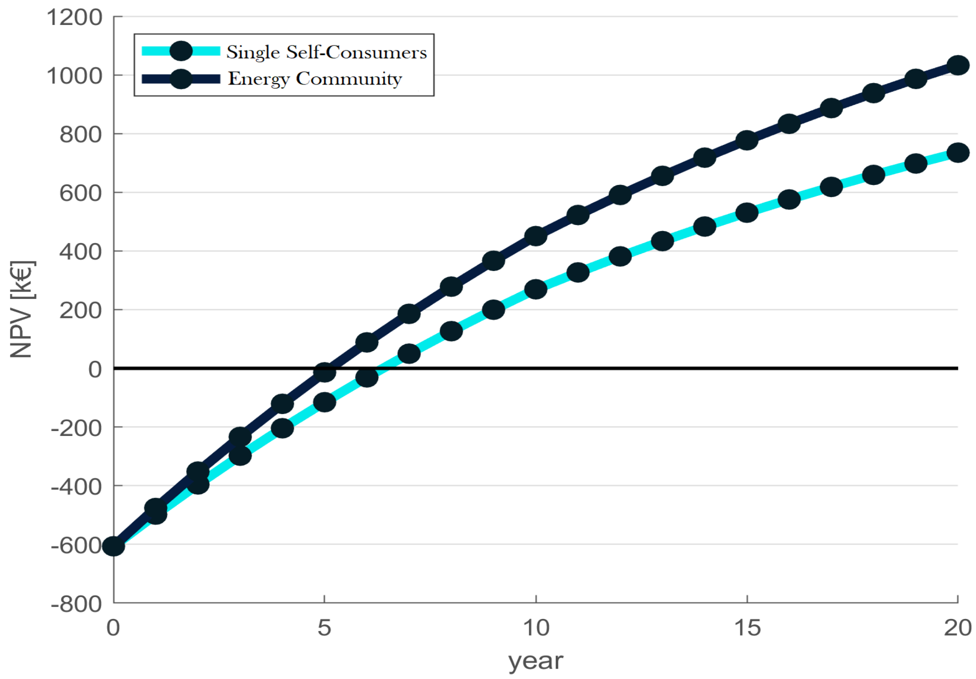

Figure 61: 1^{st} economic scenario: SSCs and EC NPV comparison.

of such taxes has a strong impact on ECs potentialities [Fig. 62].

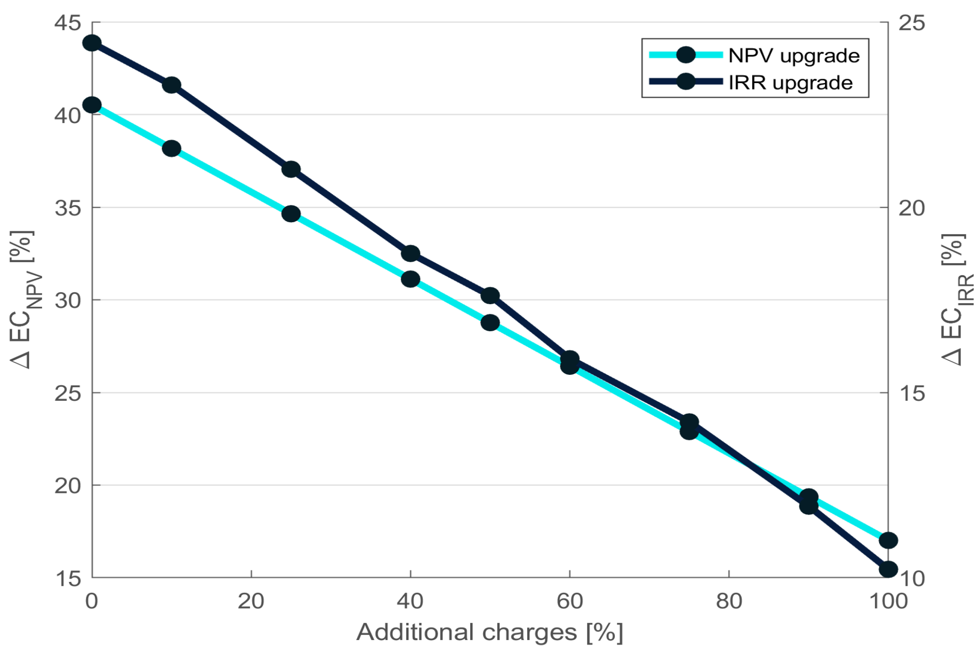

Figure 62: Impact of additional charges on EC economic potential.

The global investment is also heavily affected by the transport and system charges. Bearing in mind the considerations made before about what taxes are most likely to be paid, in a realistic hypothesis the cash flow analysis indicates a final NPV of about 950 $k€$, with an IRR equal to 20% and a PBT very close to the one of the SSCs scenario. This reinforces the previous observation about the policy-makers role in promoting energy sharing: compelling ECs to pay full charges would surely hamper their diffusion. As a

matter of fact, the differences with the SSCs configuration would be minimized and all the possible actors (municipalities, public and private investors, etc.) would not be motivated to enter into this cooperation, against the RED II principles.
The obtained conclusions are valid in the economic scenario initially defined, where the NM mechanism has been applied. Nevertheless, there are other ways to regulate energy exchanges with the grid as well as the possibility to exit from the protected market.

5.4.4 2^{nd} economic scenario

The 2^{nd} economic scenario is featured by the adhesion by all the users to the FER decree, while the CAPEX incentives and the protected market are kept [Table 39].

Feature	**Mechanism or Fares**
Grid exchange	~~NM~~ FER
Tax deductions	~~PV < 20 kW (50% on a max. expenditure of 96,000 €)~~ HP (50% on a max. expenditure of 100,000 €) CHP (65% on a max. expenditure of 100,000 €)
Market	Protected ($c_{ee,en} = 0.0841$ €$/kWh$) ~~Free~~

Table 17: 2^{nd} economic scenario definition.

The FER decree [Section 3.3.1] establishes constant tariffs, according to the PV installed capacity [Table 9], at which the produced energy can be sold. To this contribution, a possible *premium* may be added for plants below 100 kW on the self-consumed energy. In the SSCs configuration, each user will operate as follows [26]:

- **Condominium**: Given the installed capacity, it can sell at 0.105 €$/kWh$ and benefit from the SC premium.
- **Office**: Given the installed capacity, it can sell at 0.09 €$/kWh$ and benefit from the SC premium.
- **Supermarket**: Given the installed capacity, it can sell at 0.105 €$/kWh$ and benefit from the SC premium.
- **Mall**: Given the installed capacity, it can sell at 0.09 €$/kWh$ and does not benefit from the SC premium. Only the electricity from PV can be included in the FER, while the CCHP production is sold at PUN.

The EC has been considered as a unique user whose PV capacity is the sum of the single installations. Therefore, it sells at 0.09 €$/kWh$ and has access to the premium. Actually, the aspect of the premium is not so trivial, as it should be accessed only by plants up to 100 kWp; however, in the FER decree there is the mention to PV *"aggregates"* (art. 3, issue 10) that could access such a premium.

What changes from the 1^{st} economic scenario are the revenues from the energy sale, while the sum of electricity bills remains constant (equal to those shown in Table 13).

Table 18 [4] highlights the differences in gains concerning Net Metering and FER favorable rates.

User/Scenario	NM	FER	
		Sales	Premium
Condominium	0.9	1.6	0.2
Office	0.2	0.4	1.6
Supermarket	2.1	4.8	1.3
Mall	8.0	12.3	-
SSCs	11.2	20.0	3.1
EC	4.6 (−59%)	9.4 (−53%)	5.6 (+81%)

Table 18: FER and NM revenues comparison [k€].

In this economic scenario, the SC premium helps to contain the EC losses due to smaller export: gains from energy sale are reduced only by 35%. Generally speaking, the adhesion to the FER decree is much more favorable with respect to the NM mechanism, since it provides the community with 9.2 k€ more, leading to a total yearly electricity expenditure (without additional taxes) of 168 k€.
To sum up, FER tariffs are more convenient for users whose RES capacity installations is higher than 20 kW, as it is for the buildings of this case study; they can sell for 20 years at a guaranteed price always higher than the PUN, which is the benchmark for the NM mechanism. The latter was created to promote the use of the network as a virtual storage for the energy excesses in domestic dwellings, featured by small PV plants [27]. For larger buildings, and also for ECs as aggregates characterized by great capacities, the adhesion to the FER decree is absolutely the best choice.
The bar chart of Fig. 63 shows the savings from the BAU scenario with FER selling tariffs without taxes, highlighting the difference between SSCs and EC.
The greater importance of the sales term can be appreciated also graphically if compared with that of Fig. 58. Even if this economic scenario brings to bigger savings, the relative increase between achieved by the EC scenario compared to the SSCs is very similar to that of the previous framework, if not additional taxes are applied.

Finally, the cash flow analysis is provided [Fig. 64]. It is important to mention the great improvement of the mall compared to the previous economic scenario [Table 15]: by selling the huge PV production excesses, the final NPV has reached 332 k€. The FER positive effects have been confirmed also by the cash flow analysis, since the final NPV has increased by 124 k€, making the investment more attractive. Table 19 highlights the main parameters of the cash flow analysis, reaffirming that FER membership is surely the best choice.
Nevertheless, the FER adhesion reduces also the gap between the SSCs and the EC configurations, being the latter increase worse than the previous framework. The NPV increase has been almost halved and also the IRR one has undergone a substantial decline. These results may be attributed again to the advantageous FER tariffs; as a matter of fact, this framework suffers more the EC energy sales losses as they correspond to higher monetary losses due to the FER adhesion.

[4] Mall sales value considers also gains from CHP.

