Decarbonizing residential energy consumption under the Italian collective self-consumption regulation

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Abstract

The recent Italian regulatory framework is promoting Collective Self-Consumption to play a key role in the energy transition. In fact, this new scheme allows sharing and exchange of electricity produced from Renewable Energy Sources (RES) among different end-users living in the same multi-family building block.

In this context, this paper aims to perform an energy, economic and environmental assessment of creating a RES-based energy community formed by end-users located in the same residential building, taking into account the currently available incentive schemes. In particular, two different progressive scenarios have been analysed: the first one includes only a photovoltaic system to supply the aggregated electricity demand of the apartments, while a heat pump is further integrated in the second scenario for supplying and electrifying/decarbonizing also the space heating demand of the building. Available temperature and solar irradiance datasets at national level were then used to spread the analysis to the whole country, at different latitudes.

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Although differences exist at regional levels for the proposed scenarios, the results highlight how the RES-based Collective Self-Consumption scheme is economically profitable for Italian residential end-users with cost savings up to 32% and environmentally sustainable with carbon emissions reduction up to 60%.
Keywords: Collective Self-Consumption, PV, Heat Pump, Residential Building, Decarbonization

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Nomenclature and units

α	Degradation rate of PV module (%/year)
β	Fraction of HP production supplied by PV
ΔCO_2	CO_2 emission savings ($\%/year$)
η_b	Efficiency of gas-fired boiler (%)
C_{HP}	Per unit investment cost of HP (€/kW_{th})
C_m	Price of the natural gas(€/m^3)
C_{PV}	Per unit investment cost of PV (€/kW_p)
C_p	Price of electricity bought from the grid including grid costs(€/kWh)
C_s	Price of electricity sold to the grid(€/kWh)
$CAPEX_{PV}$	Investment cost for PV (€)
$CAPEX_{HP}$	Investment cost for HP (€)
COP	Coefficient of Performance
d	Discount rate
$DPBT$	Discounted Pay Back Time (years)

E_p	Electricity yearly bought from the grid (kWh)
E_{sh}	Yearly PV production shared between members of the collective self-consumption scheme (kWh)
EF_e	Emission factor of the electricity bought from the grid (tCO_2/MWh)
EF_{ng}	Emission factor of the natural gas (tCO_2/MWh)
G	Hourly solar irradiance $\left(\mathrm{kW/m^2}\right)$
H_i	Lower heating value of natural gas (kWh/m^3)
HP	Heat Pump
IRR	Internal Rate of Return (%)
NPV	Net Present Value(€)
$OPEX_{PV}$	Operational costs for PV (€/$\mathrm{kW_p}$)
$OPEX_{HP}$	Operational costs for HP (%/year)
$P_{HP,th,max}$	Size of centralized HP system ($\mathrm{kW_{th}}$)
P_{inj}	PV production injected into the distribution grid (kW)
$P_{PV,size}$	Size of PV plant ($\mathrm{kW_p}$)
P_{UE}	Hourly aggregated electricity demand of the building (kW)
P_{UT}	Hourly space heating demand (kW)
PCR	Yearly cost savings (%/$year$)
PR	Performance Ratio of the PV plant

PV	Photovoltaic
SC	Self-Consumption (%)
SS	Self-Sufficiency (%)
T_a	Hourly air temperature (°C)
YC	Yearly costs (€/year)
YCF	Yearly cash flow(€/year)
YR	Yearly revenues (€/year)

1. Introduction

Buildings are one of the largest energy consumers in European Union (EU), since their energy demand is about 40% of the whole consumption, creating around 36% of the whole carbon emission (European Commission, 2021b). The Italian residential building stock suffers a similar condition because its energy consumption accounts for around 43% of the national energy requirements, most of which concerns space heating (i.e., approximatively 70%) based on fossil fuels (ENEA, 2020). This is due to the aging infrastructures with scarce thermal insulation, which lead the sector to be one of the most energy-intensive in the country with relevant carbon emissions (Eurostat, 2021). In fact, around 85% of the residential building were built before 1990 when any national regulation for reducing energy consumption was still not in force (Palladino et al., 2019).

Consequently, to contrast the current trends, the EU has set targets for its Member States in terms of sustainability and decarbonization in the next future through the European Green Deal program (European Commission, 2021a). Therefore, to achieve the targets, a drastic change in the paradigm of energy production and consumption is needed in this "energy transition" process (Camarasa et al., 2022). This sounds particularly true in the residential sector, where most of the final energy demand is expected to be supplied by Renewable Energy Sources (RES), together with the adoption of energy efficiency measures (e.g., deep energy retrofit or renovation).

The integrated adoption of Photovoltaic (PV) systems and Heat Pumps (HP) has demonstrated to represent a valuable option in the direction of decarbonization in residential building stocks (Qu et al., 2020). Indeed, the electricity consumption, on the one hand, can be supplied by RES generation, while higher energy efficiency, on the other hand, can be pursued by the electrification of the space heating demand with a consequent reduction of primary energy consumption and carbon emissions (Apostolopoulos et al., 2022; Carella and D'Orazio, 2021). Nevertheless, such systems are generally costly (Heinz and Rieberer, 2021), so their diffusion could be compromised, especially in contexts with energy poverty, if not adequately supported by incentives and/or regulatory schemes.

In particular, the two directives EU 2018/2001 (European Parliament, 2018) and EU 2019/944 (European Parliament, 2019) (commonly referred to as RED II and IEM, respectively) could assume a relevant role in diffusing both systems (PV and HP) at the residential level in this transition process, through the introduction of Energy Communities and Collective Self-Consumption. In 2021 the Italian government fully transposed the two Directives and a series of regulations were issued to define the framework for end users to join Renewable Energy Communities (RECs) or as Jointly-Acting Renewable Self-Consumers: (ARERA, 2020) and (GSE, 2020) provided the technical and operative rules for these configurations, while (Ministero dello Sviluppo Economico, 2020) defined the incentive structure.

