Techno-economic comparison of buildings acting as Single-Self Consumers or as energy community through multiple economic scenarios

Techno-Economic Comparison of Buildings acting as Single-Self Consumers or as Energy Community through Multiple Economic Scenarios

Stefano Viti[a], Andrea Lanzini[a b], Francesco Demetrio Minuto[a b], Matteo Caldera[c], Romano Borchiellini[a b]

[a] Energy Center Lab, Politecnico di Torino, Via Paolo Borsellino 38, Turin, 10138, Italy.
[b] Department of Energy, Politecnico di Torino, Corso Duca degli Abruzzi 24, Turin, 10129, Italy.
[c] Energy Efficiency Unit Department, ENEA, Via Anguillarese 301, Rome, 00123, Italy.

Abstract

The European Union has set ambitious targets and policy objectives to move towards a society with high penetration of Renewable Energy Sources. In the forthcoming energy transition *Energy Communities* (EC), i.e., legal entities where different actors cooperate toward energy generation, storage and management, will play a crucial role. The present work assesses the energy and potential economic benefits of an EC located in the northern Italy by comparing its performances to a configuration where customers act as Single Self-Consumers (SSCs) instead that collectively. Pending the transposition of EU Directives, due by 2021, different economic scenarios have been simulated in order to determine which scheme will support more effectively the integration of Energy Communities in the National energy market. Results show that ECs (i.e., customers acting collectively) are able to reach higher overall self-consumption rates, and they represent an economically convenient option with regard all the scenarios evaluated. The sensitivity analysis carried out on system and transport charges of the electricity bill shows that they have a remarkable impact, i.e., they appreciably reduce the difference between the SSCs and the EC, making the latter less attractive for investors and citizens without a proper support schemes.

Key-words: *Energy community*, *Economic scenarios*, *Electricity market*, *Techno-economic comparison*, *Self-Consumption*

1 Introduction

Energy Communities (EC) are a pillar of the European strategy on *Low-Carbon Societies* [1], aimed at decarbonizing the energy system. ECs can boost the energy transition by promoting clean distributed energy systems [2]-[3], as well as the adoption of energy management strategies both at production and demand sides. In addition, they may reshape cities by improving their resilience, according to the concept of *smart cities* [4]-[5]. Community-based approaches have also been supported by EU Horizon 2020 funds to promote distributed energy systems [6]-[7] and renewable energy exploitation.
Nevertheless, ambiguities are encountered when it comes to precisely define ECs; Walker et al. [8] bonded the term to local people involvement, the first stakeholders to benefit from their constitution. In this perspective, ECs are promoters of *energy democratization* [9], as they boost citizens' awareness on energy by involving them in the decision-making process [10]. Other authors [11]-[12] described ECs as a group which purchases and consumes energy jointly and adopts demand-side management strategies. Such potentialities and EU interest for this solution are among the reasons for the EC techno-economic assessment presented in this study, carried out through a theoretical case study located in Turin, in northern Italy. Italy has indeed high potential for ECs based on renewable energy: energy produced and consumed *on-site* amounts to 28 TWh (i.e. around 9% of the total consumption), of which only 4.2 TWh come from RES, while the potential of photovoltaics (PV) on rooftops has been estimated in around 90 TWh [13] [Fig. 1]. Therefore, climatic conditions are not a barrier to increase self-consumption.

In Italy, several ECs were present before the nationalization (1962) of the electric grid, while today only a few consortia and historical cooperatives have survived [14]-[15]. Reasons for the absence of decentralized legisaltion may be attributed to the lack of legislation to precisely regulate ECs, even though some documents have been enacted to promote ECs [16]-[17].

List of Acronyms

ARERA: Italian Regulatory Authority for Energy
BAU: Business As Usual
CAPEX: CAPital EXpenditure
CCHP: Combined Cooling Heating and Power
CDD: Cooling Degree Days
CHP: Combined Heating and Power
COP: Coefficient Of Performance
CSC: Collective Self-Consumer
DHW: Domestic Hot Water
DOE: U.S. Department Of Energy
EC: Energy Community
EU: European Union
FM: Free Market
FM2FER: Free Market to "Decreto FER" scenario
HDD: Heating Degree Days
HE-CHP: High-Efficiency Cogeneration
HP: Heat Pump
IRR: Internal Rate of Return
KPI: Key Performance Indicator
NM: Net Metering
NPV: Net Present Value
PBT: Pay Back Time
PES: Primary Energy Savings
PM: Protected Market
PM2FER: Protected Market to "Decreto FER" scenario
PM2NM: Protected Market to Net Metering scenario
PV: Photovoltaic
REC: Renewable Energy Community
RED: Renewable Energy Directive
RES: Renewable Energy Sources
SC: Self-Consumption
SS: Self-Sufficiency
SSCs: Single Self-Consumers

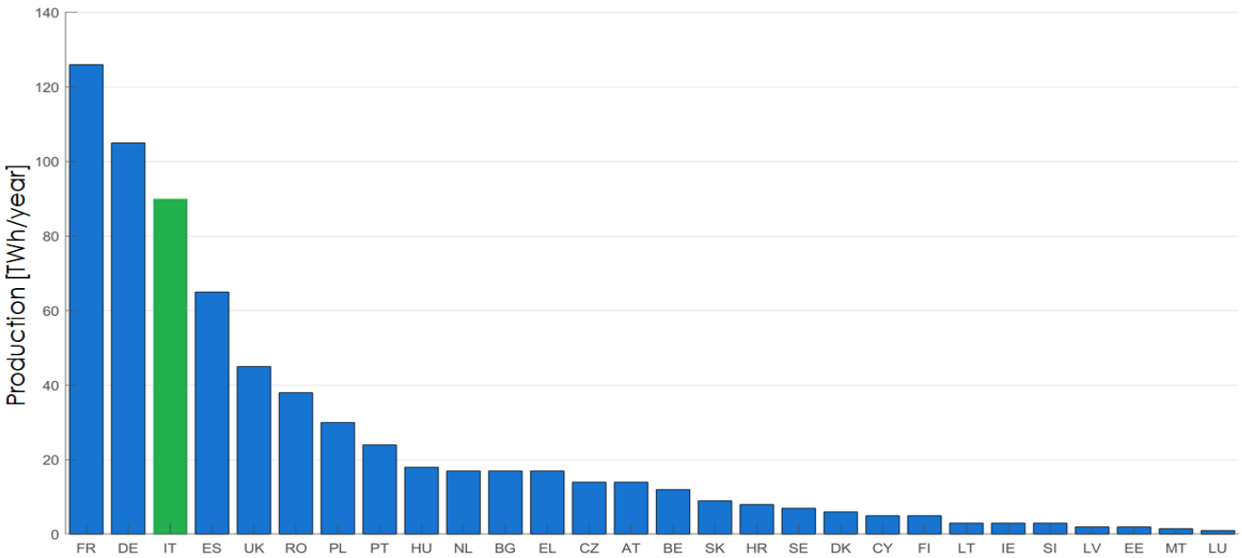

Figure 1: PV potentials on EU rooftops; Italy is highlighted [13].

In November 2018, the European Parliament published the new Renewable Energy Directive (RED II) [18], defining what a Renewable Energy Community (REC) is, with its rights and duties. Accordingly, Art. 2 of Directive 944/2019 [19] introduced the concept of Citizens Energy Community (CEC), which does not require RES generation and includes the management of electrical distribution among the rights of the community. However, these directives basically contain principles rather than operating rules. Regulation is left to the Member States that have to transpose these directives by 2021;in particular they must not apply discriminatory charges for ECs.

Starting from these considerations, this work presents the comparison between the typical scenario nowadays widespread, in which prosumers operate separately (Single Self-Consumers, in the following called SSCs scenario) and one where citizens and prosumers form an Energy Community (the EC scenario). Hence, three different economic scenarios have been investigated, with their effects at the community level.

The research work is structured as follows. Section 2 describes the state of the art related to ECs. Section 3 briefly introduces the main concepts of the Italian electricity market, in order to explain the logic behind the economic scenarios. Section 4 describes the methodology, and provides information on the analyzed energy systems and characteristics of the buildings and their energy demand. In Section 5 the scenarios are compared and evaluated, basing on techno-economic indicators, while section 6 sums up the main findings of the work.

2 Literature review

Techno-economic assessment of citizens' communities sharing the ownership of power systems is a theme plentifully tackled in literature. Baneshi et al. [20] simulated a hybrid diesel-RES system that supplies a non-residential neighborhood, studying off- and on-grid solutions. Other authors [21] highlighted the possibility of satisfying thermal demand through electricity at community level. Hybrid solutions RES-CHP are instead the objective of the works of Ma et al. [22], who assessed such systems in different Chinese cities providing sensitivity analyses about grid tariffs and RES subsidies. Amiri et al. [23] and Maleki et al. [24] adopted fuel cells for cogeneration, evidencing high CAPEX due to low commercial maturity. Finally, the strong link between ECs and local policies, which is a central theme of this work, has been demonstrated by Petersen [25].
As regards PV-based ECs, different works [26]-[27] focused on PV systems owned by the community as an attractive alternative to individual installation. At the same time, Awad et al. [28] compared 42 residential units served by a centralized and optimized installation to a scenario where dwellings are isolated, achieving a 16.18% yearly revenue increase in the former configuration. In this framework, it is worth mentioning some papers arguing that suitable PV-based ECs policies would help the development of rural areas [29]-[30]-[31]. Gerber et al.[32] proposed a method to size PV systems in ECs using monthly electricity bills and buildings' energy demand, aiming at not overloading the electrical public grid. Schiera et al. [33] analyzed shared PV systems serving more dwellings in the same condominium, i.e. the so-called *collective self-consumer* (CSC) defined in the Renewable Energy Directive, showing how such configuration increases self-consumption up to 50%. In Italy, a regulation on collective self-consumers is still missing, even though it is expected with the transposition of Art. 21 of Directive RED II ([18]). A comparisons between SSC and EC has been considered by Roberts et al. [34], who obtained an improvement by 10-30% in self consumption in ten sites equipped with PV and batteries, if a shared system is compared to stand-alone systems. Similar results have been obtained by Luthander et al. [35], who also evaluated an upgrade around 20% in the yearly revenues. Moreover, several authors studied the concept of Zero Energy Communities, i.e. aggregations aimed at being nearly self-sufficient [36]-[37]-[38].