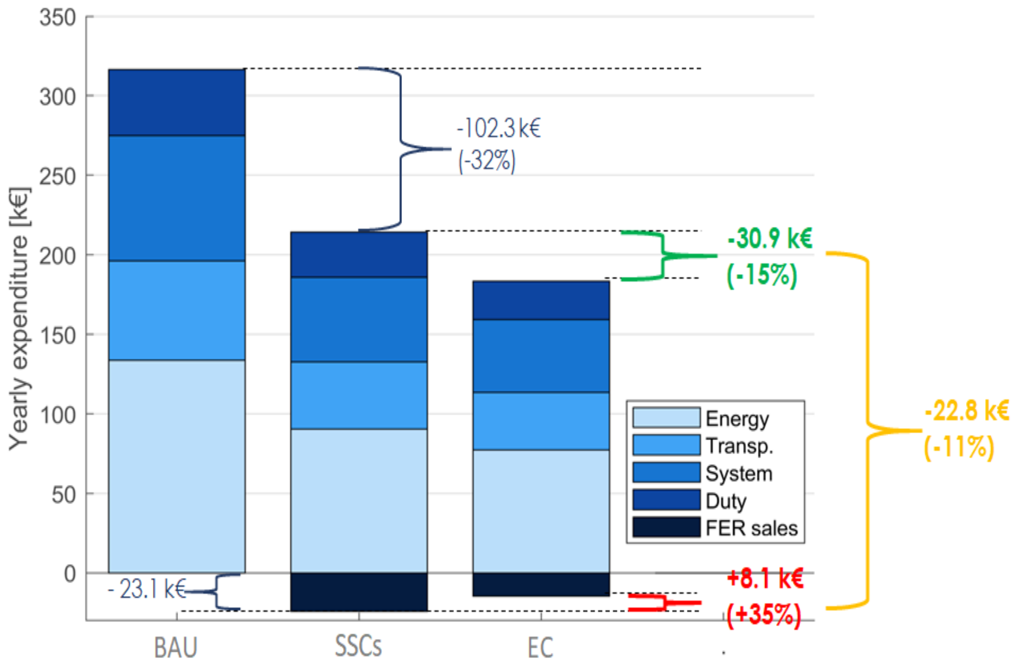

Figure 63: 2^{nd} economic scenario: EC and SSCs electricity bills.

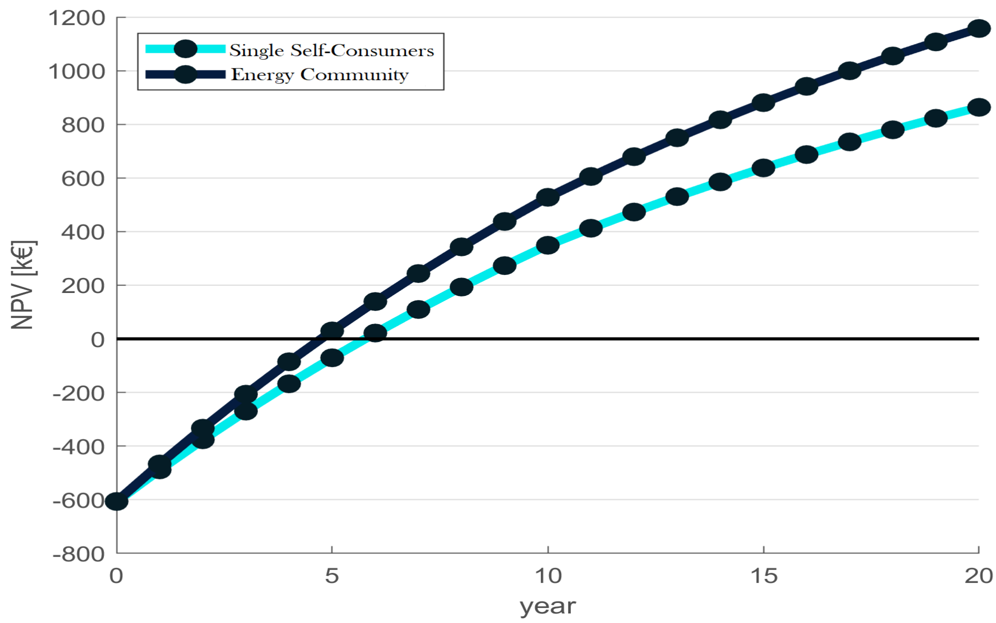

Figure 64: 2^{nd} economic scenario: SSCs and EC NPV comparison.

Scenario	**CAPEX** [$k€$]	**NPV** [$k€$]	**PBT** [y]	**IRR** [%]
Single Self-Consumers	607	914	5-6	20.3
Energy Community	607	1157	4-5	23.7
Increase	-	+26.6%	-	+16.7%

Table 19: 2^{nd} economic scenario: SSCs and EC economic KPIs comparison.

5.4.5 3^{rd} economic scenario

In the last simulated economic scenario, a discount on the electricity purchase price has been considered: the SSCs configuration has kept the same price, while the EC has left the protected market, signing an agreement with a private energy supplier. Remembering the four parts in which the electricity bill is divided [Section 3.3.1], the free market may ensure a discount on the energy item, while the other three items have to be kept constant, as they are established by the public authority. The selling mechanism is still the adhesion to the FER decree [Table 20].

Feature	**Mechanism or Fares**
Grid exchange	~~NM~~ FER
Tax deductions	~~PV $< 20\,kW$ (50% on a max. expenditure of 96,000 €)~~ HP (50% on a max. expenditure of 100,000 €) CHP (65% on a max. expenditure of 100,000 €)
Market	~~Protected ($c_{ee,en} = 0.0841$ €$/kWh$)~~ Free

Table 20: 3^{rd} economic scenario definition.

It has been hypothesized that the EC has entered into a contract where he got a 25% discount on the energy item $c_{ee,en}$, being it reduced to 0.0631 €$/kWh$, leading to a total electricity cost $c_{ee} = 0.1780$ €$/kWh$.

In Fig. 65 the histogram showing the bill items is reported. With respect to the previous cases, here the impact of the EC is more accentuated as a logical consequence of the electricity price reduction. If no additional charges are considered, the EC scenario brings to a 21% reduction in yearly expenditures compared to the SSCs one, with a total saving of 159 k€.
As expected, also the cash flow analysis has highlighted more the EC potentialities [Fig. 66]. The final NPV is 1397 k€ (52.9% more), while the IRR (equal to 27.0%) has increased by 33% [Table 21].

Scenario	**CAPEX** [k€]	**NPV** [k€]	**PBT** [y]	**IRR** [%]
Single Self-Consumers	607	914	5-6	20.3
Energy Community	607	1397	4-5	27.0
Increase	-	+52.9%	-	+33.0%

Table 21: 3^{rd} economic scenario: SSCs and EC economic KPIs comparison.

Generally speaking, the rise of transport and system charges on the energy internally exchanged causes a steady decrease (as it was in the previous economic scenarios) of the EC increase, reducing it up to 40% for the NPV. To better visualize all these data and sum up the main findings of the comparison, a table is provided in the next paragraph.

This last economic scenario is surely the most advantageous among those seen so far. However, it is based on an *optimistic* hypothesis, namely the presence of an energy

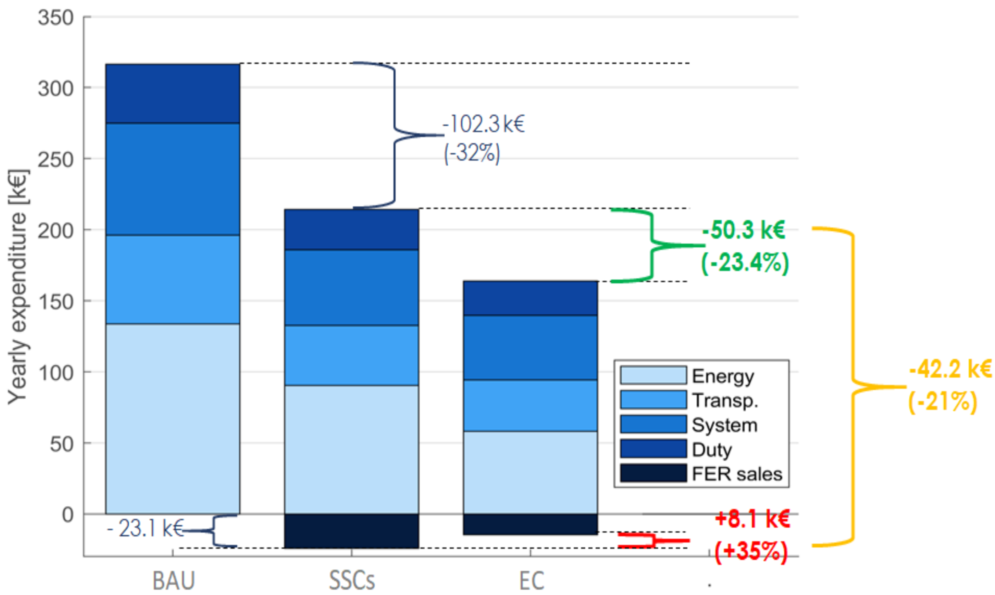

Figure 65: 3^{rd} economic scenario: EC and SSCs electricity bills.