Even though the current regulation (hence, all projects currently under development) focuses only on electricity (RSE and Utilitatis, 2021), sector coupling can be a viable means to further exploit local RES-production and decarbonize residential energy consumption. For example, families living in a multi-house residential building can integrate the centralized fossil-based heating system with a heat pump (HP), which is in part powered by the RES-production of a PV generator. In this context, the underlying concept of *energy sharing* is the enabling factor for decarbonization in the residential sector through increased production from Renewable Energy Sources (RES) and the electrification of space heating. In fact, differently from the past, the regulation introduced the possibility to share through the grid the energy production from RES (PV) with the end-users joining the community, including the consumption of the apartments and the HP. Incentives are also available for shared energy, making economically attractive these new regulatory schemes.

Several models and case studies of these new energy systems have been proposed since they came into force in the national regulation. These applications may differ in the technologies and energy vectors included, in the perimeter (e.g. REC or collective self-consumption in a single building), or the approach (with or without optimization).

In the European context, for instance, collective self-consumption in energy communities, where participants can exchange and trade energy among themselves within a given area, is discussed in (Mustika et al., 2022) to highlight the benefits of an optimal resource allocation in a demonstrator located in France. Even if HP is not included, a reduction of 12% in the energy bill is demonstrated thanks to the intelligent allocation of PV production within the community (by means of storage systems) and adopting a reduced price for the shared energy (i.e. lower than the grid rates). How the collective self-consumption initiatives can be implemented and exploited in multi-family buildings with the adoption of metering systems and optimization strategies is instead presented in (Reis et al., 2022) to promote a more efficient management of energy resources. Fixed-size PV and storage units are considered to supply residential end-users of a building located in Coimbra (Portugal). Even though HP is not integrated, the economic and energy benefits of the collective self-consumption initiative reveal that energy bills can be still reduced by around 17%. Similarly, a multi-agent simulation of collective self-consumption is analysed in (Albouys-Perrois et al., 2022) for a group of neighbour residential buildings located in the area of La Rochelle, situated in the South-West of France, to point out the benefits of energy exchange between buildings equipped with PV and electric heaters. Authors, through an energy model to calculate the energy needs of buildings, highlighted how the introduction of storage systems in the collective self-consumption can improve self-consumption up to 90% making also the buildings more autonomous and self-sufficient with a lower carbon footprint. The optimal configuration of an energy community applied to a residential building located in Zaragoza (Spain) is again presented in (Pinto et al., 2022). Even if also small-size cogeneration is considered together with PV and HP, the results pointed out how, for a totally self-sufficient building, costs and CO_2 savings of 17% and 14% can be achieved, respectively.

Also in the Italian context, literature explores the implementation of the novel regulatory framework where the integration of PV and/or HP can be boosted. For example, the case-study of a REC in northern Italy is proposed in (Cielo et al., 2021), with a PV system and a community-based electricity storage. Optimization of the power flows in a municipal REC in northern Italy was performed, to find out the optimal sizes of the community-owned

PV system and battery. The proposed optimal configuration achieves a significant Internal Rate of Return up to 14% with carbon emission savings close to 45%, but integration of HP is not explored even if residential buildings are involved in the energy community. (Zatti et al., 2021) propose an analysis of the implementation of a collective self-consumption scheme in an Italian small/medium condominium located in the North of Italy with residential and commercial end-users. In this case study, heating demand is included in the model, so the integration of PV and HP is considered. Despite the analysis is not representative of the whole Italian context, results highlight how the installation of HP in the collective self-consumption scheme contributes to increasing the self-consumption of RES production up to 86% and boosts the cost and emission savings to 32% and 65%, respectively. Similarly, a study for the conversion of a multi-family residential building into an energy community is presented and discussed in (Minuto et al., 2021), where different energy vectors and possible active solutions including PV, HP and storage are considered for a specific case study in the North-West of Italy. Also here, the adopted scheme reveals how the collective self-consumption can promote RES production and the electrification of the building energy needs. In fact, also with small size HP, self-consumption can raise up to 70% with emission savings of 30% and reduced payback time of the investment. Additionally, the evaluation of the economic profitability of PV systems under the Italian collective self-consumption scheme is presented in (D'Adamo et al., 2022) both for household and non-household electricity self-consumers. The breakeven point analysis indicates that PV installation is almost economically self-sustainable (i.e., just self-consumption higher than 13% is needed to make the investment profitable), but the study considers an average level of insolation and, thus, is not totally representative of the whole Italian context. A more recent approach (Negri et al., 2022) proposes the adoption of Artificial Intelligence to forecast electricity demand of a multi-flat building located in Milan, where the collective self-consumption scheme is considered for the installation of a PV and a storage system. The approach produces a cost reduction up to 12.5% and a CO_2 emissions reduction up to 24.7%, and further benefits can be expected if HP was also integrated.

Despite obtaining valuable results about the energy, environmental and economical sustainability of all these initiatives, these works are limited to single case-studies, most of which are in the northern part of Italy. Instead, widening the scope of these analyses can be useful to provide insight at larger scales, e.g. regional or national ones. In this way, a general overview at different latitude of Italy could be given to show how the introduction of the novel regulatory framework on energy community can promote the adoption of RES production and the electrification of the energy demand on residential buildings. An attempt in this sense has been made in (Pellegrino and Coletta, 2021), where the analysis has been extended to the national level, using statistics about secondary stations in the Italian distribution grid. However, the study considered an average case-study that was supposed to be representative of the whole country rather than considering several case studies with different weather data depending on the latitude of the location.