This work aims at providing an original contribution to this key topic, by performing a techno-economic comparison between SSCs and EC, to asses the proper conditions that make energy communities convenient for citizens. Starting from the Business As Usual (BAU), where the four types of analyzed users (residential, tertiary and commercial) represent the context currently widespread in Italy, a technological retrofit is considered for the power systems and two scenario are investigated, with the same technology and size of the power systems, i.e. single self-consumers (SSCs scenario) and energy community (EC scenario). Hence, this paper aims at providing a technical contribution to policy-makers' future decisions towards the transposition of RED II Directive as well.
As anticipated, the selected case study considers four types of buildings: one residential building (i.e., a condominium with twelve dwellings) and three civil buildings (an office building, a supermarket, and a mall). As regards the technologies of the energy systems included in the analysis, photovoltaics and a CHP unit (i.e., an internal combustion engine) have been evaluated, the latter coupled with an absorption chiller for the fulfillment of the thermal energy demand. Therefore, mature commercial technologies have been chosen, in the spirit of the energy community strategy, avoiding expensive alternatives that would lead to excessive investments, e.g. fuel cells or district heating [24]-[39] (as regards the thermal energy demand). Additionally, the four buildings have been assumed close to each other and connected to the the same secondary electrical substation, in order to minimize the extension of the connection between the users in the community and the public grid. The latter assumption is required to realistically support the sensitivity analysis carried out on transport and systems charges of the electrical bill, aimed at assessing the impact of their reduction on the economic convenience of ECs.

3 Economical context: the Italian electricity market

This section provides and overview of the Italian electricity market, in order to properly define and understand the analysed scenarios [see Section 4.2.4], i.e. the structure of the electricity bill and the RES subsidies. Similar schemes, with the appropriate differences, may apply on other European Countries as well [40]-[41].

3.1 Structure of the electricity bill

The current structure of the electricity bill for residential and commercial customers applies since 1^{st} January 2016, and it is composed of four components [42]:

- *Energy*: It includes the monetary amounts invoiced for the various activities carried out by the seller to supply electricity to the final customer.

- *Transport charges*: It includes the amounts invoiced for the activities related to delivery and metering of electricity (i.e. transmission, distribution, dispatching and meter management).

- *System charges*: It includes the amounts invoiced to cover costs related to activities of general interest for the National electricity system, such as RES subsidies.

- *Tax*: It includes components related to excise duties and value added tax (VAT).

Each price component comprises up to three items: a fixed fee related to the point of delivery (POD, $€/pod/year$), an energy fee ($€/kWh$) and a power fee ($€/kW/year$). These tariffs depend on the *regime* chosen by the user. In the *Protected* Market (PM), all the price components are established by the National Energy Authority - ARERA (in the present study prices valid in the third quarter of 2019 have been considered, as reported in [Tab. 1]), while in the *Free* Market (FM), the seller define the price of the energy component, therefore it may discount the energy price with respect to competitors and the protected market; both possibilities are addressed in this paper. Instead, transport and system charges are established by ARERA regardless of the protected or the free market.

3.2 RES subsidies and selling mechanisms

In Italy, RES production has received over time several subsidies [43], which are nowadays all ended since the prescribed thresholds have been reached.
The current RES regulatory framework is organized around the *"Decreto FER"* (i.e. "RES decree") [44]. It establishes a fixed tariff, according to the plant capacity, recognised to the electricity fed into the grid by some RES (i.e. solar PV, wind on-shore, hydro power, sewage treatment plant gas). For PV plants, such support scheme is valid for capacities higher than 20 kW_{el}. Moreover, if the energy consumed directly on-site exceeds 40% of the net production, a bonus of 0.01 $€/kWh$ is granted for plants up to 100 kW_{el}. In this paper, the adhesion to a support scheme based on the "RES decree" for PV plants exceeding 20 kW is considered in the economic analysis.
Alternatively, the *Net Metering* mechanism (NM) has been considered for solar PV plants up to 500 kW. Net metering provides a refund on the electricity withdrawn from the grid, depending on the the electricity fed into the grid and on a flat-rate exchange fee; the details of such mechanism are provided in [45]. The reference prices are the hourly values of the Single National Price (abbreviated PUN, i.e. *Prezzo Unico Nazionale*, in Italian) and the zonal price; this paper considers the 2018 values [46].
As regards high-efficiency cogeneration (HE-CHP), plants with a nominal electrical size below 200 kW, can access to the net metering mechanism; more details are provided in Section 4.1.2. While "Decreto FER" is dedicated to plants with nominal capacity exceeding 20 kW_{el}, owners of smaller solar PV plants can deduct 50% of the initial cost from taxes in ten annual instalments. Also this mechanism has been considered in the present economic analysis.

4 Methodology and case study

This section describes the approach followed to setup the case study and the various scenarios, and the governing equations of the techno-economic analysis.

4.1 Methodology

The following paragraphs focus on the determination of buildings' loads, as well as on the equations used and the indicators defined to compare the various scenarios.

4.1.1 Energy loads and demand

Building loads are related to the hourly profiles for heating, cooling, electricity, and domestic hot water (DHW). A scaling methodology from already existing profiles has been devised to generate hourly profiles of building archetypes included in the analysis. The methodology has been based on a database developed by the U.S. Department of Energy, because it turned out to be the most exhaustive dataset in terms of data availability and richness, as it includes several types of commercial buildings spread in different climatic regions. The full dataset is available from [47] and contains the hourly profiles of 16 reference buildings for 841 American cities. Further details about the procedure followed to determine these profiles are reported in [48].
First, among the 841 cities, it has been selected those whose climate was most similar to the case study location, so that comparable load profiles would be available for heating and cooling demands. More precisely, a climatic analysis based on Heating Degree Days (HDD), Cooling Degree Days (CDD), and monthly mean external temperatures has been performed for selected American cities. Jefferson, the Missouri capital, turned out to be the best option. Thus, the buildings energy profiles have been scaled and adapted, starting from the available dataset of this city. Each profile has been scaled according to significant parameters (considering the available data), and basing on Italian benchmarks as well:

- *Heating demand*: The heating profile has been scaled based on HDD and U-values (i.e. the thermal transmittances of the building envelope), considering the different envelope material employed between American and Turin buildings according to the year of construction.

- *Cooling demand*: The cooling profile has been scaled considering only CDD.

- *Electricity*: Electricity profiles of commercial buildings have not been scaled because of the lack of reliable data. For the condominium, reference was made to the consumption of the

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 1: Electricity bill components for residential customers in the protected market [42].

typical family provided by ARERA, equal to $E_{el,y} = 2,700\ kWh/y$ [49].

- DHW: hot water demand has been neglected for commercial buildings, while hot water for residential users has been scaled considering a daily DHW demand of 60 $lt/day/person$ supplied at 40 °C [50].

By following the above-described procedure, the thermal and electricity demands of the selected buildings have been determined.

4.1.2 Energy systems models

The selected technologies are solar PV, heat pumps, and a CCHP unit. Each one has been modeled in the MATLAB environment. Then, according to the retrofit strategy [see Section 4.2.3], they have been associated to the specific building.

Photovoltaic system (PV)

PV performance have been calculated with different values of tilt (β) and azimuth (γ) angles of the PV arrays, aiming at finding the value pair that minimizes the annual electricity bills [see Section 5.1]. The formula through which the average output power can be evaluated in the generic hour $1 \leq i \leq 8760$ is:

$$P_{PV}(i) = A_{PV} \cdot \eta_{PV}(i) \cdot G_T(i) \cdot \eta_{inv} \quad (1)$$

A_{PV} $[m^2]$ is the total PV surface, $\eta_{inv} = 0.9$ is the efficiency of the inverter, $\eta_{PV}(i)$ is the efficiency of the PV array, and $G_T(i)$ $[W/m^2]$ is the total incident solar radiation per unit area. The solar-to-power efficiency $\eta_{PV}(i)$ depends on several factors [51]; here a linear expression based on $G_T(i)$ taken from a commercial datasheet [52] has been considered:

$$\eta_{PV}(i) = 0.1986 + 1.175 \cdot 10^{-5} \cdot (G_T(i) - 200) \quad (2)$$

Once the latitude has been established, $G_T(i)$ can be computed with different solar radiation models. In this paper, the model proposed by ASHRAE [53] has been chosen; its equations allow to write a MATLAB function which computes $G_T(i)$ as a function of β and γ:

$$G_T(i) = f(\beta, \gamma) \quad (3)$$

In this way, the optimization can be easily performed.

Heat Pump (HP)

HPs are electrically-driven devices used to extract heat from a low-temperature source and transfer it to an environment at higher temperature. They have been installed to satisfy the thermal demands (heating only or heating and cooling [54]). Nevertheless, relying only on such a device for heating purposes in cold climates is rarely the best solution, as its average Coefficient Of Performance (COP) would be too low [55]. Therefore, in the strategy adopted, the HP integrates the existing gas condensing boiler. The control logic during the heating season is thus COP-based, and it works as follows:

- *The $COP(i)$ is below a threshold COP_{lim}*: if there is on-site electricity generation from PV, the HP works (alone or alongside with the boiler). Otherwise, it is off.
- *The $COP(i)$ is above a threshold COP_{lim}*: the HP works (alone or alongside with the boiler).

To perform the cost optimization, the threshold value COP_{lim} must be defined following an economic criterion: it is the minimum HP efficiency that makes it economically advantageous with respect to the boiler:

$$C_b(i) = \frac{P_h(i)}{\eta_b \cdot LHV} \cdot c_{gas} \quad (4)$$

$$C_{HP}(i) = \frac{P_h(i)}{COP(i)} \cdot c_{el} \quad (5)$$

$$\begin{gathered} C_{HP}(i) \leq C_b(i) \\ COP(i) \geq \frac{c_{el}}{c_{gas}} \eta_b \cdot LHV = COP_{lim} \end{gathered} \quad (6)$$

Where c_{gas} and c_{el} are the natural gas and electricity unitary costs, LHV is the lower heating value of the natural gas, η_b is the boiler efficiency and $P_h(i)$ is the thermal load at the i-th hour.
The $COP(i)$ is assessed by means of efficiency curves taken from a commercial catalog [56], and with equations provided by [57]. The necessary input data are the external temperature $T_{ext}(i)$ and the hot water supply temperature $T_w(i)$, which, given a set-point temperature $T_{sp} = 20$ °C, is calculated according to the climatic curve:

$$T_w(i)[°C] = 24 - \frac{50-24}{28}\Big(T_{ext}(i)[°C] - T_{sp}[°C]\Big) \quad (7)$$

and the HP partialization factor CR_{HP}:

$$CR_{HP}(i) = \frac{P_h(i)}{P_{th,max}(i)} \tag{8}$$

Where $P_h(i)$ is the thermal load and $P_{th,max}(i)$ is the maximum useful thermal power, depending on $T_{ext}(i)$ and $T_w(i)$.
Different HP sizes have been simulated for the whole season, aiming at finding the one that minimizes the overall heating bill. Thanks to the implemented control logic, the chosen HP has the higher capacity factor F_{HP}:

$$F_{HP} = \frac{\sum_{i=1}^{8760} P_{h,HP}(i)}{\sum_{i=1}^{8760} P_h(i)} \tag{9}$$

It is important to remember that the HP could also meet the cooling demand, by operating reversibly. In this case, the algorithm requires an additional constraint: the HP cooling capacity must be higher than the cooling peak demand $P_{c,max}$:

$$P_{c,max,HP} \geq P_{c,max} \tag{10}$$

Where $P_{c,max,HP}$ is the HP cooling capacity.