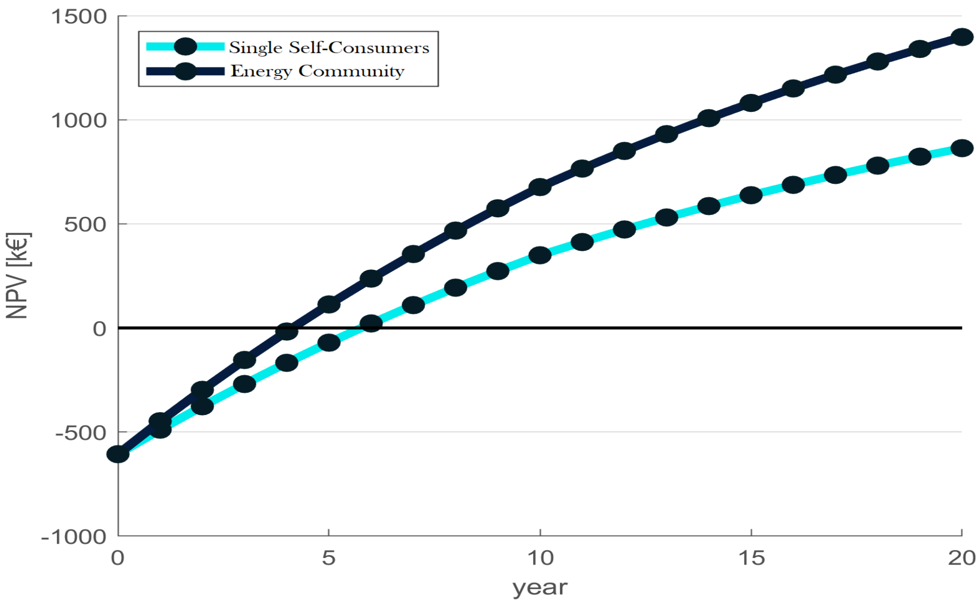

Figure 66: 3^{rd} economic scenario: SSCs and EC NPV comparison.

supplier who, perhaps identifying in the community a great consumer, offers a favorable price to it. On the other hand, the willingness of the owner (the entrepreneur/manager, head of the legal entity represented by the EC) could play an essential role in achieving such a contract, one of its tasks being to maximize participants' revenues [23].

5.4.6 Recap of economic scenarios results

Table 22 sums up the main findings about the SSCs-EC comparison in each economic scenario. The *cost* column represents the yearly electricity expenditures, while the *savings* one refers to the money saved from the BAU scenario. Percentages in brackets indicate the relative EC increase compared to the SSCs configurations.
By looking to these numbers, the following conclusions can be drawn:

Economic scenario		Bills analysis		Cash flow	
Number	Additional taxes	Cost [$k€$]	SSCsvings [$k€$]	NPV [$k€$]	IRR [%]
1^{st}	0%	179 (−12.1%)	130 (+23.3%)	1033 (+40.5%)	21.9 (+24.4%)
	50%	186 (−8.7%)	123 (+16.8%)	946 (+28.8%)	20.7 (+17.6%)
	100%	192 (−5.3%)	116 (+10.2%)	860 (+17.0%)	19.4 (+10.2%)
2^{nd}	0%	168 (−11.7%)	140 (+16.9%)	1157 (+26.6%)	23.7 (+16.8%)
	50%	176 (−8.1%)	133 (+11.1%)	1071 (+17.2%)	22.5 (+10.8%)
	100%	182 (−4.4%)	126 (+5.3%)	984 (+7, 7%)	21.2 (+4.4%)
3^{rd}	0%	149 (−21.7%)	159 (+34.6%)	1397 (+52.9%)	27.0 (+33.0%)
	50%	156 (−18.1%)	152 (+28.6%)	1311 (+43.4%)	25.8 (+27.1%)
	100%	163 (−14.5%)	145 (+22.5%)	1225 (+34.0%)	24.6 (+21.1%)

Table 22: Recap of the main findings of each economic scenario.

- FER tariffs are much more convenient than NT mechanism for large users (as usually an EC is). Moreover, being constant for 20 years, they protect the community by possible PUN sudden changes that have been neglected in this economic assessment.
- The 2^{nd} economic scenario brings to the lowest increase in the cash flow economic KPIs: below its regulations, ECs do not present a so big advantage. On the other hand, such advantage is achieved if, always with FER tariffs, the EC obtains a discount on the electricity purchase price by joining the free market (3^{rd} economic scenario).
- Apart from the numeric results, the possible payment of transport and system charges for the public grid exploitation strongly affects all the economic KPIs of the community, reducing its expediency and making it less attractive. Nevertheless, also in the worst case, positive increases have been always registered, meaning that the self-consumption enhancement always overcomes the lost sales.

5.5 Sensitivity analysis: PV installed capacity

To close the results presentation, a pertinent sensitivity analysis of the total PV installed capacity is provided. This parameter heavily affects the energy and economic performance of ECs; thus, understanding the existence of possible optima is a key issue. The PV capacity has been established, for the previous simulations, accordingly to the constraint of

the building dimension. Each roof has been supposed to be covered as much as possible by PV panels: considering a proper clearance factor, 70% of each roof is occupied. Proceeding with this logic, capacities reported in Table 9 have been obtained, for a total installed capacity of 417 kW.
Without varying the optimal tilt and orientation previously found [Section 5.2.1], here the comparison is simulated also with bigger PV area. In other words, neglecting the geometric constraints, it is analyzed the impact that larger PV capacity would have, aiming at finding optimal ratio between produced and consumed energy. Please note that the percentage contribution of each PV user to the total PV capacity is kept constant; in other words, starting from the base case, the PV area A_{PV} has been changed without varying the ratio $A_{PV,i}/A_{PV}$, where i indicates the generic building. In this way, the aid of each user to the total RES production, as a proportion of the total, remains constant.

The *Production-Load* ratio steadily rises as the PV installed capacity increases, since the energy produced is directly proportional to it (this is completely true for high PV areas, when the CCHP contribution becomes negligible), while the load remains constant. Fig. 67 shows what happens to EC produced and self-consumed energy and how the SC changes.

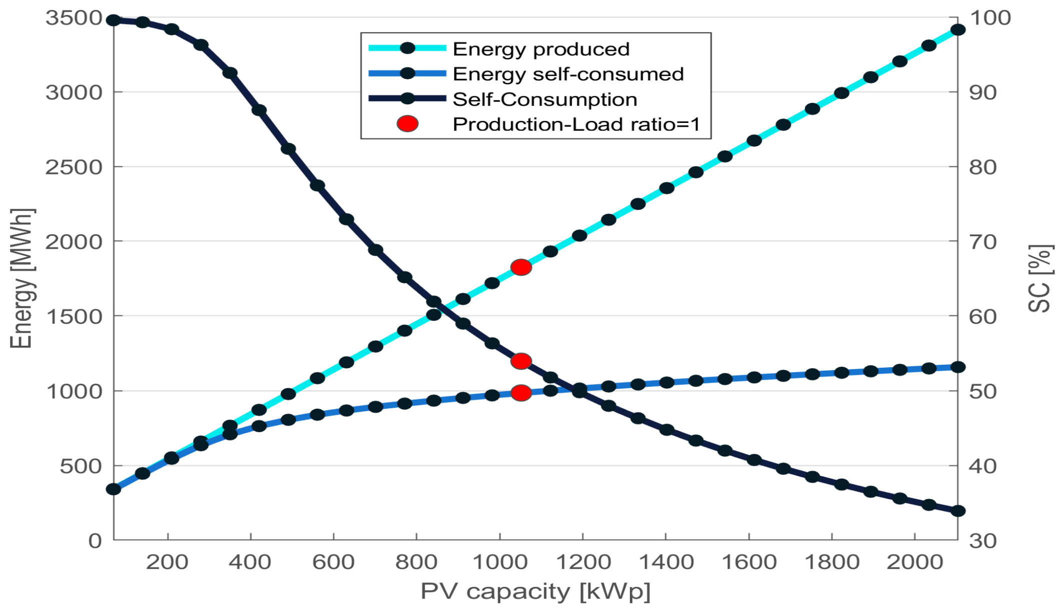

Figure 67: Produced and self-consumed energy trends.

As expected, the fraction of the energy directly consumed on-site goes down when the produced one becomes bigger. More precisely, the plot presents three different zone:

- At the beginning, the production is so low that, even adding new PV panels, all the energy is always consumed on-site and there is none left for exports. Both self-consumed and produced energy follows a linear law and SC is consequently constant;
- In the central part, the path is similar to a decreasing straight line, meaning that the self-consumed energy increases more slowly compared to the produced one, which follows always a linear law.
- Finally, the last part (that begins more or less when the P/L ratio is equal to one) follows an inversely proportional law, where $SC \propto 1/A_{PV}$. The energy that can be

locally consumed has reached its maximum value and it can no more rise, thus the electricity coming from the new PV panels must be all exported.

With this foreword, it is interesting to analyze how the PV capacity affects the SC enhancement achieved by the EC with respect to the SSCs scenario. Fig. 68 reports again the *SC* curve, together with its increase value in the community configuration. Such parameter has a maximum for the PV installed capacity corresponding to a $SC = 87.5\%$. The physical reason for such a point are evident if the impact of the community in offering energy to other users is taken into account. As a matter of fact, for low PV area, *SC* is always high, both in the SA and the EC configurations: each prosumer own consumes its energy and there is no availability for extra loads. As the production increases, energy excesses rise and the community aid to transform them in *SC* can be appreciated: the EC impact thus grows until the maximum is reached. If the PV capacity increases again, an ever-decreasing share of the buildings' load will remain unsatisfied by self-production, causing an EC contribution less marked. In other words, for very large PV areas, so much energy is produced that all the SSCs prosumers have enough it for their needs.