For these reasons, the present work analyzes the economic and environmental potentiality of collective self-consumption in promoting RES production and decarbonization for multi-family residential buildings across the whole of Italy. The results can be useful both for investors and policy-makers, since a general overview can support the diffusion of PV and HP at urban level fostering a better air-quality in cites. More in detail, a spatial approach is used here, which considers the variability of weather conditions at the different latitudes of Italy. These variations can in fact influence the economic and environmental results of adopting collective self-consumption, since both RES production and the energy demand of a residential building are influenced as well. In particular, two scenarios are considered: in the first one (Scenario A), the families only install a PV system on the building's rooftop to partly fulfil their electricity demand, while the centralized heating demand is fulfilled by means of a gas-fired boiler; in the second one (Scenario B), a heat pump (HP) is installed to partially fulfil the heating demand and at the same time increase the local consumption of renewable electricity. These scenarios were adopted since they are incremental in terms of electrification of the building energy demand, so the impact of decarbonising the space heating demand, within the collective self-consumption scheme, is better highlighted. The analysis is repeated over a multitude of points Italy-wide, using a Geographical Information System (GIS) tool to process and visualize economic and environmental results, and using open databases, i.e. PVGIS (JRC, 2018), to obtain weather data at different locations of Italy. Therefore, a reference building is needed, whose energy demands (electricity and space heating) are evaluated using statistical and weather data at different latitudes. In other words, the reference building is used as representative of a building typology widely diffused in the Italian context, so economic and environmental results can be assumed as representative too.

The rest of the paper is organized as follows. An overview of the Italian framework for energy sharing in a residential building is provided in Sec. 2; methods for the evaluation of the energy and economic assessments are thoroughly described in Sec. 3, and Sec. 4, respectively. Finally, the results of the analyses under the two scenarios conducted across the whole Italian country are reported in Sec. 5 and discussed Sec. 6, which concludes the paper.

2. Energy sharing in the Italian framework

In the Italian regulatory framework, RECs are legal entities composed of electricity end-users: citizens, local authorities and Small-to-Medium Enterprises (SMEs), who are entitled to own and manage renewable generation assets. RECs are expected to enhance decarbonization in end uses involving citizens and small communities, through increased production and consumption of energy from RES. Hence, energy sharing among REC's members has been introduced to increase the local consumption of self-generated energy. Indeed, RES-based overproduction of some REC members (i.e. energy that is produced but not consumed on-site) can be consumed by others using the distribution grid to share the electricity. In the Italian regulation, this represents a "virtual" scheme which is defined to allow the sharing of electricity. In other words, all the electricity not consumed on-site is assumed as "virtually" consumed by other members. According to this scheme, electricity overproduction is shared when it is simultaneously injected into and withdrawn from the grid by members of the REC. Shared electricity is therefore defined as the minimum, in each hourly time step, between the sum of the total injections and withdrawals into/from the grid of the end users present in the REC (Governo Italiano, 2020). In addition, for the shared energy, economic incentives are available to support the exploitation of this scheme.

This new regulatory opportunity introduced in 2021 represents a radical change for the Italian energy framework. In the recent past, energy sharing between different subjects was not admitted at all. The only way to share energy between two end-users was the so-called *SEU* scheme (Lazzeroni et al., 2017), where the exchange of electricity was only allowed in the "*one-to-one*" rule, but through a private connection line. Alternatively, a RES-based prosumer could adopt the net-billing schemes (still in force) where the grid is used as a virtual storage unit, so that the overproduction injected into the grid can be economically recovered to compensate electricity bought form the grid when RES production is absent (IEA, 2018). However, net-billing does not permit energy sharing with other end-users through the grid. Instead, the introduction of REC overcome these limitations by admitting "*one-to-many*" and "*many-to-many*" rules for the energy exchange through the distribution grid, promoting RES diffusion, electrification and contrasting energy poverty.

2.1. Collective self-consumption scheme in residential buildings

Collective Self-Consumption (CSC) is a particular scheme of electricity sharing, where all the end users are located in the same building or apartment block (Di Silvestre et al., 2021). In this work, the CSC is assumed as the reference scheme adoptable by residential end-users since it has the potentiality to support the installation of RES (PV) production and electrification of the building energy consumption (LoSchiavo et al., 2022).

For instance, Fig. 1, shows a scheme for CSC in a multi-family residential building. A collectively-owned PV system is installed on the building's rooftop. RES-based electricity generation can be consumed on-site for common services (e.g., elevator, lighting of common spaces) and the overproduction can be injected into the grid to be shared with the other end-users who joined the CSC. Thus, these household users in the building can use this injected energy to fulfil their own electricity demand. Injected energy that is not shared is then exchanged with the national electricity grid. Similarly, electricity demand (both on-site and virtual) that cannot be fulfilled using local RES generation, is taken from the national grid.

In Fig. 1, where an example of the CSC scheme is presented, on-site consumption of RES generation is attributable only to a HP, which is used to integrate a gas-fired boiler in fulfilling the centralized heating demand of the apartments. While the virtual consumption is represented by the electricity demand of the flats.