Combined Cooling Heating and Power (CCHP) system

The CCHP system is a gas-fired internal combustion engine (ICE), co-producing power and heat using the hot exhaust gas and the engine cooling system. During winter, heat can be directly used for heating purposes, while in summer it can feed an absorption chiller and produce chilled water.
The CCHP is sized in order to cover the thermal demand of the building where it is installed. The electrical efficiency η_e depends on the external temperature and the partialization factor, defined by Eq. (8). At the same time, the thermal efficiency η_{th} is a function of the latter, namely the complement to the nominal efficiency. For such curves, the CHP ICE E286 unit manufactured by MAN [58] has been considered, while absorption chiller data have been taken from [59]. Therefore, the natural gas power $P_{fuel}(i)$ and the power output $P_{CCHP}(i)$ are given by:

$$P_{fuel}(i) = \frac{P_h(i)}{\eta_{th}(i)} \tag{11}$$

$$P_{CCHP}(i) = P_{fuel}(i) \cdot \eta_e(i) \tag{12}$$

In Italy, cogeneration can be recognised as High-Efficiency Cogeneration (HE-CHP) if it respects a requirement on the primary energy saving. Such a qualification ensures an economic bonus and advantageous tariffs regarding the natural gas purchase; therefore, it is essential for the economic feasibility of the installation. The Italian legislative decree nr. 20/2007 [60] acknowledges this certification if the Primary Energy Savings (PES):

$$PES = \frac{\Delta E_c}{\frac{E_t}{\eta_t} + \frac{E_e}{\eta_e}} \tag{13}$$

is higher than a threshold which depends on the size (in particular, $PES > 0$ for CHP units with nominal electrical capacity below $1MW_e$). E_t and E_e are the annual thermal and electrical energy produced, η_t and η_e are the efficiencies in separated production mode [60] and ΔE_c is given by:

$$\Delta E_c = \left(\frac{E_t}{\eta_t} + \frac{E_e}{\eta_e} \right) - E_c \tag{14}$$

with $E_c = m_c \cdot H_i$ is the primary energy introduced in the system.

4.1.3 Energy key performance indicators

The following hourly electrical profiles have been calculated for $j-th$ building, and have been used for the techno-economic analysis: the electrical load $P_{req,j}(i)$, the power produced by the PV (or the CCHP) $P_{prod,j}(i)$, the power self-consumed $P_{self,j}(i)$, the power fed into the grid $P_{exp,j}(i)$ and the power withdrawn from the grid $P_{imp,j}(i)$.
In the SSCs scenario, global profiles are calculated as the sum of each user:

$$P_{self}^{SSCs}(i) = \sum_{j=1}^{4} P_{self,j}(i) \tag{15}$$

Instead, in the EC scenario, profiles have been calculated as follows. If it exists at the same time a user that is importing and another who instead is exporting power, the latter can feed the former, increasing the overall self-consumption rate of the community and thus saving money. Fig. 2 shows what happens when the energy surplus produced by a prosumer feeds other users of the community, reducing the net energy flux with the grid. Fig. 2 helps to visualize how the community works.
With these profiles, the following KPIs are defined in order to compare both scenarios:

- *Self-Sufficiency* (SS): the ratio between self-consumed and requested energy. It describes the degree of independence from the public grid:

$$SS = \frac{\sum_{i=1}^{8760} P_{self}(i)}{\sum_{i=1}^{8760} P_{req}(i)} = \frac{E_{self}}{E_{req}} \tag{16}$$

- *Self-Consumption* (SC): the ratio between self-consumed and produced energy. It indicates the capability to consume onsite the power locally produced:

$$SC = \frac{\sum_{i=1}^{8760} P_{self}(i)}{\sum_{i=1}^{8760} P_{prod}(i)} = \frac{E_{self}}{E_{prod}} \tag{17}$$

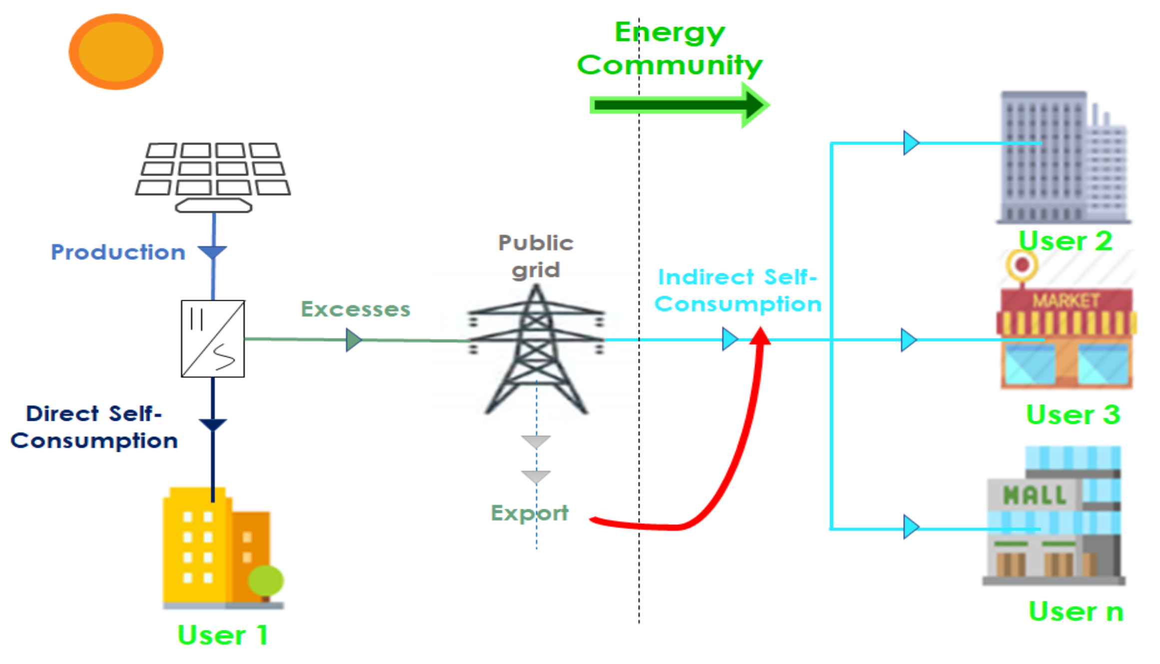

Figure 2: Energy Community enhancement of the SC fraction by using internal exchanges to reduce import/export with the public grid.

The ratio between these two KPIs is called *Production-Load* ratio, which suggests the matching of the system [61]:

$$P/L = \frac{SS}{SC} = \frac{E_{self}/E_{req}}{E_{self}/E_{prod}} = \frac{E_{prod}}{E_{req}} \quad (18)$$

Since technologies and users do not change between the SSCs and EC configurations, this ratio remains constant in the comparison between the two scenarios.

4.1.4 Economic key performance indicators

For the economic analysis, the following quantities have been used: energy bills, net present value (NPV), internal rate of return (IRR), and payback time (PBT). The NPV has been calculated based on a yearly discounted cash flow analysis:

$$NPV = -I + \sum_{k=1}^{n} \frac{B_t(k)}{(1+i)^k} \quad (19)$$

Where I is the initial CAPital EXpenditure (CAPEX), namely the investment costs of newly installed energy production technologies; such values have been taken from the Danish Energy Agency database [62], as it contains in a unique file all the costs required by the analysis. The interest rate i is equal to 5%, the number of years considered for the analysis is $n = 20$, while $B_t(k)$ are the revenues in the generic year k:

$$B_t(k) = SAV - C_{O\&M} + C_{sub}(k) \quad (20)$$

Every year, compared to the BAU scenario, both the configurations lead to an economic saving SAV due to overall lower energy (i.e. gas and electricity) bills. $C_{O\&M}$ refer to the technical maintenance cost, provided again by [62], while C_{sub} is the single 10-year instalment of the retrievable CAPEX part [Tab. 3 and Section 4.2.4], calculated indeed for the first ten years ($1 \leq k \leq 10$) for PV and HP.

4.2 Case study definition

The case study is introduced by providing a description of the buildings' geometric characteristics, the location, and the retrofit intervention for promoting energy efficiency and self-production. Then, the three economic scenarios are presented.

4.2.1 Buildings' geometric features

The Energy Community studied in this work comprises of four different types of building: a condominium and three commercial buildings (an office, a supermarket, and a mall), each one with its specific different loads. Number of floors N_f, volume V, and roof area A_r of each building are reported in Tab. 2. Geometric features and year of construction of the condominium have been taken from the Italian National Bureau of Statistics [63]. For both parameters, this database shows how many condominiums fall in a specific range of values; hence, in this work, the values shared by the largest number of buildings in Turin has been considered. The year of construction has been used to choose the proper U-values from the database TABULA [64]. The characteristics of the commercial buildings have been selected from the already mentioned DOE database [48]. U-values have instead been suggested by the analysis of the Italian

User	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 2: Geometric features of the four buildings.

non-residential buildings stock, provided by [65].
The last column of Tab. 2 shows the ratio between the roof area A_r and the volume V. It is a geometric indicator useful to evaluate the building shape: the lower it is, the more the building develops vertically. To sum up, the buildings included in in this work are different in shape and end-use, thus resulting in various energy needs (i.e. electricity consumption in residential and commercial users) and profiles. In this way, the potentialities of ECs are better highlighted and examined.