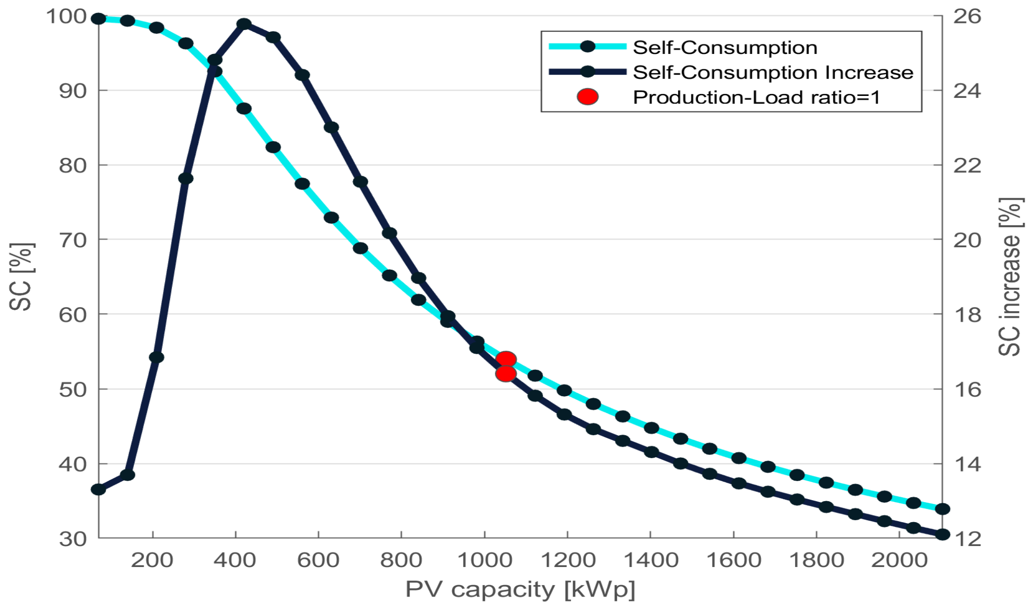

Figure 68: *SC* (left) and its relative increase (right) in the EC scenario.

To sum up, it exists a precise PV capacity for which the potentialities of ECs are maximized; however, saying that this is the best size for the community is probably too risky. What is certain is that to install disproportionate PV areas compared to the loads they meet makes little sense if the goal is to establish an EC, as its headline objective is to implement the on-site consumption and not to export energy. In this framework, it is worth citing the Piedmont Regional Law about ECs [28] [Section 3.1]: it establishes a threshold value for the *SC* fraction equal to 70% for being recognized as an EC. Even though this law has not been directly considered in this thesis, the logic behind it is important. Beyond the number, the requirement of a minimum *SC* could be taken by the future EC law, as it represents one of the main reasons for which a community is created: increase *local* consumption of renewable energy and *not* installing as much PV as possible for exports.

This is how an EC is *energetically* affected by the capacity of its production plants. To close the sensitivity analysis, also the economic KPIs study is necessary [Figg. 69-70].

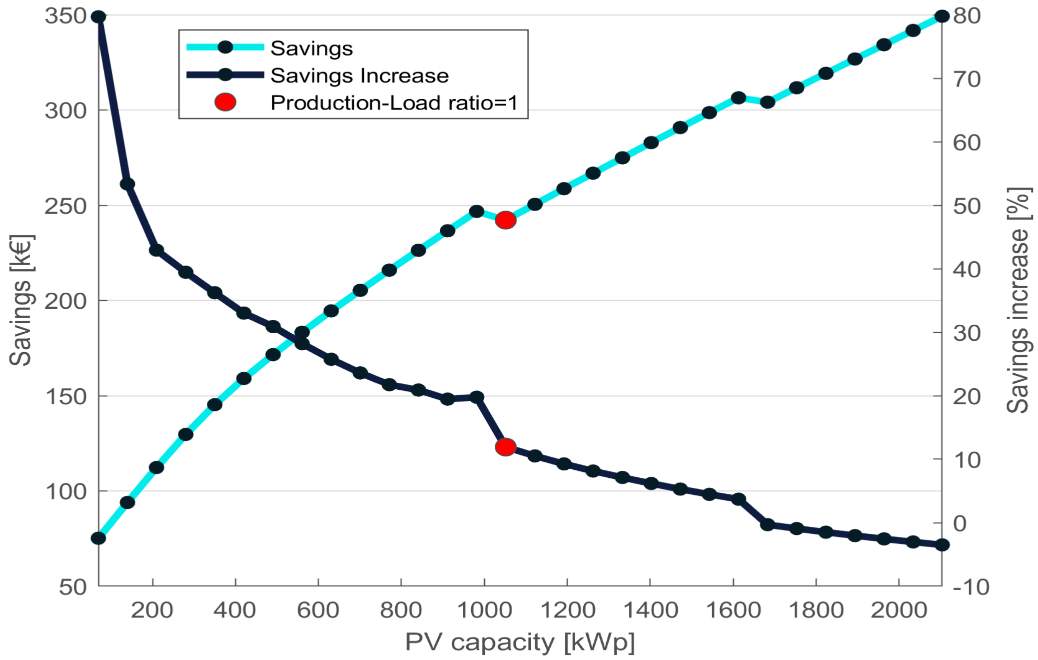

Figure 69: Final Savings (left) and their relative increase (right) in the EC scenario.

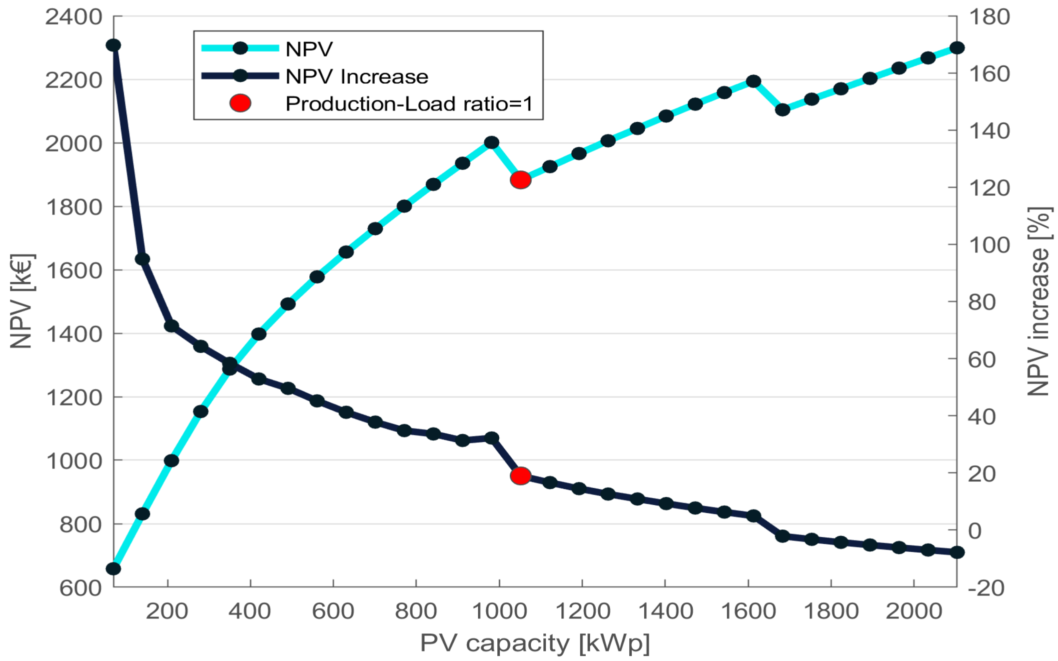

Figure 70: Final NPV (left) and its relative increase (right) in the EC scenario.

Since the worth considerations do not depend so much on the economic scenario, the results are shown supposing to be in the third, without any additional charges. Both the yearly savings and the final NPV increases with the PV capacity, meaning that the rise of the former overcomes the one of the CAPEX for the higher quantity of purchased PV. On the other hand, the increase from the SSCs configuration diminishes for the reasons explained before: most of the energy is exported and there are no more appreciable differences when the community is set. Moreover, both plots present two sudden decreases due to the adhesion to the FER decree:

- The first is registered when the PV installed capacity overcomes 1000 kW. As a matter of fact, the FER sales tariff passes from 0.09 €/kWh to 0.07 €/kWh, reducing the gains for exports,
- The second happens when the SC fraction becomes smaller than 40% [Fig. 68], causing the loss of the premium of 0.01 €/kWh on the energy consumed on-site.

In conclusion, increasing the size of electricity production devices brings more earnings to the EC, but at the same time, it reduces its attractiveness compared to the SSCs scenario. Remembering the previous considerations, the question of whether sharing makes sense is answered negatively if the production systems are oversized (for instance if they imply a *Production-Load* ratio higher than one) compared to the load they have to meet.
Seeing the issue from another point of view, when dealing with disproportionate PV capacities, it is no more a matter of local ECs, but rather of RES electricity production plants aimed at selling energy. Nevertheless, the main ECs' purpose is to promote the own consumption directly on-site, therefore big PV installed capacities come right out of the scope of this work.

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6 Conclusions

This thesis has tried to answer the question: *"When and to which extent is it economically convenient to establish an EC for a group of local prosumer?"*. To this aim, the EC has always been compared to a situation where prosumers are alone, considering indeed that some efforts are necessary to start such a project (setting up this new legal entity, reaching an agreement between members and perpetuate the collaboration, choosing together the technologies, etc.). It is by assessing the difference between these two solutions that the potentialities of a strategy *load-production sharing* are highlighted. Moreover, it is indeed through this methodology that this thesis implements the existing literature. Since a precise legislation about ECs has not yet been issued in Italy, waiting for the transposition of the EU Directive RED II expected in 2021, the comparison has been carried out in three different economic scenarios, also to test the resilience of the community as the *rules of the game* change.