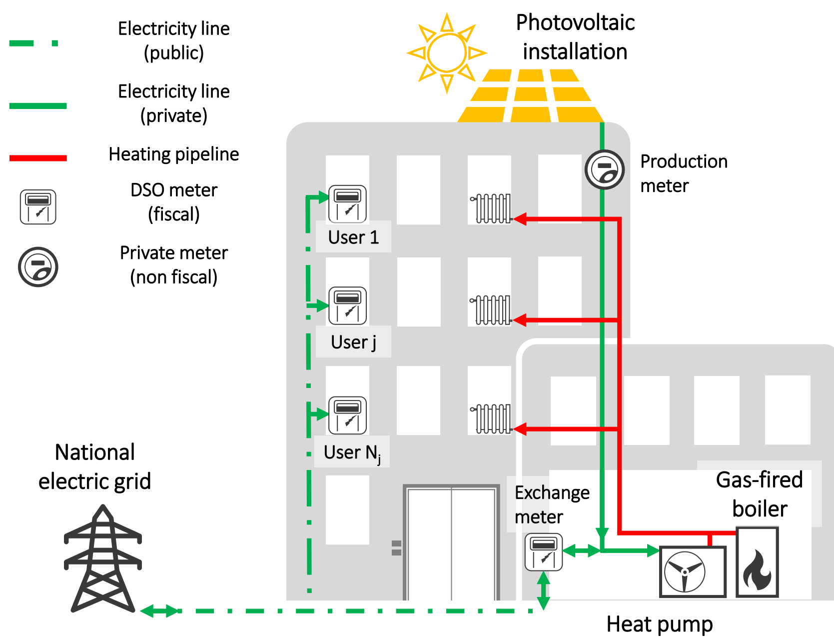

Figure 1: Collective self-consumption in a multi-house residential building with coupling of electricity and heating demand (adapted from (RSE and Utilitatis, 2021)).

In Fig. 2 the power flows realized in the configuration of Fig. 1 are shown. On-site flows are divided into: a. electricity side; b. heating side.

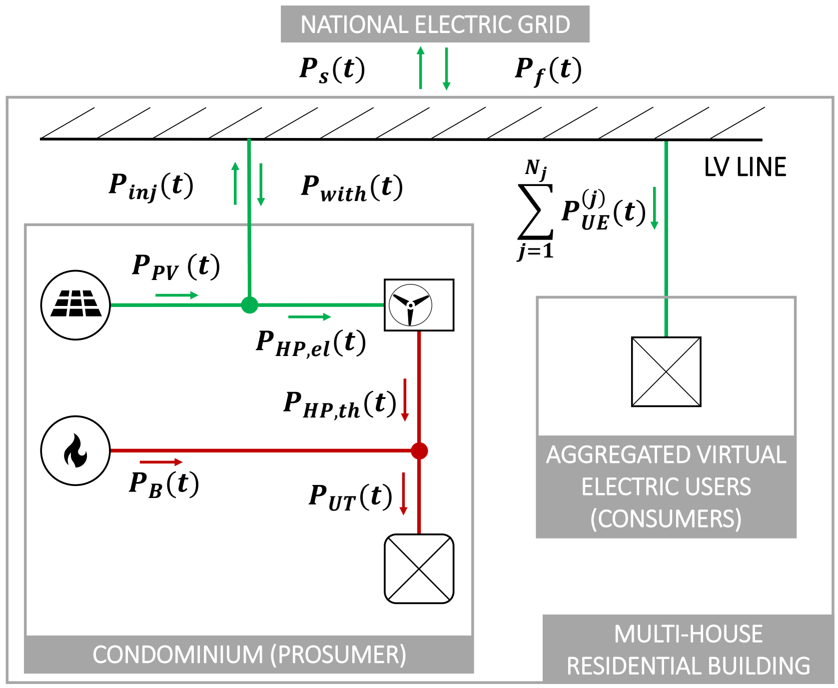

Figure 2: Scheme of the energy flows in the collective self-consumption configuration with a production node and multiple consumption nodes..

On the heating side, the centralized demand of the apartments, P_{UT}, can be fulfilled either by means of the HP ($P_{HP,th}$), or of the gas-fired boiler, P_B (details are reported in Section 3.2). On the electric side, the PV electricity production, P_{PV}, is used to power the HP ($P_{HP,el}$), while any overproduction is injected into the grid (P_{inj}). When PV production is smaller than on-site demand (or null), electricity is also purchased from the grid (P_{with}). For modeling purposes, the household end-users in the building can be considered as an aggregated virtual load, which withdraws from the grid a quantity of electricity equal to the sum of the households' demands, $P_{UE} = \sum_j P_{UE}^{(j)}$. Shared energy in each hourly time step h, $E_{sh}(t_h)$, is calculated according to (Governo Italiano, 2020), as follows:

$$E_{sh}(t_h) = \min\Big(P_{inj}(t_h)\Delta\tau; P_{UE}(t_h)\Delta\tau\Big), \qquad \forall h = 0, \ldots, N_h \tag{1}$$

where N_h is the total number of time steps considered and $\Delta\tau$ the length of each time step, e.g. 8760 hourly time steps in one year.

Electricity withdrawn from the same connection point as the PV (i.e. P_{with}) does not appear in (1), as the two quantities are mutually-exclusive. Finally, the REC (i.e. the building) exchanges net electricity production and demand with the national grid, thus completing the energy balance on the distribution grid. Net electricity flows can be directed toward the grid (P_f) or toward the REC (P_p) and are calculated as follows:

$$P_f(t_h) = \max\Big(0; P_{inj}(t_h) - E_{sh}(t_h)/\Delta\tau\Big) \tag{2}$$

$$P_p(t_h) = \max\Big(0; \Big(P_{UE}(t_h) + P_{with}(t_h)\Big) - E_{sh}(t_h)/\Delta\tau\Big) \tag{3}$$

As is evident from (2) and (3), shared energy is consumed within the REC's boundaries, and hence decreases the exchanges with the national grid. Therefore, the current national regulation economically recognises electricity sharing in collective self-consumption configurations (ARERA, 2020; GSE, 2020; Ministero dello Sviluppo Economico, 2020), as follows:

- Transportation fees (transmission, distribution) on the shared energy are reimbursed to the users, with respect to the variable costs (8.22 €/MWh in 2020);

- Costs related to the distribution losses on the shared energy are also reimbursed (c.a. 1.3 €/MWh in 2020);

- Finally, shared energy is subject to a fixed incentive equal to 100 €/MWh for a period of 20 years.