4.2.2 Geographic location and climatic data

The selected location for the case study is Turin, a metropolitan city in north-western Italy. Climate is classified by Köppen [66] with the acronym *Cfa*: the average temperature in the coldest month is between -3 °C and 18 °C, while that of the hottest month exceeds 22 °C, and it rains every month. Geographic information and climatic data (temperature and solar radiation profiles) have been taken from PV-GIS weather database [67]. Fig. 3 reports Turin geographic location and histograms of monthly mean solar radiation and temperature. Such trends present a wide seasonal variation, typical of the continental climate; they increase till a peak is reached in summer, starting then to decrease. The computed HDD are equal to 2657 with an indoor reference temperature of 20 °C, consistent with the value proposed in [68], while CDD are only 245 (with an indoor temperature equal to 24 °C). Therefore, the heating demand is higher than the cooling demand.

4.2.3 Retrofit intervention

For each user, the retrofit intervention takes place as follows [Fig. 4]:

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

- **Office**: In the base case (BAU), the situation is the same as the condominium; in the retrofit the existing cooling system has been replaced by a centralized reversible HP for both heating and cooling. The gas boiler has been kept, while PV panels have been added.

- **Supermarket**: This is the building where fewer retrofit interventions have been considered. Rooftop PV is installed, while the gas boiler and the existing cooling system remain in operation.

- **Mall**: Both heating and cooling systems have been replaced by a high-efficiency CCHP unit (HE-CHP), consisting of an internal combustion engine coupled with an absorption chiller for heat recovery from the cogeneration unit. Moreover, electrical energy is produced on-site also by a PV system installed on the roof.

4.2.4 Economic scenarios definition

The economic comparison of the SSCs and EC configurations has been performed under three different economic scenarios, which determine the electricity sales/purchase tariffs, and by different support mechanisms. Such a methodology allows to assess the implications of future policies on the stakeholder' decisions. Indeed, the multiple-scenarios analysis carried out in the present study shows the EC impact according to policymakers' decisions. Tab. 3 depicts the three economic schemes; keeping in mind the Italian electricity market [Section 3] and already mentioned EU Directives, the following clarifications are necessary:

- 1^{st} *economic scenario*: Protected Market to Net Metering (PM2NM). Electricity is sold according to the NM mechanism. For the EC, the total size of the energy system is the sum of the single installations' capacities (PV and CCHP). Subsidies are applied to PV and HP investment costs [Section 3]. Tab. 3 shows the percentage of such costs recovered with tax deductions 10-years [70]. Finally, in this scenario the prosumers adhere to the protected market [see Section 3.1].

- 2^{nd} *economic scenario*: Protected Market to *Decreto FER* (PM2FER). It differs from the 1^{st} scenario for the sales mechanism, and for the subsidies on the investment cost, that are considered just for the HP. For PV palnts, the net metering has been replaced by a support scheme based on the Italian *Decreto FER*. In the SSCs scenario, each user has a sales price for the electricity generated on-site related to the PV capacity and, if the PV size is smaller

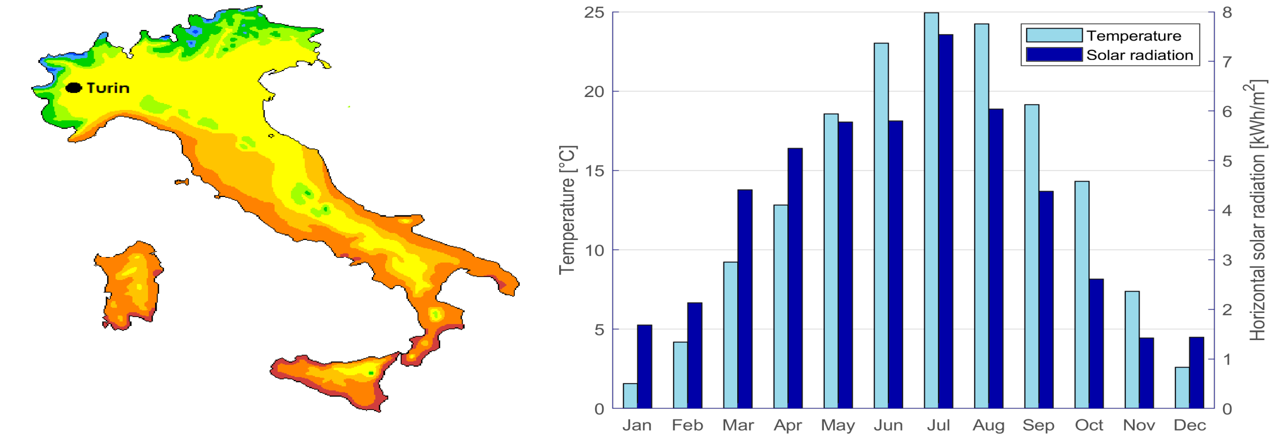

Figure 3: Turin geographic location (left) [69] and monthly mean temperature and solar radiation on a horizontal plane (right).

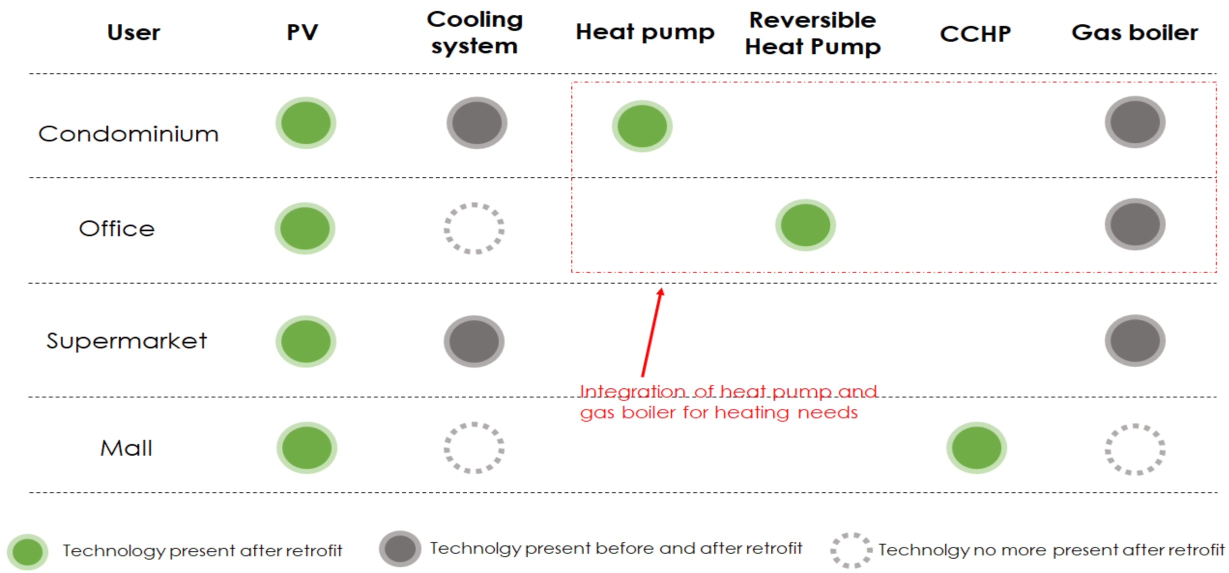

Figure 4: Retrofit intervention for each user.

than 100 kW, it benefits from the bonus for self-consumtpion. The EC has been considered as a unique prsoumer whose total PV capacity is the sum of the single PV installations in each building. Since the "Decreto FER" concerns only RES, the surplus of electricity produced by the CCHP must be necessarily sold according to the NM mechanism.

- 3^{rd} *economic scenario*: Free Market to *Decreto FER* (FM2FER). It differs from the 2^{nd} scenario due to the EC adhesion the free electricity market. It has been hypothesized that the EC has been recognised a 25% discount with respect to the PM on the energy component by the supplier. Therefore the overall electricity price reduces to $c_{ee} = 0.1780$ €$/kWh$, while the SSCs adhere to the protected market. Such an assumption is based on the presence of an energy supplier who, identifying in the community a great consumer, offers a favorable price to it. Indeed, energy suppliers can acknowledge the EC as a big customer, thus recognising favorable tariffs.

5 Results and discussion

In this section, results based on the mathematical model previously described are discussed. Firstly, the system configuration deriving from the optimization process is presented. Then, the two configurations, SSCs and EC, are compared from an energy and economic point of view. The economic analysis has been executed through the three economic scenarios defined in Section 4.2.4, providing in each one sensitivity analyses on the impact of the additional transport and system charges of the electricity bill applied to the energy exchanged among the community members.

Economic scenario	Selling mechanism	Subsidies	Energy price
1^{st}: **PM2NM**	Net metering	PV (50%) HP (50%)	Protected marked $c_{ee} = 0.1989$ €$/kWh$
2^{nd}: **PM2FER**	*"Decreto FER"*	HP (50%)	Protected marked $c_{ee} = 0.1989$ €$/kWh$
3^{rd}: **FM2FER**	*"Decreto FER"*	HP (50%)	Free marked $c_{ee} = 0.1780$ €$/kWh$

Table 3: Economic scenarios definition.

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 4: Yearly specific demand $[kWh/m^3]$ for the various users. Brackets indicate the share for each end-use.

User	PV $[kW_{el}]$	HP $[kW_{th}]$	CCHP $[kW_{el}]$	Abs. Chil. $[kW_{th}]$
Condominium	30	32	-	-
Office	99	92	-	-
Supermarket	98	-	-	-
Mall	190	-	190	75

Table 5: Size of the retrofit energy production systems.

5.1 System configuration

This paragraph describes the system configuration, namely the specific energy needs of each building and the size of the new technologies considered.

5.1.1 Buildings' load definition

Table 4 sums up the specific energy demand of each user obtained through the methodology described in Section 4.1.2. The mall is the most energy-intensive building, especially regarding electricity consumption. Cooling demand is minimum in the condominium, since in the DOE hypotheses it is usually empty during daytime when people are at work, unlike commercial buildings. The heating demand far outweighs the cooling demand, as a consequence of Turin climatic conditions [Section 4.2.2].
The adopted methodology to compute the energy demand has led to results consistent with the literature. [71]-[72]-[73].

5.1.2 Retrofit results

The size of the PV plants has been defined according to the roof area available in each building [Tab. 2], and by considering that PV array installations cover 60% of the roof (in order to avoid shading among the modules and for maintenance). Then, the β-γ combination that minimizes the annual electricity bill has been found as described in Section 4.1.2. Results indicate $\beta = 33°$ and $\gamma = 6°$ as optimal values; as expected, the tilt is smaller than the latitude to capture more radiation in summer, while the azimuth angle is slightly oriented towards west to better match the demand.