The first step of the work has been to create the model of the community to be analyzed. The case study of this work is made by four different users: one residential, a six-floor condominium, and three commercial, an office, a supermarket and a mall. The buildings' dimensions, the energy demand, and the technologies to meet have been defined and modeled for the simulation. To generate the demand, a scaling of American load profiles provided by the DOE has been done; such methodology has led to acceptable results if compared with those provided by the existing literature. It has been observed that the union of commercial and residential profiles leads to a total load quite flat during the day, avoiding excessive peaks difficult to be managed.
At the beginning, in the BAU scenario, each user has been equipped with old devices, without being a prosumer. From this situation, electricity production devices (PV-CCHP) and HPs have been installed in the various buildings. Among the models, it is worth mentioning the integration HP-boiler optimization algorithm, aimed at selecting the best HP size which minimizes the heating expenditure, reducing them by 42%.

The EC strategy brings to enhance the on-site consumption of 156 MWh, increasing the SC fraction from 70% to 88% and the SS one from 36% to 45%. Such energy causes both a saving, as it is no more imported, but also an economic loss as it can no longer be sold.
The thesis has then demonstrated that the extent of the net economic gain strongly depends on the economic scenario below which the EC is; both the configurations have been simulated in different situations, to see how the EC increase changes. In the upbeat hypothesis of no additional charges for the public grid exploitation, the total yearly savings with respect to the BAU scenario are for the three frameworks 130 $k€$, 140 $k€$ and 159 $k€$, with an EC increase of 23%, 17% and 35% respectively. Moreover the final NPV is 1033 $k€$, 1157 $k€$ and 1397 $k€$, while its increase is 41%, 27% and 53% respectively.
FER selling tariffs have proved to be more advantageous than the Net Metering mechanism even though they make the community stand out less, while the possible participation in the electricity-free market would be important for the community. Observing the impact of every possible element that will form the future regulatory framework is essential to understand when the community can be a convenient choice.
Furthermore, the percentage of transport and system charges to be paid on the energy passing through the public grid has been varied from 0 to 100%. As such parameter increases, a steady decrease of the EC increase has been observed in each framework; considering the NPV, it is reduced up to 17%, 8% and 34%, respectively in each economic

scenario, when full taxes are paid. Remembering the efforts necessary to build a community, suitable policies are necessary when the reception of the RED II directive will take place.

Finally, pretending to have infinite space to install PV panels, a sensitivity analysis about the size of production devices has been provided. Findings have shown that it exists a capacity ($417\,kW$) for which the SC increase in the EC scenario is maximized, as a consequence of the trend of self-consumed and produced energy. Moreover, the economic impact is reduced as the capacity increases, tending it towards zero as no appreciable differences are registered between the two configurations. Anyway, it has been observed that, when dealing with disproportionate installations, it is no more a matter of ECs, but rather production plants; in other words, the RED II transposition should establish a threshold value for the SC fraction.

6.1 Future developments

This last paragraph is aimed at introducing some suggestions and hints for future works concerning the theme of ECs, in the spotlight of what has been done in this thesis. The present work has been focused mainly on assessing the EC energy and economic potentiality in the perspective of the forthcoming legislation. The topic is however much more complex as it presents several multi-faceted aspects.

In this thesis, the number and the type of users within the community has established at the beginning and kept for all the following analyses. Therefore, a proposal for future studies could be to discover how the EC answers to the addition of new users with different demand profiles. Alternatively, having the availability of a building with electricity production excesses, the possibility to establish a community (i.e. sell such excesses to his neighbors), compared to the option of selling to the grid or purchasing a battery, may be evaluated.
Another possible aspect concerns the new devices to be installed. In this work, the type has been chosen *a priori*, while only the size and the scheduling of the HPs have been selected following an optimization criterion. Therefore, since finding the right technological mix is a key issue for the performances of the community, suitable optimization algorithm (MILP, Linear Programming, etc.) should be considered. Such a method could be very helpful especially when it comes to optimize the size of possible storage energy systems. Certainly, this topic has been already plentiful debated, nevertheless here the suggestion is to apply it to both the EC and the SSCs configurations, observing and discussing possible change in the planning strategy.
Furthermore, in the case of an established PV capacity to be installed, an interesting problem could be one of finding the optimal location for such devices. More precisely, pretending to have different roofs each one with limited space, the optimization problem would consist in defining the percentage of the total capacity on each roof. Logically, this issue makes sense only if additional taxes have to be paid, otherwise, all the combinations lead to the same result.

These proposals are all about a strategy to assess more thoroughly the techno-economic performance of the community; they can be implemented in other works or even be an integration of this thesis. The last reported suggestion concerns instead a study about ECs' contractual and legal aspects. No questions have been arisen about what happens from a logistic point of view if, for instance, a user wants to leave the community, a new

one would like to get in, or about how the possible bankruptcy of commercial users could be handled by other members. These aspects become crucial especially considering that usually the money for the investment cost is borrowed by a bank, with a loan that must be repaid during years.
Integrating these issues in a techno-economic study is basically impossible and far from the objective of this thesis; however, they have been mentioned here to specify that the theme of EC, being based on a collaboration among different people and being a reality that by definition should continuously expand, is featured also by contractual and legal aspects often neglected in the literature.

Annex A - Users' load profiles

Figg. from 71 to 78 reports the load profiles in representative days, while Figg. from 79 to 82 shows the yearly trend.

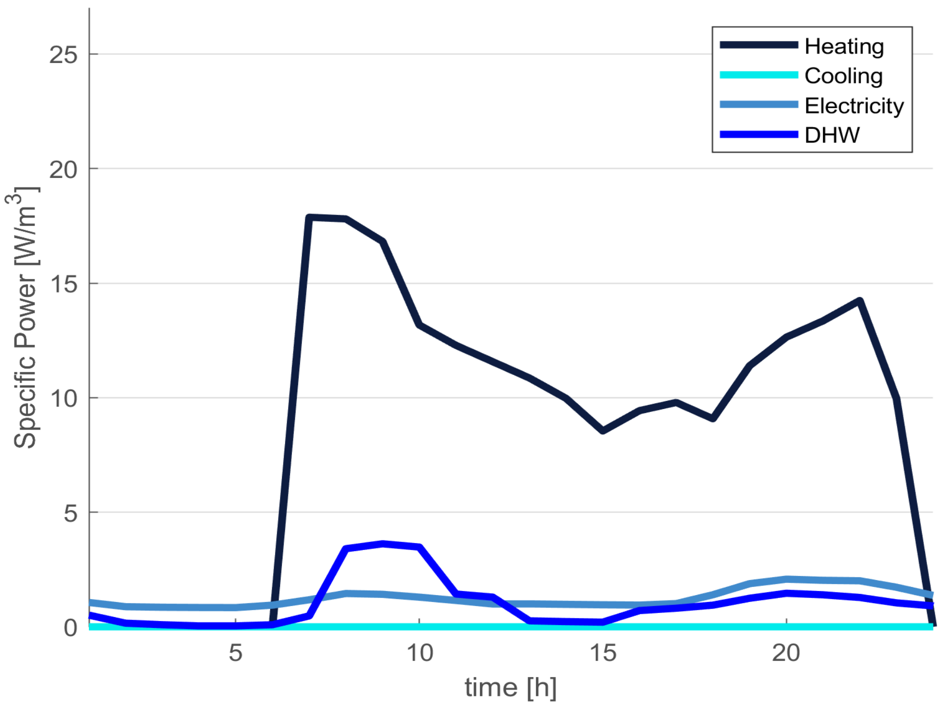

Figure 71: Condominium: load profiles in a winter day (31st January).

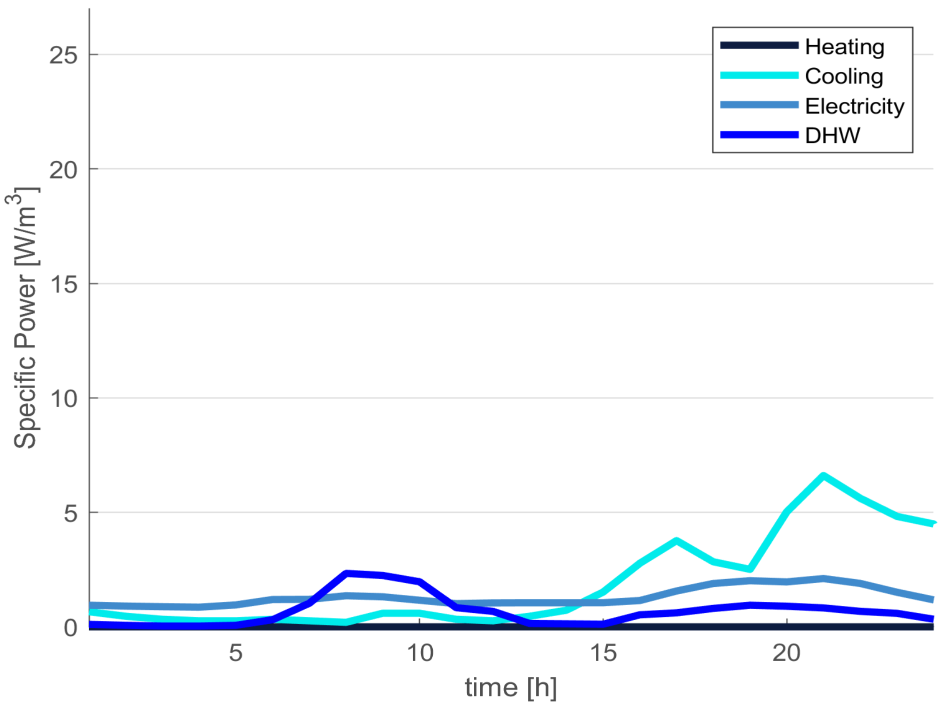

Figure 72: Condominium: load profiles in a summer day (15th July).