Globally, the economic value of shared energy in CSC configurations can be considered roughly equal to 110 €/MWh. Moreover, all electricity injected into the grid (i.e. all the PV production that is not consumed on-site) can benefit from the dedicated withdrawal (*ritiro dedicato*) service (GSE, 2018), hence be sold at the hourly zonal market price, generally lower than the retail price. On the other side, all electricity withdrawn from the grid is still purchased by the users from the suppliers at retail price.

3. Energy and Environmental assessment

As already pointed out, the collective self-consumption scheme could promote the deployment of RES (PV) production in residential building as well as the electrification of its energy consumption. In particular, the integration of HP could significantly contribute to decarbonizing the building space heating needs. Hence, energy demand and carbon emission of the building need to be estimated to highlight the corresponding potential benefits at different latitude of Italy. For this reason, this section presents the approach adopted to evaluate and estimate the space heating and electricity demand of the building, the corresponding carbon emission and the RES production. Additionally, according to the estimated energy demand, the sizing of the HP and the PV is also proposed.

3.1. Heating demand of residential building

The introduction of the collective self-consumption scheme has boosted the interest in the electrification of energy consumption within the residential

Italian context. Among the others, space heating demand appears to be the one with great potential (Kavvadias et al., 2019). For this reason, the estimation of the heating demand in residential buildings becomes crucial if a territorial analysis of decarbonizing the heating load has to be performed.

However, the heterogeneity of the current residential building stock, across Italy, leads to focus the analysis on a specific representative building typology. In particular, the most widespread multi-family residential building (i.e. the one constructed in the period 1961-1975) was selected as a reference, according to the current composition of the Italian building stock (ISTAT, 2021) shown in Fig. 3. In this way, the analysis performed in the following, at the different latitudes of Italy, can be assumed as representative for each locations, as well.

Figure 3: Share of residential building in Italy by construction period.

Once the reference building was chosen and the corresponding main physical characteristics were extracted from (Corrado et al., 2014; Ballarini et al., 2017), the heating demand was estimated through a simplified (steady-state) approach where only thermal losses due to transparent/opaque surfaces and ventilation are considered, neglecting the contribution due to internal loads, solar gain and thermal mass. The proposed approach is based on (EN 12831-1:2017, 2017), taking into account the hourly variation of the air temperature T_a and assuming a fixed (reference) internal air temperature T_{int}.

Consequently, the hourly space heating load of the reference building can be calculated adding up five different contributions:

- the heat loss through external walls Q_{ext};
- the heat loss through the building roof Q_r;
- the heat loss through the ground Q_g;
- the heat loss through the internal walls Q_i;
- the heat loss through transparent surfaces (i.e. windows) Q_w;
- the heat loss due to ventilation Q_v.

In this way, the heating load P_{UT} can be calculated as follows:

$$P_{UT}(t_h) = \frac{Q_{ext}(t_h) + Q_r(t_h) + Q_g(t_h) + Q_i(t_h) + Q_w(t_h) + Q_v(t_h)}{\eta_d}, \quad (4)$$

where η_d is the efficiency of the heat distribution system.

In particular, each thermal flows can be calculated as follows:

$$Q_{ext}(t_h) = U_{ext} \cdot S_{ext} \cdot [T_{int} - T_a(t_h)] \quad (5)$$

$$Q_r(t_h) = U_r \cdot S_r \cdot [T_{int} - T_a(t_h)] \tag{6}$$

$$Q_g(t_h) = U_g \cdot S_g \cdot [T_{int} - T_a(t_h)] \tag{7}$$

$$Q_i(t_h) = U_i \cdot S_i \cdot [T_{int} - T_a(t_h)] \cdot b \tag{8}$$

$$Q_w(t_h) = U_w \cdot S_w \cdot [T_{int} - T_a(t_h)] \tag{9}$$

$$Q_v(t_h) = \frac{\rho_{air} \cdot C_{p,air} \cdot n \cdot V_{net} \cdot [T_{int} - T_a(t_h)]}{3600} \tag{10}$$

where U and S are the heat transfer coefficients and the dispersion area for the different opaque and transparent surfaces, respectively, V_{net} is the net heated volume, n is the air exchange rate, ρ_{air} is air density, $C_{p,air}$ is the specific heat of air and b is the correction factor for unheated indoor spaces (see Table 1).

Table 1: Main physical characteristics assumed for the reference building (Corrado et al., 2014; Ballarini et al., 2017).

S/V (m^{-1})	Floors	Apartments	U_{ext} (W/m^2K)	U_r (W/m^2K)	U_g (W/m^2K)	U_i (W/m^2K)	U_w (W/m^2K)	b	η_d	n (h^{-1})
0.46	8	40	1.10	1.65	1.56	1.13	4.90	0.4	0.86	0.6

According to equations from 4 to 10, the heating load demand can be thus estimated, at the different latitudes of Italy, on an hourly basis using the air temperature data. In this work, data were extracted from the JRC

Table 2: Other physical characteristics assumed for the reference building (Corrado et al., 2014; Ballarini et al., 2017).

V_{net}	S_{ext}	S_r	S_g	S_i	S_w
(m^3)	(m^2)	(m^2)	(m^2)	(m^2)	(m^2)
6815	2514	325	325	770	407

dataset available for all EU countries (JRC, 2021). Other layout characteristics of the reference building, like the wall thickness, were also extracted from (Corrado et al., 2014; Ballarini et al., 2017) and taken into account in the estimation of the thermal load.

Thermal demand was finally corrected considering the current Italian framework regulating the daily and seasonal on/off status of the heating systems based on the yearly heating degree days (HDDs) and climatic zones (DPR412/93, 1993). Tables 3 and 4 summarize these seasonal and daily operational limits of the heating system considered in the simplified approach under different environmental (i.e. HDDs or latitude) conditions.

Table 3: Seasonal and daily limits of the heating systems operations.