The HP size has been established with the optimization algorithm that maximizes its capacity factor. Smaller capacities would curtail the HP potentialities, making it not able to meet a high load percentage. On the other hand, higher capacities would involve that HPs work for long periods in off-design conditions with low performance. The algorithm has lead to a 32 kW_{th} HP unit for the condominium and a 92 kW_{th} HP unit for the office. It must be highlighted that, due to the defined control logic, this is the configuration that minimizes the bill for heating purposes. In the BAU scenario, the unitary heating cost (with only natural gas boiler) was 0.0844 €$/kWh_{th}$, while the optimized hybrid system (natural gas boiler + HP) has reduced it up to 0.0594 €$/kWh_{th}$.

Finally, the size of the CCHP and of the absorption chiller have been determined in order to satisfy the heating and cooling demands of the mall, resulting in 190 kW_{el} and 75 kW_{th} respectively. Simulations

User	Electrical Demand $[MWh]$			Production $[MWh]$		P/L [%]
	Heating	Cooling	Electricity	RES	not RES	
Condominium	28.5	6.2	47.0	46.0	-	56
Office	106.9	45.2	651.3	153.2	-	19
Supermarket	-	8.6	247.0	149.4	-	58
Mall	-	-	543.1	287.2	235.7	96
TOTAL	135.4	60.0	1488.4	635.8	235.7	52

Table 6: Yearly electricity balance of each user. P/L is calculated according to Eq. (18)

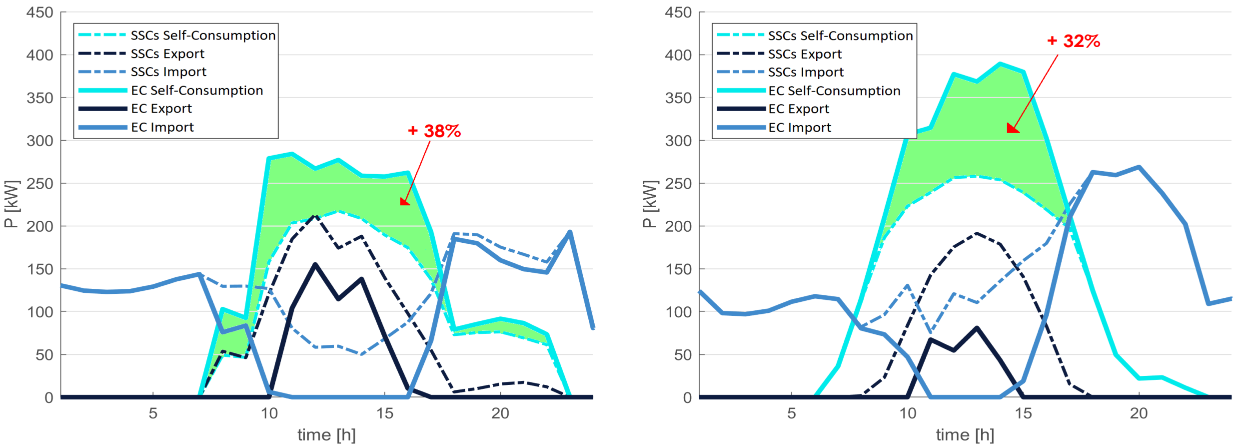

Figure 5: EC and SSCs power profiles in a typical day in winter (left, 31^{st} January) and in summer (right, 15^{th} July).

indicate a positive *PES* (2.48 %), thus the CCHP can benefit from the incentives granted to HE-CHP plants, i.e. tax reduction on the purchase of natural gas, the right to access to net metering, white certificates [74]-[75].
Tab. 5 sums up the size of each new technology for each type of user, while Tab. 6 reports the annual electrical demand and production. These are the starting points for the techno-economic comparison of the SSCs and EC configurations.

5.2 Energy assessment

Self-Sufficiency (SS) and Self-Consumption (SC) are the KPIs used for the assessment and comparison of the energy performance of the two configurations. Fig. 5 shows the differences in the annual power profiles, including power exported/imported to/from the grid, and power self-consumed, in a typical winter and summer day.
The dot-dashed trends are referred to the SSCs configuration (i.e. no direct energy exchange among prosumers); it is evident the contemporaneity of the power withdrawn-from/ fed-into the public grid. This situation is remarkably improved in the EC, where members can directly exchange energy; therefore the energy produced in excess by any member can be directly used by another member whose demand exceeds the production. Continuous lines in Fig. 5 show how the EC increases the self-consumption. The plots also highlight this enhancement, which corresponds to the increase of both the *SS* (fraction of the load satisfied by energy *locally* generated) and the *SC* (ratio between the energies *locally* produced and consumed simultaneously). Nevertheless, energy exchanged among EC member has to transit through the public grid, so it could not represent a full saving from an economic point of view, as it is instead for the *traditional* self-consumption. *SC* fraction always exceeds 80%,and it is 25.8% higher than SSCs on an annual basis. Best performances of ECs are encountered in winter. Indeed, in this season the CCHP production is high, because heat cogenerated must cover the space heating demand of the building, instead the PV production is limited due to the low solar radiation.

Fig. 6 depicts the monthly increase in self-consumption achieved by the EC compared with SSCs. Therefore, the mall may provide its electrical overproduction to other members of the EC. When solar radiation is low, (e.g. 14^{th} January) the SC increase reaches 90%. However, it is worth noting that energy balances during summer have a higher contribution on the total self-consumption, since production is higher in this season thanks to PV yield. A similar trend can be observed for the self sufficiency parameter, because the ratio between the two KPIs has to remain constant and equal to the P/L ratio of the system, according to Eq. (18).

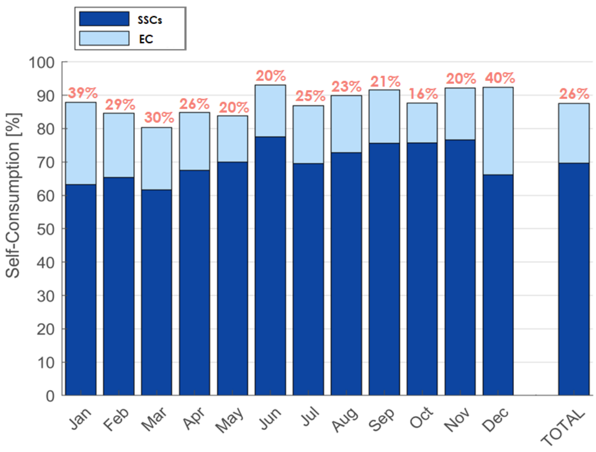

Figure 6: Monthly self-consumption for SSCs and EC. Percentages on the bars indicate the increase with EC compared with SSCs.

Fig. 7 shows the distributions in terms of relative frequency of the daily electrical energy exported and imported with the public grid, while Tab. 7 summarizes the yearly energy balance of each configuration. The net energy exchanged (import/export) by the EC with the public grid is appreciably lower than the SSCs configuration, thanks to the higher self-consumption at the community level. It must be highlighted that the public grid connecting the members of the EC is actually used in the same way as in the SSCs configuration. Nevertheless, in the perspective of the EC, what matters is the energy exchanged with the public grid at the boundaries of the community. In other words, the demand in the EC is satisfied by power produced in a bounded area, reducing the grid losses associated with energy coming from production plants located far from the users.

Tab. 7 confirms the link between SS and SC, being their increase identical and equal to 25.8%. This value coincides with the findings presented by [34]-[35]; however, the final SC they calculated for the EC is much lower (60% against 87% of our work), since here a broader mix of building typologies and technologies has been considered. The general achievement is that ECs make more sense if they consist of a variety of users and production energy systems.

More precisely, the type of users considered in the case study is suited to form a community, as the four buildings match very well in order to share demand and production. Since in our case study solar PV is common to all the prosumers, main differences are related to the geometry of the buildings. For example, resulting from the ratios A_r/V [Tab. 2] and the P/L [Tab. 6], the office has limited roof area to install PV with size tailored for its loads, unlike the mall. Therefore, their cooperation in an EC brings benefits to both.

Tab. 7 shows that the EC strategy leads to an increase of self-consumption of 156 MWh more than SSCs. To introduce the economic assessment, it is worth noting that:

- The 156 MWh no more imported from the grid represent a saving for the EC since in the SSCs configuration the same amount of energy is purchased. Costs are reduced according to the transport plus system charges applied for the transit of this 156 MWh through the public grid.
- The 156 MWh no more exported represent a loss for the EC, since in the SSCs configuration this energy is sold to the grid.

As it will be demonstrated by the economic analysis, the first effect prevails on the second, making the EC an economically convenient solution. Nevertheless, if high charges have to be paid on the self-consumption at EC level, this advantage might reduce drastically, making the community less attractive for citizens and stakeholders.

5.3 Economic assessment

The economic assessment has been carried out through KPIs as NPV, PBT, and IRR, as well as the analysis of the yearly electricity bill. The comparison between EC and SSCs has included the three economic scenarios introduced in Section 4.2.4 and, in each scenario, the impact of system and transport charges applied to the energy exchanged among EC members has been studied.