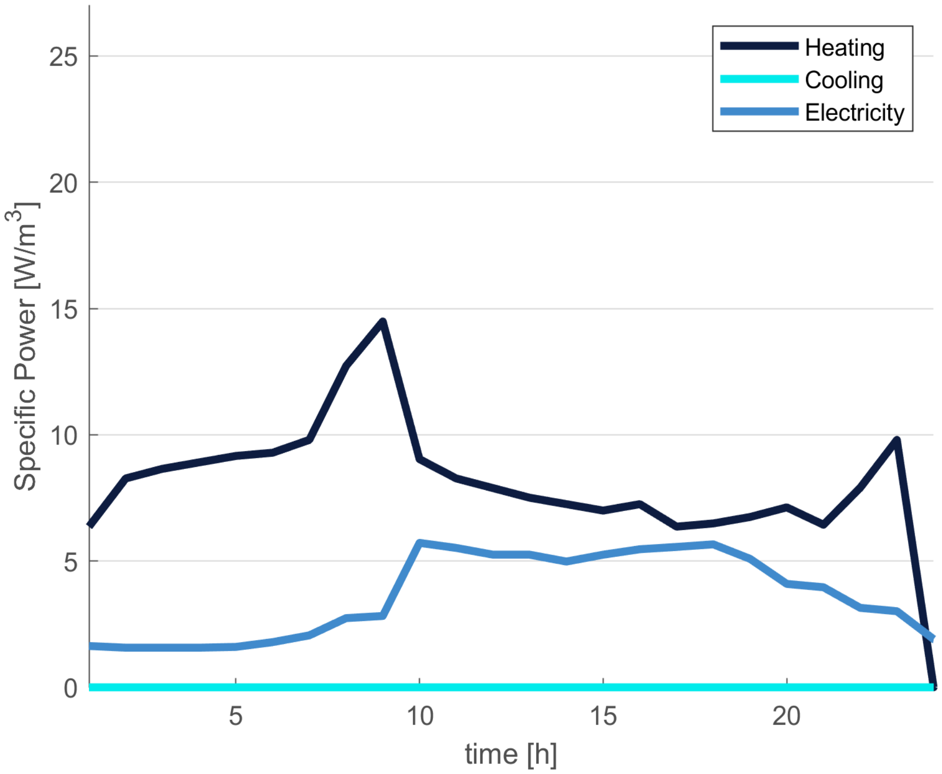

Figure 73: Office: load profiles in a winter day (31st January).

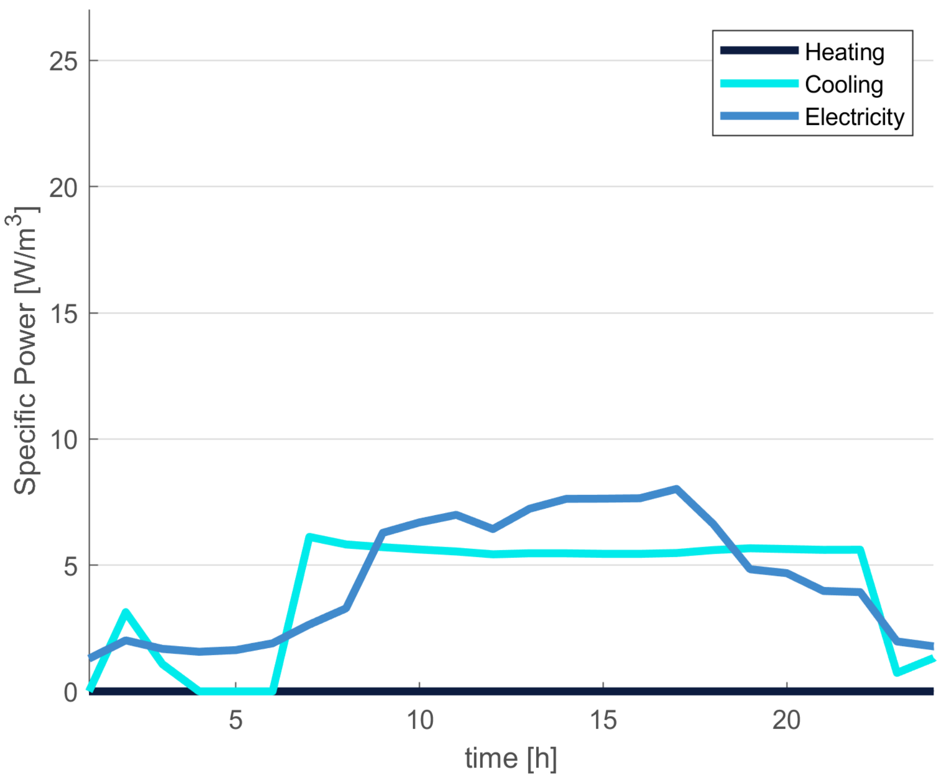

Figure 74: Office: load profiles in a summer day (15th July).

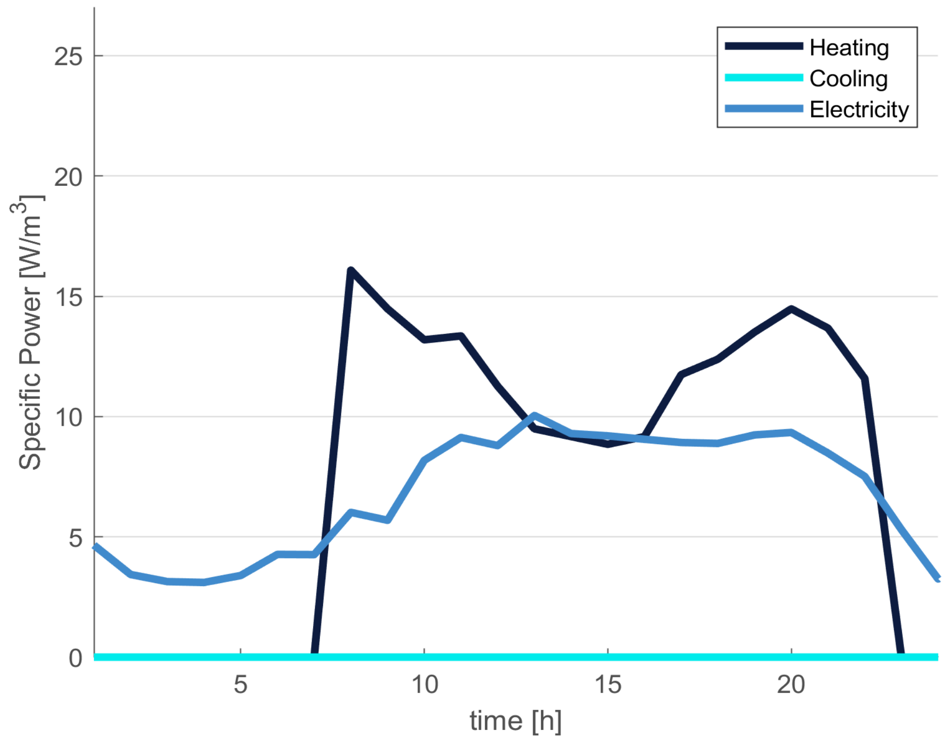

Figure 75: Supermarket: load profiles in a winter day (31^{st} January).

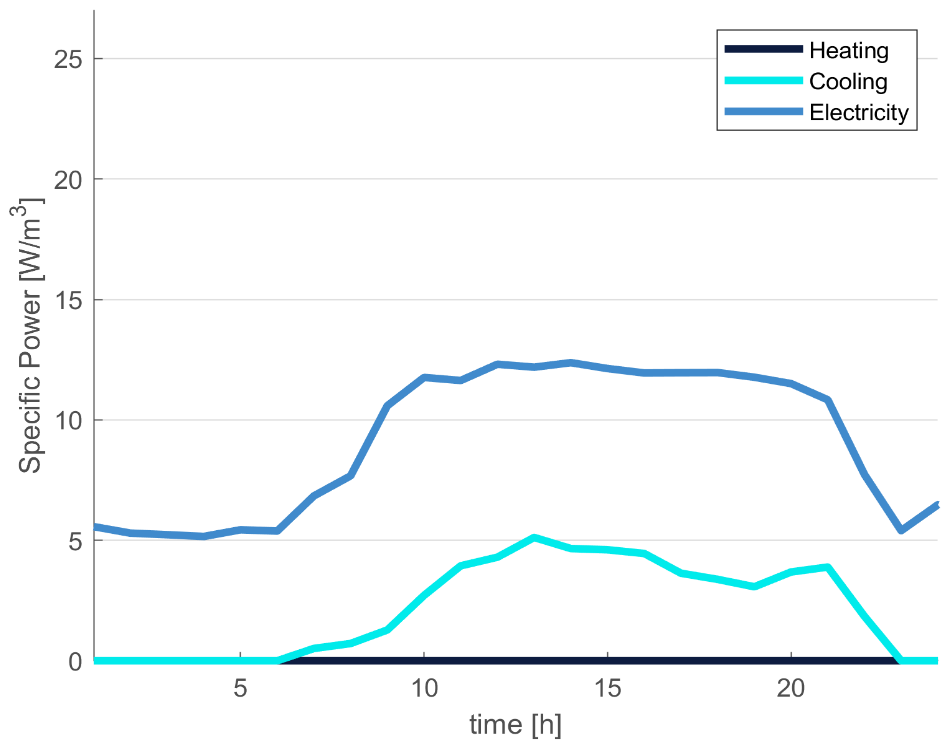

Figure 76: Supermarket: load profiles in a summer day (15^{th} July).