Climatic Zone	HDDs	Maximum daily hours	Starting date	Closing day
A	from 0 to 600	6	December 1st	March 15th
B	from 601 to 900	8	December 1st	March 31st
C	from 901 to 1400	10	November 15th	March 31st
D	from 1401 to 2100	12	November 1st	April 15th
E	from 2101 to 3000	14	October 15th	April 15th
F	> 3000	No Limitation		

Fig. 4 shows an example of the hourly heating demand estimated for a reference residential building located in North-Western Italy.

Table 4: Daily operation of heating systems supposed for the different Climatic Zones.

Climatic Zone	Hours of operation
A	7.00-10.00 18.00-21.00
B	7.00-11.00 17.00-21.00
C	7.00-12.00 17.00-22.00
D	6.00-10.00 12.00-16.00 18.00-22.00
E	5.00-10.00 12.00-16.00 18.00-23.00
F	All day

3.2. Heat Pump sizing and operation

The primary energy demand for space heating in the current Italian residential sector is still based on fossil fuels (ENEA, 2021). In particular, natural gas is the main one adopted in space heating applications. In fact, more than 50% of the total energy consumption is still burned in conventional boilers. However, the increasing performance of alternative solutions like HPs is paving the way for a wider diffusion of this technology, contributing to the electrification and decarbonization of energy consumption in residential buildings. The heat production by an HP is generally more efficient than a boiler from the primary energy point of view, so positive ef-

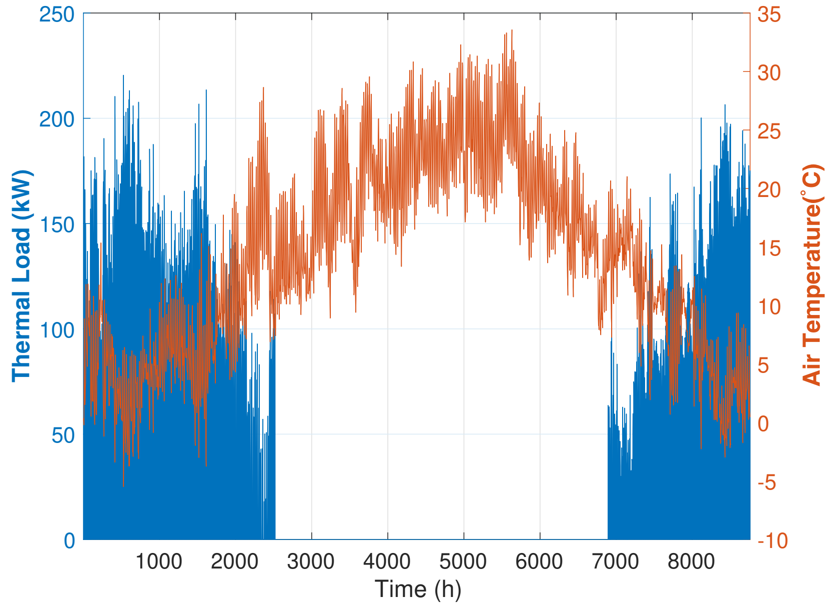

Figure 4: Hourly space heating demand estimated for a residential building located in the North-West of Italy.

fects are expected in terms of energy, costs and emission savings (Kavvadias et al., 2019).

For these reasons, the adoption of an Air Source Heat Pump (ASHP) is introduced within the collective self-consumption scheme to integrate the existing conventional boiler. However, HP needs to be properly sized according to the space heating demand estimated in section 3.1. In particular, the potential oversize of the HP has to be avoided to limit the economic impact of this technology, while maximizing the heat production from HP compared to the one from the existing gas-fired boiler. Oversize could in fact occur if HP was tailored according to the space heating peak demand, because the HP utilisation factor could significantly fall, even if demand would be completely fulfilled. In this view, the maximum HP capacity was not calculated considering the overall peak of the heating demand, but according to the average peak demand within December and January (i.e. typically the coldest period of the heating season), as follows:

$$P_{HP,th,max} = \frac{\sum_{i=1}^{N_{dj}} \widehat{P}_{UT,i}}{N_{dj}} \tag{11}$$

where $P_{HP,th,max}$ is the HP size, N_{dj} is the number of days within December and January and $\widehat{P}_{UT,i}$ is the peak demand in the i-th day within the same period. As a consequence, the boiler can still contribute in covering peak demand, while HP utilisation factor increases.

Once the HP size was estimated, operational characteristics were also taken into account to estimate its hourly production profile and the corresponding electric hourly load profile. Particularly, the Coefficient of Performance (COP) of the ASHP was defined as a function of the air temperature. Thus, according to the simplified model proposed by (Ruhnau et al., 2019), COP variation for the ASHP can be calculated through the following non-linear function:

$$COP(t_h) = 6.08 - 0.09\Delta T(t_h) + 0.0005\Delta T(t_h)^2, \tag{12}$$

where $\Delta T(t)$ is calculated, as follows:

$$\Delta T(t_h) = T_{sink}(t_h) - T_a(t_h) \tag{13}$$

and the heat sink temperature $T_{sink}(t_h)$ is derived from the air temperature $T_a(t_h)$, as follows:

$$T_{sink}(t_h) = 40 - 1.0 \cdot T_a(t_h). \tag{14}$$

Fig. 5, shows an example of COP variation estimated for a location in North-West of Italy.