Fig. 8 compares the electricity bill of the BAU, SSCs, and EC scenarios, showing the savings obtained in the EC and SSCs configurations. The electricity expenditures, shown in Fig. 8, have been reported without applying additional charges on the energy exchanged among EC members. Above zero, the bars show the yearly energy bill, which is split into the four items outlined in Section 3.1; below zero, the bars show the earnings coming from energy sales, which are equal to zero in the BAU scenario. The SSCs configuration lead to 102.3 $k€$ savings in the purchase of electricity, which have to be added to the revenues from electricity sales, i.e. 11.2 $k€$ with net metering scheme (PM2NM) or 23.1 $k€$ with the "Decreto FER" scheme (PM2FER or FM2FER). Therefore, the adhesion to a support mechanism "Decreto FER" results in higher revenues, since it provides twice as much income as the net metering mechanism, thanks also to the premium awarded for the energy consumed on-site, equal to 0.01 $€/kWh$ for PV plants up to 100 kW_{el}

As far as the EC-SSCs comparison is concerned, Fig. 8 highlights the economic consequences of the self-consumption increase previously discussed. In every economic scenario, if an EC strategy is chosen, the reduced import clearly produces a further energy and economic saving (in green) equal to 30.9 $k€$ in the protected marked (PM2NM and PM2FER) or to 50.3 $k€$ if the EC adheres to the free market

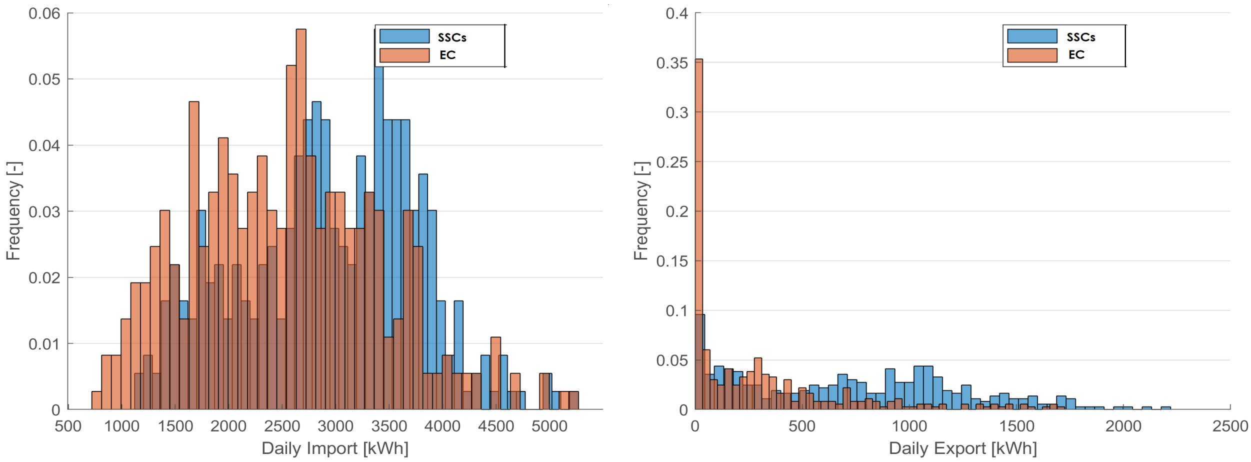

Figure 7: Distribution of the daily energy import (left) and export (right) with the public grid in SSCs and EC.

Scenario	E_{sc} $[MWh]$	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 7: Energy comparison between SCCs and EC.

(FM2FER). On the other hand, there is an income loss, as this energy is internally consumed and not sold to the grid. However, the first effect prevails on the second with a global positive effect for the EC, resulting in 24.3 $k€$, 22.8 $k€$ and 42.2 $k€$, respectively, more savings than the SSCs configuration in the three economic scenarios.

Such quantities may decrease if additional charges are applied, as the avoided imports represent no more full savings. The bottom-right plot in Fig. 8 shows the *total* savings (i.e. including the natural gas contribution) with respect to the BAU scenario for SSCs and EC if a percentage (0%, 50% and 100%) of system and transport charges is applied to energy self-consumed by EC members. Even if the EC is still the most convenient scenario, its benefits decrease substantially as these charges increase. Fig. 9 highlights the impact that transport and system charges have separately on the yearly savings registered by the EC; since the general trend is similar, only the PM2NM economic scenario is shown. Given these results, some considerations are necessary:

- *Transport Charges*: In the present analysis, buildings in the EC are located in the same neighborhood and they are connected to the same low voltage public grid. Therefore, the energy exchanged by members of the EC does not make use of transmission lines, so they may be exempted to pay a percentage of the transport charges.

- *System Charges*: They cover costs concerning the whole national electrical system, so it is expected that they will be paid also by EC members [76].

If EU Directives transpositions will respect these forecasts, Fig. 9 shows that the margin of the EC annual savings would be about 5% – 8%.

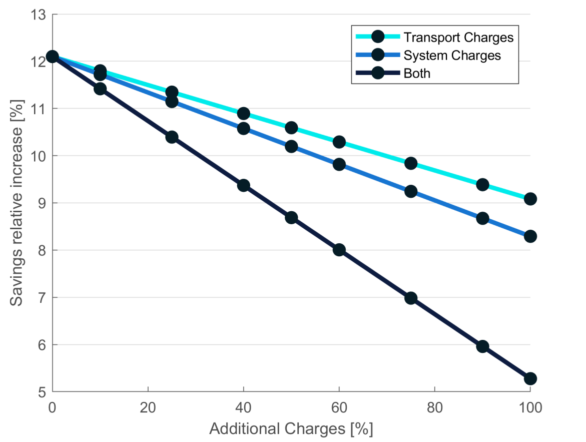

Figure 9: Correlation between savings increase and transport+system charges in the EC-PM2NM scenario.

The second part of the economic assessment concerns the cash flow analysis to evaluate the profitability of the investment, aiming again at comparing EC and SSCs under the three economic scenarios. Every year, the two configurations profit from electricity sale and saved bills, while they must pay for the maintenance of the energy systems. Fig. 10 shows the NPV and the IRR after 20 years, as well as their reduction for the EC if increasing shares of the transport and system charges (up to those due in the SSCs configuration) are applied.

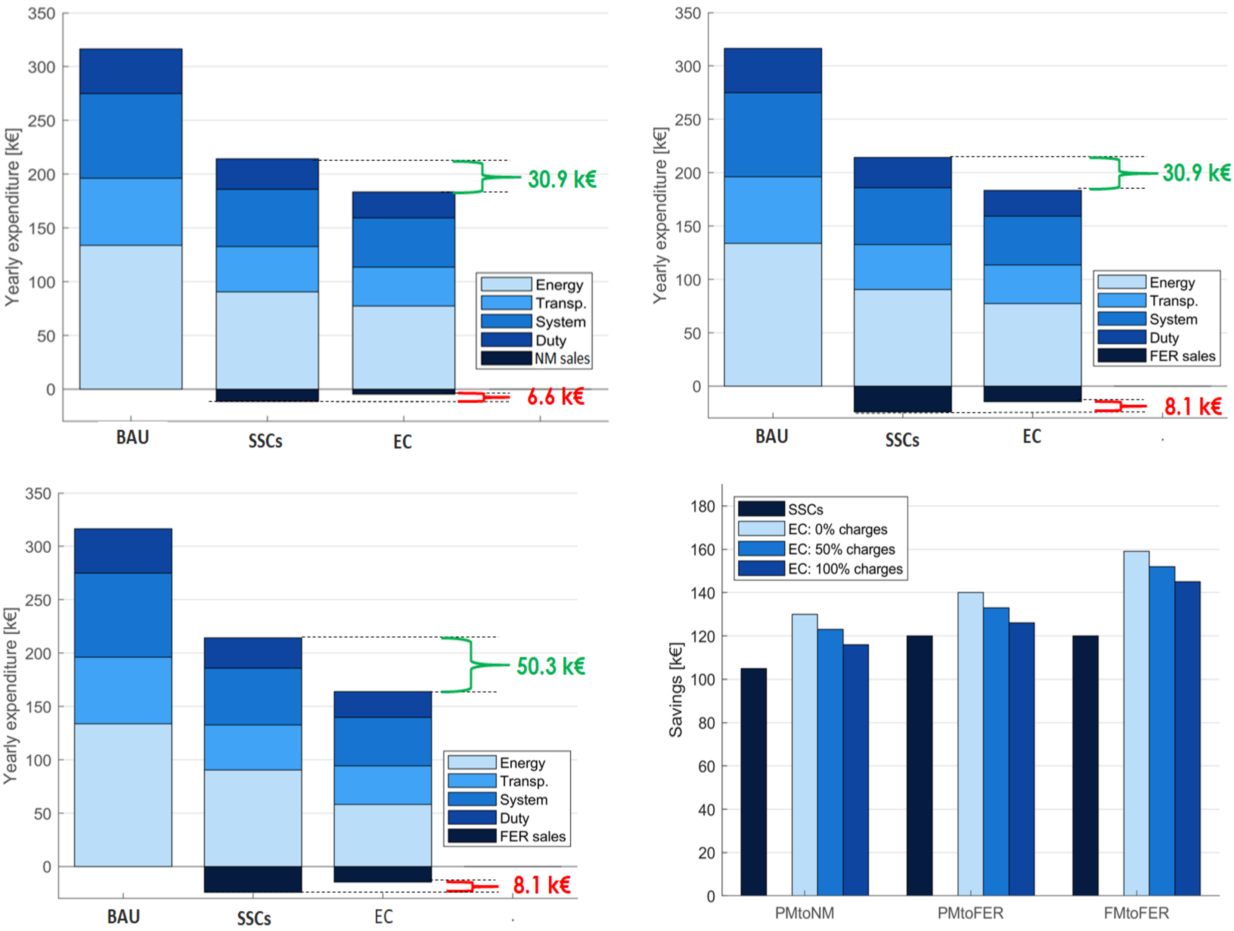

Figure 8: Electricity bill. No system and transport charges are applied to energy internally exchanged in the EC configuration. Bottom right: savings compared to BAU configuration for SSCs and EC, with different ratios of transport+system charges applied to energy internally exchanged in the EC.

The total CAPEX of 607 $k€$ is always recovered and, consequently, the IRR is always higher than the interest rate; moreover, the EC configuration shortens the PBT of one year. FM2FER turned out to be the best scheme for the EC compared to the SSCs scenario, both in terms of absolute NPV (1397 $k€$), and in terms of NPV increase (483 $k€$ more). This is basically because the advantageous feed-in tariffs, alongside the discount on the purchased electricity in the free market, imply the highest yearly income. As expected, the net metering mechanism leads to the lowest profits, and it resulted less advantageous than the support scheme based on "Decreto FER".

Nevertheless, the economic scenario presenting smaller differences between the EC and the SSCs is the PM2FER, since money loss on avoided energy sales are more important, as the adhesion to "Decreto FER" grants good feed-in tariffs, because of the convenient feed-in tariffs considered in this scenario.

Tab. 8 sums up the main findings obtained for the EC configuration in each economic scenario. The *cost* column is the sum of electricity bills, while the *savings* one is computed starting from the BAU configuration. The following conclusions can be obtained:

- Tariffs granted by "Decreto FER" are more convenient than the net metering mechanism. Moreover, being constant for 20 years, they protect against possible unfavourable changes in the electricity market prices.
- The PM2FER scenario leads to a modest economic convenience for the EC compared to the SSCs, while it is much more interesting if the EC, as a big customer, obtains a discount on the energy price (i.e. the FM2FER scenario).
- Increasing shares of transport and system charges worsen the economic KPIs of the EC. Nevertheless, also in the less convenient case, a profit has been registered, meaning that the bill savings due to the self-consumption enhancement always prevails over the missed sales.