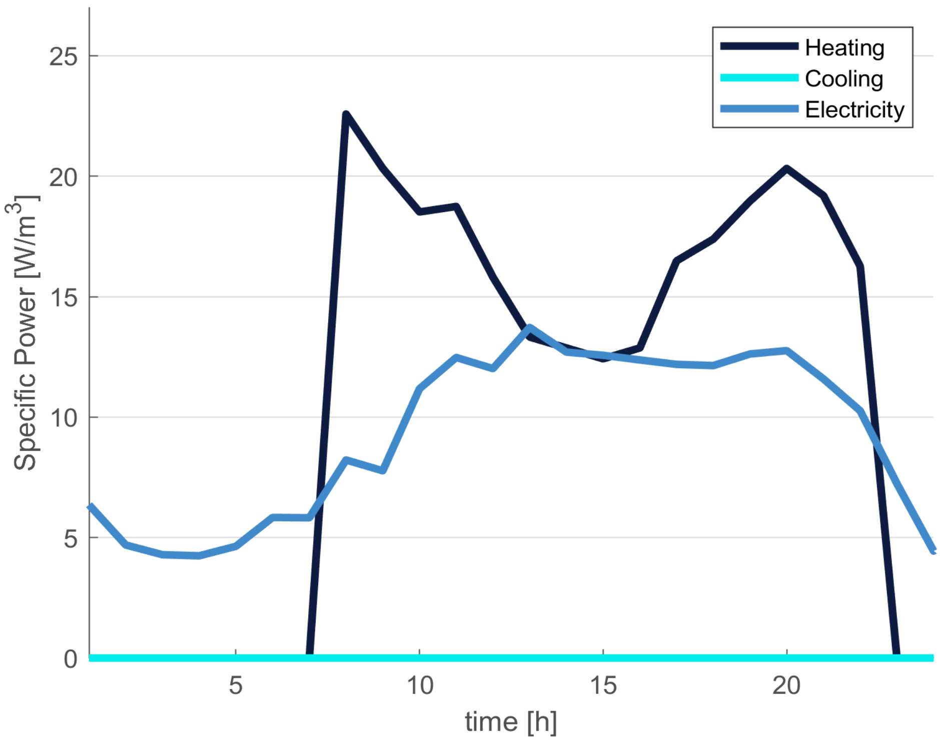

Figure 77: Mall: load profiles in a winter day (31st January).

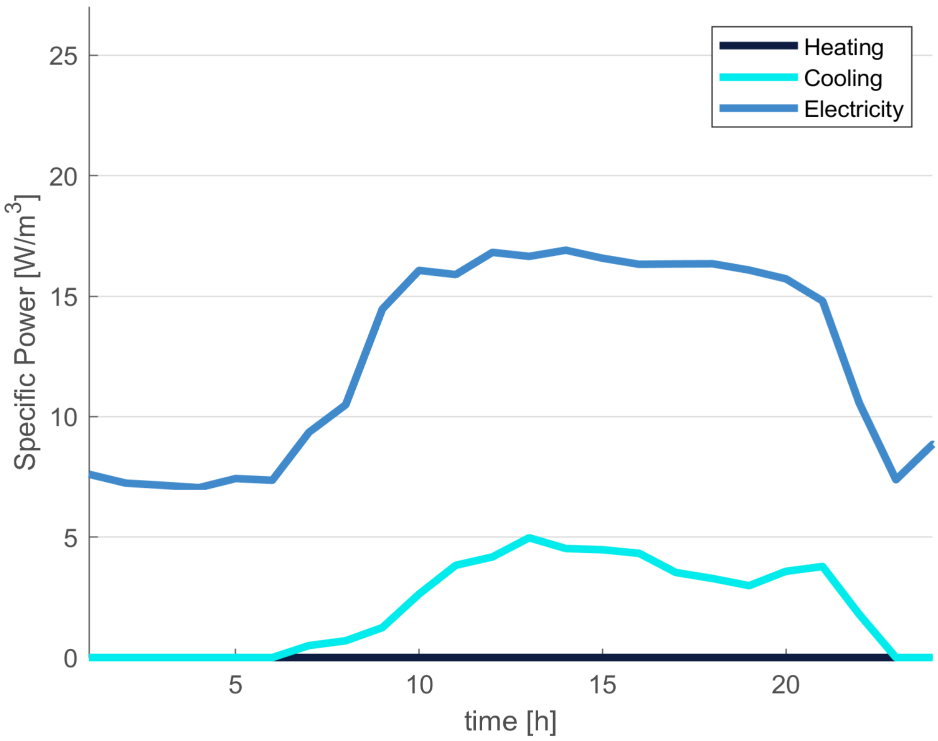

Figure 78: Mall: load profiles in a summer day (15th July).

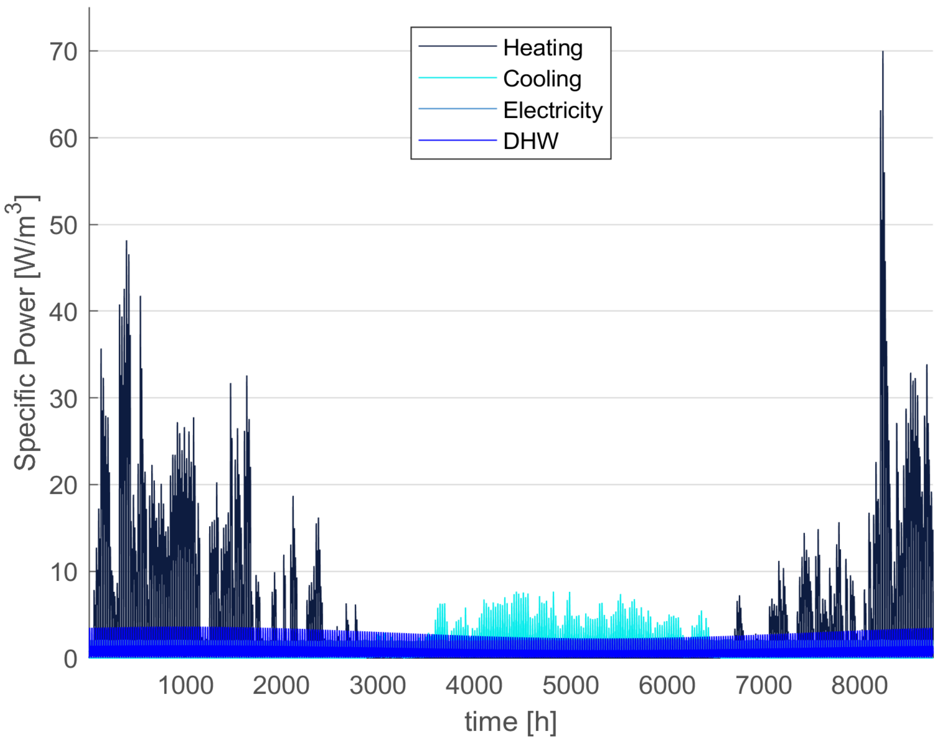

Figure 79: Condominium: Hourly load profiles during the year.

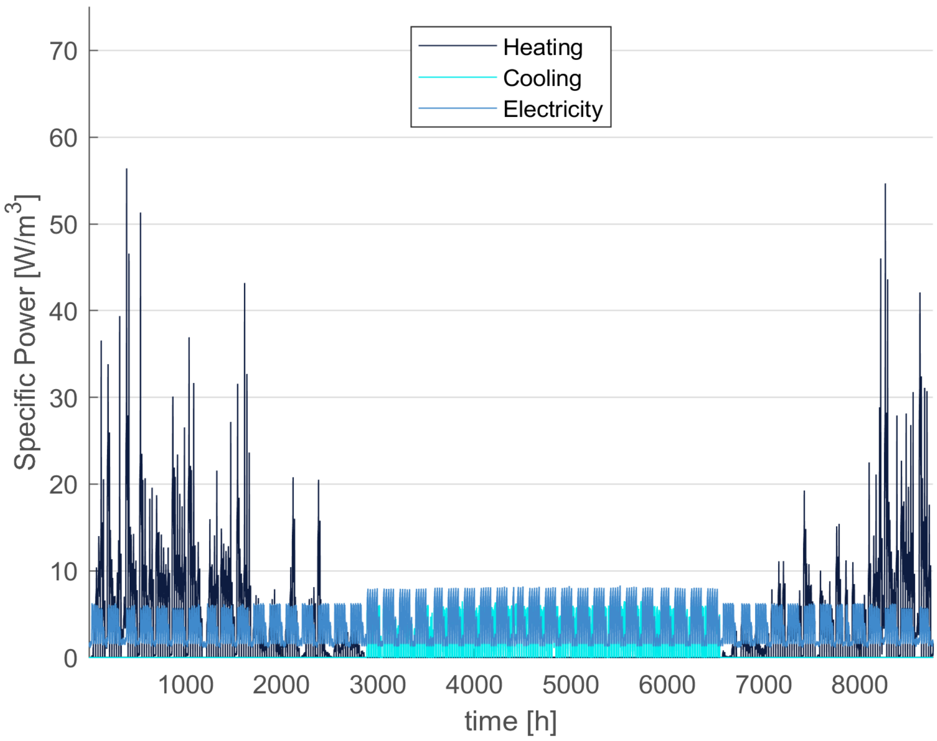

Figure 80: Office: Hourly load profiles during the year.