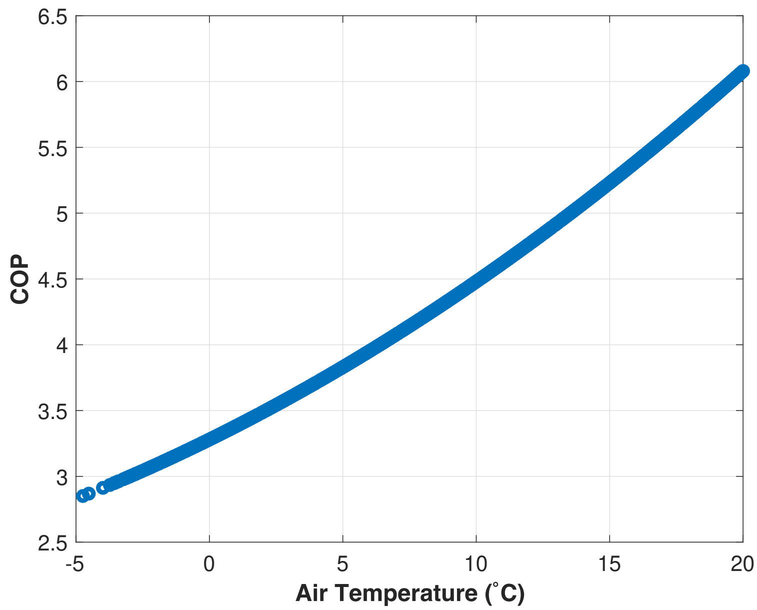

Figure 5: COP as function of the air temperature estimated for a HP in the North-West of Italy.

Afterward, limitations of HP operation were also introduced to improve the economic performance of this heating technology, as proposed by (Minuto et al., 2021; Viti et al., 2020). Specifically, HP is operated only if its cost per unit of energy produced C_{hp} is lower than the cost per unit of energy produced by the gas-fired boiler C_b. This condition can be expressed as

$$C_{hp} < C_b, \tag{15}$$

or, equivalently,

$$\frac{c_e}{COP} < \frac{C_m}{H_i \eta_b}, \tag{16}$$

where c_e and C_m are the per unit cost of electricity (in €/kWh) and natural gas (in €/m^3), respectively, H_i is the lower heating value of the natural gas (in kWh/m^3) and η_b is the efficiency of the gas-fired boiler. Of course, if all the electricity supplying the HP is locally produced by RES (i.e. it is not purchased from the grid), the electricity cost c_e should be set to zero. Differently, when just a portion of the electricity feeding the HP is produced by RES, the electricity cost c_e should be reduced proportionally.

As a consequence, the threshold value of COP identifying the on/off status of the HP can be derived from eq. (16), as follows:

$$COP_{lim}(t_h) = \frac{\beta(t_h) \cdot C_p}{C_m} \cdot H_i \cdot \eta_b, \tag{17}$$

where $\beta(t_h)$ is the portion of the HP electricity demand supplied by RES and C_p is the fixed per unit cost of the electricity purchased from the grid. Thus, if the COP calculated by eq. (12) is greater than COP_{lim} estimated by eq. (17), the heat production by the HP $P_{HP,th}$ is preferred, so the boiler should work just as a backup source to eventually cover part of the space heating demand. Otherwise, if COP significantly decreases due to lower air temperatures, the gas-fired boiler should be adopted as the only source of heat and HP should not be used. Finally, the electric load profile of the HP can be calculated considering the variability of the COP:

$$P_{HP,el}(t_h) = \frac{P_{HP,th}(t_h)}{COP(t_h)}. \tag{18}$$

3.3. Electricity demand of the residential building

As already presented in Section 3.1, the reference multi-family residential building considered in this study is composed of 40 flats. Under the as-

sumption that all the households have joined the collective self-consumption agreement, the hourly load profile P_{UE} of the household appliances within the building needs to be estimated. In fact, shared energy, as well as electricity exchanged with the grid by the collective self-consumption, are strictly related to it.
As proposed in (Lazzeroni et al., 2020), the hourly load profile P_{UE} has been estimated assuming the yearly demand E_{UE} of all the household appliances and considering a normalized load profile for residential end-users derived by (CESI, 2005; Di Liddo et al., 2014). Then, the normalized load profile was properly scaled to preserve the aggregated yearly electricity demand E_{UE} using a scaling factor SF calculated, as follows:

$$SF = \frac{E_{UE}}{\sum_{i=1}^{12} \left(N_i \sum_{h=1}^{24} LF(t_h) \cdot \Delta\tau \right)}, \tag{19}$$

so that

$$P_{UE}(t_h) = SF \cdot LF(t_h). \tag{20}$$

where N_i represents the number of days in the i-th month, while $LF(t_h)$ is the h-th hourly load factor from the normalized load profile. Finally, the hourly load profile of the households appliances was then added to the electricity demand of the HP:

$$P_L(t_h) = P_{UE}(t_h) + P_{HP,el}(t_h), \tag{21}$$

so that the overall electricity consumption of the residential building P_L is influenced by the building thermal demand to highlight the cross-coupling nature of the configuration analyzed in this work. Other electricity consumption due to appliances in the common area of the reference building (e.g. stairwell lighting) is instead neglected.

3.4. PV sizing

The collective self-consumption configuration considered in this work is integrated with a PV plant to include RES generation for supplying the building electricity demand and consequently reduce environmental impact. For the sake of simplicity, the technology considered here for the PV modules is the polycrystalline one, since it is the most diffused in Italy (GSE, 2022). Clearly, the sizing of PV plant is fundamental to optimize local self-consumption (SC) and self-sufficiency (SS) limiting the mismatch between generation and the overall electricity demand of the building.
For this reason, a parametric analysis was adopted to identify the optimal PV size maximizing SC and SS indexes (IEA, 2016). Firstly, the PV generation has been estimated according to the approach proposed in (Lazzeroni et al., 2017) where the hourly PV profile is calculated as a function of the PV size ($P_{PV,size}$), taking into account the loss of productivity due to yearly degradation of PV modules (α_y) and loss due to temperature effects (PR):

$$P_{PV}(t_h) = \frac{G(t_h)}{1000} \cdot P_{PV,size} \cdot PR \cdot \alpha_y, \tag{22}$$

where $G(t_h)$ is the hourly irradiance of the solar beam extracted from PVGIS dataset (JRC, 2018). In particular, since this approach already take into account loss of PV producibility due the air temperature through the PR, temperature data from (JRC, 2021) were not directly used here.