This last point needs further discussion. The magnitude of such charges will be decided in the next years when the Renewable Energy Directive will be transposed by Member States, while today only assumptions are possible. RED II requires Member States to promote ECs formation transport and system charges in the electricity bill are paid seems unlikely. On the

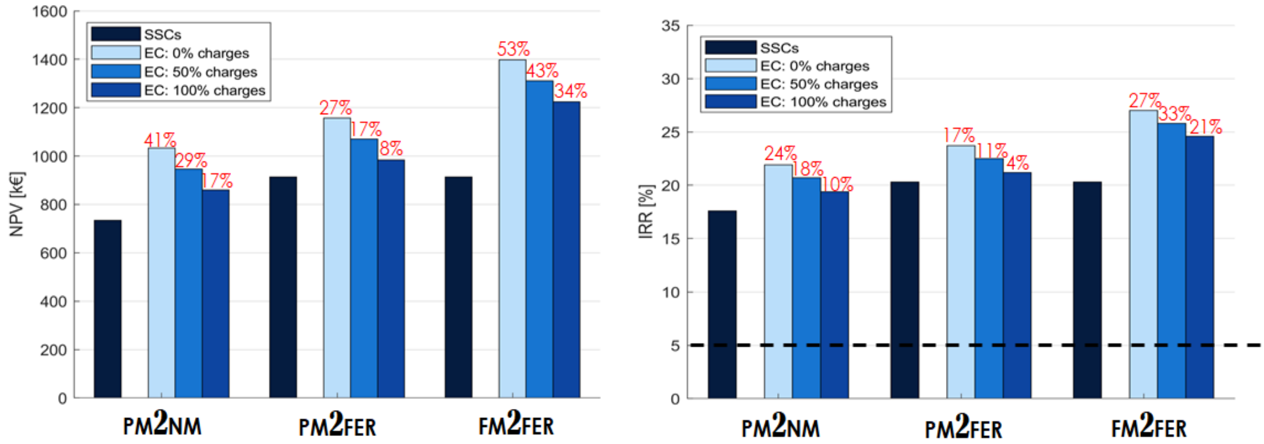

Figure 10: NPV (left) and IRR (right) for SSCs and EC in the three economic scenarios, with variable rate of the transport+system charges on the energy self-consumed by members of the EC.

Economic scenario		Bills		Cash flow	
Scheme	Additional charges	Cost [k€]	Savings [k€]	NPV [k€]	IRR [%]
PM2NM	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%)
PM2FER	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%)
FM2FER	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 8: Main results of the economic analysis. Percentages in brackets indicate the EC increase with respect to the SSCs scenario. Column "Additional charges" refers to the percentage transport+system charges applied on the energy self-consumed by the members of the EC.

other hand, also the total absence of such charges is unrealistic, since the EC is expected to pay for the use the public grid and the secure operation of the National electricity system. Nowadays, the most logical scenario foresees an average percentage of these charges is due by EC members.

This is a key point, since transport and system charges have a significant impact on the economic feasibility of ECs. Full charges could make ECs less convenient, since the EC operation is more complex than an SSCs configuration. These aspects require a mindful national legislation in accordance with the EC regulatory framework.

6 Conclusions

With ECs expected to be widely spread in the next years to promote RES diffusion and distributed energy systems, this work has tried to address the issue *"when and to which extent is it economically convenient to establish an EC for a group of local prosumers?"*

The techno-economic assessment has envisaged a comparative analysis of the EC performances, in which buildings act collectively in terms of energy exchange of self-produced electricity, with a consolidated configuration characterised by single prosumers. The case study is composed of four commercial and residential users located in Turin; starting from a Business As Usual scenario, which represents traditional customers that simply purchase electricity from the grid, a technological retrofit with PV, HPs, and CCHP has been implemented. For the comparison, they can operate separately (SSCs) or as a community (EC). Following the definition of the characteristics of buildings, weather conditions, and thermal and electrical loads, the energy system has been sized and techno-economic KPIs have been defined. The comparison has been carried out under three economic scenarios, differing in energy price and selling mechanism, and with a sensitivity analysis aimed at revealing the impact of variable transport and system charges in the electricity bill of the EC members. Results have demonstrated the EC potentialities, providing suggestions for policy-makers to promote ECs diffusion. It is worth mentioning that results are affected by users' behaviour and energy prices volatility; changing hypotheses about occupancy rates of residents (e.g., full occupancy during the day due to the presence of elderly people), firms schedules (e.g., holiday and opening hours), and energy prices, may lead to different results. Nevertheless, Energy Communities, through aggregation and cooperation, are more resilient than single customers to withstand these variations [77]-[78]. To sum up, the following conclusions can be obtained:

- The EC configuration enhances the on-site consumption of 156 MWh, increasing the self-consumption and the self-sufficiency rates by 25.8% compared to SSCs. Such energy can be seen both as a saving, since it is no more imported, but also as an economic loss, since it can no longer be sold.
- Regarding the economic scenarios, a support scheme based on the Italian "Decreto FER" has proved to be more advantageous than the net metering mechanism even though they reduce the profit margin of ECs compared to the SSCs configuration. At the same time, the participation in the electricity-free market gives a significant contribution to the economic KPIs of the EC.
- The EC turns out to have always higher economic KPIs compared to SSCs, also in the worst scenario with full transport and system charges applied in the electricity bill. Nevertheless, such charges worsen all KPIs: NPV increase with respect to the SSCs configuration is reduced in the three economic scenarios up to 17% (PM2NM), 8% (PM2FER), and 34% (FM2FER), respectively. A suitable regulatory framework, when the transposition of the Renewable Energy Directive will take place, is the basis for an ECs large scale diffusion.

These points can be seen also from another perspective. With respect to other works, this paper has highlighted some critical aspects of ECs policies and, based on the results obtained in a representative case study, it has demonstrated how the feasibility and the economic appeal of Energy Communities is strongly bonded to electricity market rules and regulatory frameworks.

References

[1] European Union, *"Renewable Energy Communities"*, Interreg Europe, 2018, retrieved from `https://www.interregeurope.eu/fileadmin/user_upload/plp_uploads/policy_briefs/2018-08-30_Policy_brief_Renewable_Energy_Communities_PB_TO4_final.pdf`.

[2] Doci, G., Vasileiadou, E., Petersen, A.C., *"Exploring the transition potential of renewable energy communities"*, Future, vol. 66, 2015, pp. 85-95.

[3] Dvarioniene, J. et al., *"Stakeholders involvement for energy conscious communities: The Energy Labs experience in 10 European communities"*, Renewable Energy, vol. 75, 2015, pp. 512-518.

[4] Walker, G, Devine-Wright, P., *"Harnessing Community Energies: Explaining and Evaluating Community-Based Localism in Renewable Energy Policy in the UK"*, Global Environment Politics, vol. 7, 2007, pp. 64-82.

[5] Jank, R., *"Annex 51: Case studies and guidelines for energy efficient communities"*, Energy and Buildings, vol. 154, 2017, pp. 529-537.

[6] Strasser, H. et al., *"IEA EBC annex 63–implementation of energy strategies in communities"*, Energy and buildings, vol. 158, 2018, pp. 123-134.

[7] *Interreg Europe* [website], 2017, `https://www.interregeurope.eu/coalescce/`, accessed 14 July 2019.

[8] Walker, G, Devine-Wright, P., *"Community renewable energy: What should it mean?"*, Energy policy, vol. 36, 2008, pp. 497-800.

[9] Roby, H. & Dibb, S., *"Future pathways to mainstreaming community energy"*, Energy policy, vol. 135, 2019, in press.

[10] Morrison, C. & Ramsey, E., *"Power to the people: Developing networks through rural community energy schemes"*, Journal of Rural Studies, vol. 70, 2019, pp. 169-178.

[11] European Union, *REScoop.eu* [website], 2017, `https://www.rescoop.eu/definitions`, accessed 16 October 2019.

[12] Moroni, S. et al. *"Energy communities in the transition to a low-carbon future: A taxonomical approach and some policy dilemmas"*, Journal of Environmental Management, vol. 236, 2019, pp. 45–53.

[13] Bodis, K. et al., *"A high-resolution geospatial assessment of the rooftop solar photovoltaic potential in the European Union"*, Renewable and Sustainable Energy Reviews, vol. 114, 2019, in press.

[14] Osti, G., *"The uncertain games of energy transition in the island of Sardinia (Italy)"*, Journal of Cleaner Production, vol. 20, 2018, pp. 681-689.

[15] *"Gruppo ACSM"*, [website], 2019, https://www.gruppoacsm.com/il-gruppo-p597, accessed 17 October 2019 (in Italian).

[16] Regione Piemonte, Regional Law n. 12, *"Promozione ed istituzione delle comunitá energetiche"*, 2018 (in Italian).

[17] Regione Puglia, Regional Law n. 45 *"Promozione dell'istituzione delle comunitá energetiche"*, 2019 (In Italian).

[18] European Parliament, *"Renewable Energy Directive"*, Bruxelles, 2018, retrieved from http://www.free-energia.it/w/wp-content/uploads/2018/11/NEN188647IT11.pdf.

[19] European Parliament, *"Directive 2019/944 concerning common rules for the internal market in electricity"*, Bruxelles, 2019, retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019L0944&from=EN.

[20] Baneshi, M., Hadianfard, F., *"Techno-economic feasibility of hybrid diesel/PV/wind/battery electricity generation systems for non-residential large electricity consumers under southern Iran climate conditions"*, Energy Conversion and Management, vol. 127, 2016, pp. 233-244.

[21] Brum. M. et al., *"A comparative study of district and individual energy systems providing electrical-based heating, cooling, and domestic hot water to a low-energy use residential community"*, Energy and Buildings, vol. 92, 2015, pp. 306-312.

[22] Ma, W. et al., *"Techno-economic evaluation of a community-based hybrid renewable energy system considering site-specific nature"*, Energy Conversion and Management, vol. 171, 2018, pp. 1737-1748.

[23] Amiri, S., Weinberger, G., *"Increased cogeneration of renewable electricity through energy cooperation in a Swedish district heating system - A case study"*, Renewable Energy, vol. 118, 2018, pp. 866-877.

[24] Maleki, A. et al., *"Optimization of a grid-connected hybrid solar-wind-hydrogen CHP system for residential applications by efficient metaheuristic approaches"*, Applied Thermal Engineering, vol. 123, 2017, pp. 1263-1277.

[25] Petersen, J.P., *"The application of municipal renewable energy policies at community level in Denmark: A taxonomy of implementation challenges"*, Sustainable Cities and Societies, vol. 38, 2018, pp. 205-218.