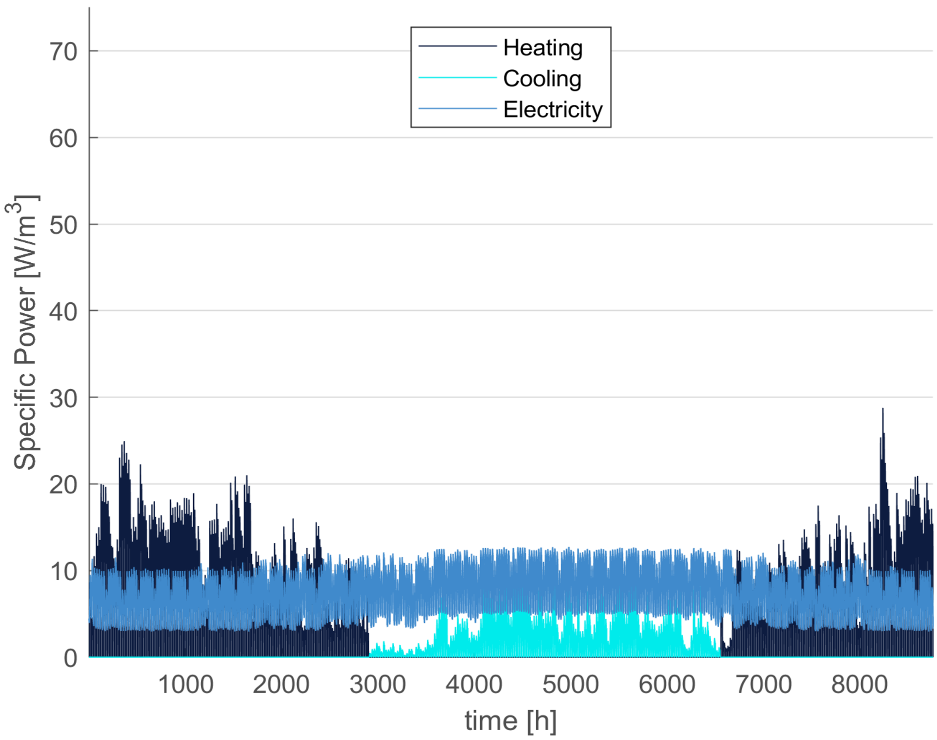

Figure 81: Supermarket: Hourly load profiles during the year.

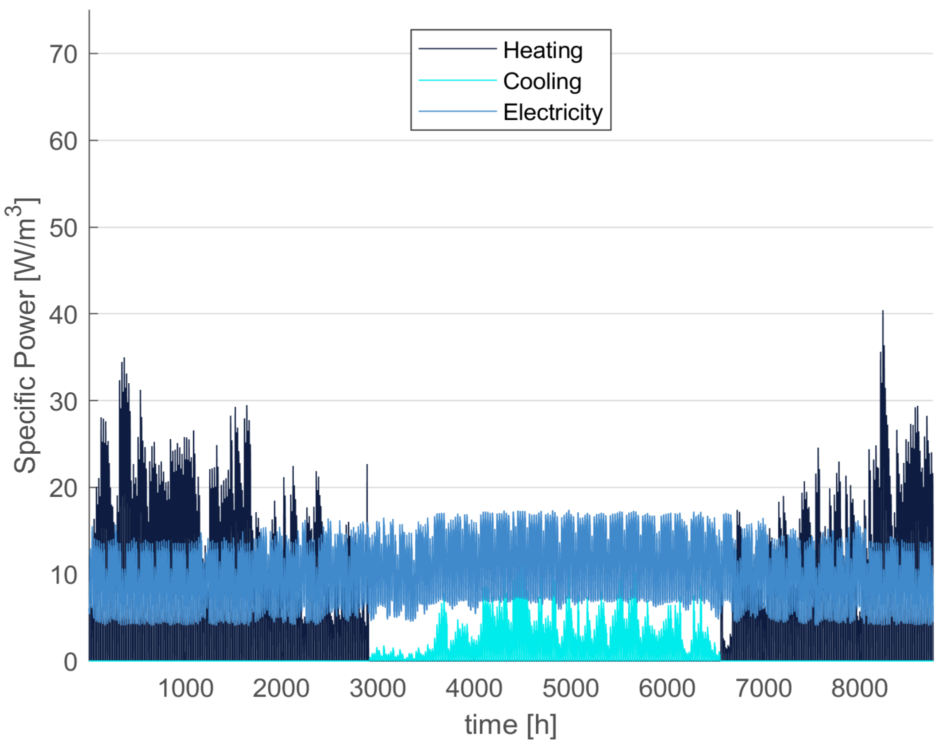

Figure 82: Mall: Hourly load profiles during the year.

Annex B - Parameter for Net Metering computation

This annex reports the coefficients CU_{sf}, $CU_{sf,grid}$ and $CU_{sf,sys}$ [Fig. 83], as well as the *yearly threshold* values [Fig. 84], both used to compute the Net Metering contribution in eqq. 77-78 [Section 4.5.2].

Non-electricity-intensive companies	Year 2018		
	CU_{sf} [c€/kWh]	$CU_{sf,grid}$ [c€/kWh]	$CU_{sf,sys}$ [c€/kWh]
Domestic Tariff (DT) home for experimenting with the supply of electric heat pumps	5,782	1,895	3,887
Low Voltage (LV) home for applications related to the customer's personal residence			
consumption ≤ 1.800 kWh/anno	4,355	1,895	2,460
consumption > 1.800 kWh/anno	8,045	1,895	6,150
LV home for applications other than those related to the customer's personal residence			
consumption ≤ 1.800 kWh/anno	4,355	1,895	2,460
consumption > 1.800 kWh/anno	8,045	1,895	6,150
LV public lighting appliances	9,507	3,168	6,339
LV utilities for powering public charging infrastructures for electric vehicles	17,673	7,498	10,175
LV other users	7,204	1,957	5,247
Medium Voltage (MV) public lighting appliances	7,963	2,229	5,734
MV other users	6,433	1,614	4,819
High Voltage (HV) users	6,170	1,569	4,601
Very High Voltage (VHV) users with voltage lower than 380 kV	6,133	1,549	4,584
VHV users with voltage higher than or equal to 380 kV	6,131	1,548	4,583

Consumption units in the ownership of companies with high consumption of electricity with the concession classes VAL.1, VAL.2, VAL.3 and VAL.4 pursuant to paragraph 2.2 of Annex A to Resolution 921/2017/R/eel	Year 2018		
	CU_{sf} [c€/kWh]	$CU_{sf,grid}$ [c€/kWh]	$CU_{sf,sys}$ [c€/kWh]
LV users	2,082	1,957	0,125
MV users	1,723	1,614	0,109
HV users	1,584	1,569	0,015
VHV users with voltage lower than 380 kV	1,561	1,549	0,012
VHV users with voltage higher than or equal to 380 kV	1,560	1,548	0,012

Consumption units in the ownership of companies with high consumption of electricity with class of facilitation FAT.1 pursuant to paragraph 2.2 of Annex A to Resolution 921/2017/R/eel	Year 2018		
	CU_{sf} [c€/kWh]	$CU_{sf,grid}$ [c€/kWh]	$CU_{sf,sys}$ [c€/kWh]
LV users	4,465	1,957	2,508
MV users	4,072	1,614	2,458
HV users	3,712	1,569	2,143
VHV users with voltage lower than 380 kV	3,682	1,549	2,133
VHV users with voltage higher than or equal to 380 kV	3,681	1,548	2,133

Consumption units in the ownership of companies with a high consumption of electricity with concessionary class FAT.2 pursuant to paragraph 2.2 of Annex A to Resolution 921/2017/R/eel	Year 2018		
	CU_{sf} [c€/kWh]	$CU_{sf,grid}$ [c€/kWh]	$CU_{sf,sys}$ [c€/kWh]
LV users	3,815	1,957	1,858
MV users	3,431	1,614	1,817
HV users	3,132	1,569	1,563
VHV users with voltage lower than 380 kV	3,104	1,549	1,555
VHV users with voltage higher than or equal to 380 kV	3,102	1,548	1,554

Consumption units in the ownership of companies with a high consumption of electricity with concessionary class FAT.3 pursuant to paragraph 2.2 of Annex A to Resolution 921/2017/R/eel	Year 2018		
	CU_{sf} [c€/kWh]	$CU_{sf,grid}$ [c€/kWh]	$CU_{sf,sys}$ [c€/kWh]
LV users	3,165	1,957	1,208
MV users	2,791	1,614	1,177
HV users	2,551	1,569	0,982
VHV users with voltage lower than 380 kV	2,525	1,549	0,976
VHV users with voltage higher than or equal to 380 kV	2,524	1,548	0,976

Figure 83: CU_{sf}, $CU_{sf,grid}$ and $CU_{sf,sys}$ for various users in 2018. The values used for the buildings of the case study have been highlighted in green.

Plant type	Incentive	Power range [kW]		
		P≤20	20<P≤200	P≥200
PV	yes	no limit	0	0
	no	no limit	11.020 c€/kWh	0
wind	yes	no limit	7.314 c€/kWh	0
	no	no limit	17.209 c€/kWh	0
hydro power	yes	no limit	12.314 c€/kWh	0
	no	no limit	22.209 c€/kWh	0
biomass	yes	no limit	4.814 c€/kWh	0
	no	no limit	14.709 c€/kWh	0
others	yes	no limit	0	0
	no	no limit	0	0

Figure 84: *yearly threshold* for various plants in 2018. The values used for the buildings of the case study have been highlighted in green.

According to these data, Table 23 shows the value of the parameters applied to each user and to the community as a whole, according to eqq. 77-78.

User	$CU_{sf,grid}$	$CU_{sf,sys}$	YT	CU_{sf}
Condominium	1.895	6.150	11.020	8.045
Office	1.957	5.247	11.020	7.204
Supermarket	1.957	5.247	11.020	7.204
Mall	1.957	5.247	0	1.957
Community	1.957	5.247	0	1.957

Table 23: NM parameters for each user [$c€/kWh$]. **Y.T.**=*yearly threshold.*