[26] Thakur, J., Chakraborty, B., *"Impact of compensation mechanisms for PV generation on residential consumers and shared net metering model for developing nations: A case study of India"*, Journal of Cleaner Production, vol. 218, 2019, pp. 696-707.

[27] Gupta, R., Bruce-Konuah, A., Howard, A., *"Achieving energy resilience through smart storage of solar electricity at dwelling and community level"*, Energy and Buildings, vol. 195, 2019, pp. 1-15.

[28] Awad, H., Gül, M., *"Optimisation of community shared solar application in energy efficient communities "*, Sustainable Cities and Society, vol. 43, 2018, pp. 221-237.

[29] Rathore, P.K.S., Chauhan, D.S., Singh, R.P., *"Decentralized solar rooftop photovoltaic in India: On the path of sustainable energy security"*, Renewable Energy, vol. 31, 2019, pp. 297-307.

[30] Kalamapur, G.D., Udaykumar, R.Y., *"Rural electrification in India and feasibility of Photovoltaic Solar Home Systems"*, International Journal of Electrical Power System, vol. 33(3), 2011, pp. 594-599.

[31] Chan, D., Cameron, M., Yoon, Y., *"Implementation of micro energy grid: A case study of a sustainable community in China"*, Energy and Buildings, vol. 139, 2017, pp. 719-731.

[32] Gerber, S., Rix, A.J., Booyseen, M.J., *"Towards sustainable developing cities: A simplified forecasting model for sizing grid-tied PV using monthly electricity bills"*, Sustainable Cities and Societies, vol. 54, 2020, in press.

[33] Schiera, D.S. et al., *"Analysis of Rooftop Photovoltaics Diffusion in Energy Community Buildings by a Novel GIS- and Agent-Based Modeling Co-Simulation Platform"*, IEEE, vol. 7, 2019.

[34] Roberts, M.B., Bruce, A., MacGill, I., *"A comparison of arrangements for increasing self-consumption and maximising the value of distributed photovoltaics on apartment buildings"*, Solar Energy, vol. 193, 2019, pp. 372-386.

[35] Luthander, R. et al., *"Self-consumption enhancement and peak shaving of residential photovoltaics using storage and curtailment"*, Energy, vol. 112, 2016, pp. 221-231.

[36] Mittal, A. et al., *"An agent-based approach to modeling zero energy communities"*, Solar Energy, vol. 191, 2019, pp. 193-204.

[37] Gonzalez, F.F., Sauma, E., van der Weijde, A., *"The Scottish experience in community energy development: A starting point for Chile"*, Renewable and Sustainable Energy Reviews, vol. 113, 2019, in press.

[38] Suh, H.S. & Kim, D.D., *"Energy performance assessment towards nearly zero energy community buildings in South Korea"*,Sustainable Cities and Societies, vol. 44, 2019, pp. 488-498.

[39] Rosato, A. et al., *"Impact of seasonal thermal energy storage design on the dynamic performance of a solar heating system serving a small-scale Italian district composed of residential and school buildings"*, Journal of Energy Storage, vol. 25, 2019, in press.

[40] European Commission, *"Energy prices and costs in Europe"*, Bruxelles, 2019, retrieved from https://ec.europa.eu/energy/sites/ener/files/epc_report_final_1.pdf.

[41] RES legal, *"Legal sources on renewable energy"* [website], 2019, http://www.res-legal.eu/compare-support-schemes/, accessed 22 November 2019.

[42] ARERA, *"Bolletta 2.0: Guida alla lettura delle voci di spesa per i clienti serviti in regime di tutela "* [website], 2019, https://bolletta.arera.it/bolletta20/images/guidaele.pdf, accessed 22 July 2019 (in Italian).

[43] Marcantonini, C., Valero, V., *"Renewable energy and CO_2 abatement in Italy "*, Energy Policy, vol. 106, 2017, pp. 600–613.

[44] Repubblica Italiana, D. Lgs. 4 July 2019, *"Incentivazione dell'energia elettrica prodotta dagli impianti eolici on shore, solari fotovoltaici, idroelettrici e a gas residuati dei processi di depurazione"*, 2019 (in Italian).

[45] ARERA, Annex A - resolution ARG/elt 74/2008, *"Testo integrato delle modalitá e delle condizioni tecnico-economiche per lo scambio sul posto"*, 2008 (in Italian).

[46] Gestore Mercati Energetici, *"Dati di sintesi MPE-MGP - riepilogo"* [website], 2019, http://www.mercatoelettrico.org/It/Statistiche/ME/DatiSintesi.aspx, accessed 10 September 2019 (In Italian).

[47] U.S. Department of Energy, *"Open Data Catalog"* [website], 2018, http://en.openei.org/datasets/files/961/pub/, accessed 14 August 2019.

[48] Deru, M. et al., *"U.S. Department of Energy Commercial Reference Building Models of the National Building Stock"*, NREL, DOE, 2011.

[49] ARERA, *"Composizione percentuale del prezzo dell'energia elettrica per un consumatore domestico tipo"* [website], 2019, https://www.arera.it/it/dati/condec.htm, accessed 18 July 2019 (in Italian).

[50] Ente Italiano di Normazione, Annex A - Regulation UNI 9182/14, 2014 (in Italian).

[51] Al Garni, H.Z., Awasthi, A., Wright, D., 2019, *"Optimal orientation angle for maximizing energy yield for solar PV in Saudi Arabia"*, Renewable Energy, vol. 133, pp. 538-550.

[52] LG, *LGNeON®Solar Catalogue*, retrieved from http://www.lg-solar.com/downloads/products/IT_NeON%20R%2060cells.pdf (in Italian).

[53] American Society of Heating, Refrigeration and Air-Conditioning Engineers, *"Handbook of Fundamentals"*, New York, 2017.

[54] Hernan, E.S. et al., *"Numerical model for liquid-to-liquid heat pumps implementing switching mode"*, Applied Thermal Energy, vol. 160, 2019, in press.

[55] Ayele, G.T. et al., *"Optimal placement and sizing of heat pumps and heat only boilers in a coupled electricity and heating networks"*, Energy, vol. 182, 2019, pp. 122-134.

[56] RIELLO, *"NXH Catalogue"*, retrieved from www.riello.it/catalogo/pompe-di-calore/nxh-026-040_R-IT-PL-0006057?k=Product+Line%7CR-IT-PL-0004766%7C- (in Italian).

[57] Rossi, N., *"Manuale del Termotecnico"*, Chapter 10, 4^{th}*edition*, Hoepli, 2014 (in Italian).

[58] MAN, *"MAN gas engines for cogeneration units"*, retrieved from https://www.engines.man.eu/global/en/power/gas-power-generation/in-focus/In-Focus.html.

[59] Shuangliang, *"Eco-Energy Catalogue"*, retrieved from http://essb.my/wp-content/uploads/2017/10/Folleto-enfriadoras-Shuangliang.pdf

[60] Repubblica Italiana, Annex IV - D.Lgs. 20/2007, *"Attuazione della direttiva 2004/8/CE sulla promozione della cogenerazione basata su una domanda di calore utile nel mercato interno dell'energia"*, 2007 (in Italian).

[61] Luthander, R. et al., *"Graphical analysis of photovoltaic generation and load matching in buildings: A novel way of studying self-consumption and self-sufficiency"*, Applied Energy, vol. 250, 2019, pp. 748-759.

[62] Danish Energy Agency (DEA), 2019, *"Technology Data for Generation of Electricity and District Heating"*, retrieved from https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-generation-electricity-and.

[63] ISTAT, *"Edifici Residenziali"* [website], 2011, http://dati-censimentopopolazione.istat.it/Index.aspx?DataSetCode=DICA_EDIFICIRES#, accessed 22 August 2019 (in Italian).

[64] Politecnico di Torino - Energy Department, *"Tabula web Tool"* [website], 2017, http://webtool.building-typology.eu/#bd, accessed 22 August 2019.

[65] Citterio, M., *"Analisi statistica sul parco edilizio non residenziale e sviluppo di modelli di calcolo semplificati"*, ENEA, RSE, 2009 (in Italian).

[66] Belda, M. et al., *"Climate classification revisited: from Köppen to Trewartha"*, Climate Research, vol. 59, 2014, pp. 1-13.

[67] European Commission, *"PV-GIS"* [website], 2018, https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html, accessed 21 August 2019.

[68] Repubblica Italiana, Annex A - DPR 412/93, *"Regolamento recante norme per la progettazione, l'installazione, l'esercizio e la manutenzione degli impianti termici degli edifici ai fini del contenimento dei consumi di energia"*, 1993 (in Italian).

[69] Pinna, M., *"L'atmosfera e il clima"*, Utet, 1978 (in Italian).

[70] ENEA, *"Detrazioni fiscali per l'efficienza energetica"* [website], 2019, http://www.acs.enea.it/, accessed 03 October 2019 (in Italian).

[71] Macchi, E., Campanari, S., Silva, P., *"La microcogenerazione a gas naturale"*, Chapter 8, 2^{th}*edition*, Polipress, 2006 (in Italian).

[72] Moneta, R., Bertini, I., Di Franco, N., *"Rapporto Annuale Efficienza Energetica*, Enea, 2017 (in Italian).

[73] De Pasquale, A. (supervised by), *"Benchmark di consumo energetico degli edifici per uffici in Italia"*, Enea - Assoimmobiliare, 2019 (in Italian).

[74] Macchi, E., Campanari, S, Silva, P., *"La microcogenerazione a gas naturale"*, Chapter 2, 2^{th} edition, Polipress, 2006 (in Italian).

[75] Gestore Mercati Energetici, *"Energy efficiency certificates - sessions results"* [website], 2019, `http://www.mercatoelettrico.org/en/Esiti/TEE/TEE.aspx`, accessed 23 Oct. 2019 (in Italian).

[76] Senato della Repubblica, *"sostegno alle attività produttive mediante l'impiego di sistemi di generazione, accumulo e autoconsumo di energia elettrica"*, 2019, retrieved from `http://www.senato.it/documenti/repository/commissioni/comm10/Aff_Ass_59_Documenti_depositati.pdf` (in Italian).

[77] Gupta, R., Bruce-Konuah, A., Howard, A., *"Achieving energy resilience through smart storage of solar electricity at dwelling and community level"*, Energy and Buildings, vol. 195, 2019, pp. 1-15.

[78] Valcamonico, D., Sansavini, G., Zio, E., *"Cooperative co-evolutionary approach to optimize recovery for improving resilience in multi-communities"*, Reliability Engineering & System Safety, vol. 197, 2020, in press.