After that, the comparison between generation profile and the aggregated load profile of the reference building has been performed to evaluate the SS and SC indexes (IEA, 2016). More precisely:

$$SC = \frac{E_{sc}}{E_{PV}} = \frac{\sum_{h=1}^{N_h} P_{sc}(t_h) \cdot \Delta\tau}{\sum_{h=1}^{N_h} P_{PV}(t_h) \cdot \Delta\tau}; \tag{23}$$

$$SS = \frac{E_{sc}}{E_L} = \frac{\sum_{h=1}^{N_h} P_{sc}(t_h) \cdot \Delta\tau}{\sum_{h=1}^{N_h} P_L(t_h) \cdot \Delta\tau} = \frac{\sum_{h=1}^{N_h} P_{sc}(t_h) \cdot \Delta\tau}{\sum_{h=1}^{N_h} [P_{UE}(t_h) + P_{HP,el}(t_h)] \cdot \Delta\tau}, \tag{24}$$

where the self-consumed PV production $P_{sc}(t)$ represents the RES production locally consumed within the collective self-consumption scheme:

$$P_{sc}(t_h) = min[P_{PV}(t_h), P_L(t_h)]. \tag{25}$$

In general, changing the PV size while keeping fixed the aggregated yearly electricity demand E_L means obtaining different SC and SS. Moreover, the trends of the two indexes with the PV size are typically in contrast, since smaller PV size has greater SC with lower SS, and vice versa. Thus, the PV size maximizing both SC and SS must be identified on an energy basis through a parametric approach (i.e. increasing the PV size), as proposed by (Cielo et al., 2021). Specifically, the optimal PV size is the one with SC and SS ensuring the lowest distance with respect to the *Utopia point* in the SC-SS plane (i.e. the point where SC and SS are equal to 1). In this way, the chosen PV size represents a suitable compromise, from the energy point of view, between the need of increasing, at the same time, SC and SS of the collective self-consumption configuration.

3.5. Environmental impact

Finally, the environmental impact of the collective self-consumption scheme was measured through the evaluation of the CO_2 emission reduction (i.e., CO_2 savings) due to integration of a PV system and the HP in the reference residential building. In particular, the (percentage) emission savings are defined as

$$\Delta CO_2 = \frac{CO_{2,csc}}{CO_{2,ref}} \cdot 100 = \frac{E_p \cdot EF_e + \dfrac{E_b}{\eta_b} \cdot EF_m}{E_L \cdot EF_e + \dfrac{E_{UT}}{\eta_b} \cdot EF_m} \cdot 100, \tag{26}$$

where EF_e represents the national CO_2 emission factor for the electricity purchased from the grid (Istituto Superiore per la Protezione e la Ricerca Ambientale, 2021), and correspondingly E_p is the yearly energy demand of the building not fulfilled by RES production; EF_m is the emission factor of natural gas used to feed boiler (Kona et al., 2020) and E_b is the yearly heat production from the gas-fired boiler.

Specifically, equation (26) compares the CO_2 emissions obtained by the collective self-consumption scheme ($CO_{2,csc}$) with the ones calculated for the reference residential building ($CO_{2,ref}$) when PV and HP are not installed (i.e. when the yearly electricity demand E_L is supplied with electricity from the grid and the yearly heating demand E_{UT} is supplied by the gas-fired boiler).

4. Economic assumption

The energy assessment presented in Section 3 is fundamental to identify energy demands of the reference buildings as well as the shared energy within the collective self-consumption scheme and the exchanged energy with the grid. In fact, all these data are relevant to perform an economic analysis of the proposed configuration where investments in PV and HP are needed to decarbonize energy consumption. Typically, the size of this investment I_0 is related to the PV and HP sizes in terms of installation ($CAPEX$):

$$I_0 = CAPEX_{PV} + CAPEX_{HP} = C_{PV} \cdot P_{PV,size} + C_{HP} \cdot P_{HP,th,max}, \quad (27)$$

where C_{PV} and C_{HP} are the per unit installation cost for PV and HP, respectively. However, the Italian government introduced a further incentive scheme to promote the diffusion of RES production in the residential sector (Governo Italiano, 2018, 2006). Under this scheme, 50% of the capital costs for the installation of PV system and 65% of the investment costs for HP can be recovered over ten years as tax deduction (TD). Alternatively, as assumed in this work, the tax credit can be transferred to the firm installing the assets converting the credit into cash to reduce the investment costs, as follows:

$$I_0 = k_{PV} \cdot C_{PV} \cdot P_{PV,size} + k_{HP} \cdot C_{HP} \cdot P_{HP,th,max}, \quad (28)$$

where k_{PV} and k_{HP} are equal to 0.5 and 0.35, respectively, when tax credit is transferred to eligible third party for reducing installation costs of PV and HP.

The sustainability of this investment is strictly dependent on the remunerations gained by the collective self-consumption configuration, which in turn are linked to the achievable cost-saving and the available incentives. Both costs and revenues of the configuration were then evaluated and included in the economic analysis to identify the corresponding economic indicators and reliability.

4.1. Costs and Revenues

Section 2 already pointed out the economic benefits gained by a collective self-consumption scheme where RES production is shared among members. Nevertheless, according to the Italian technical rules adopted for REC (GSE, 2020), the aggregated virtual end-users of Fig. 2 (i.e. the households that joined the self-consumption scheme) "formally" purchase electricity only from the distribution grid. While the HP (as well as any other appliance used in the common areas of the building) is assumed to be the asset "directly" fed by PV production, so part of its demand can be also supplied by electricity from the grid. Additionally, the costs for the natural gas feeding the gas-fired boiler will be also reduced, since the boiler is expected to reduce its operation due to HP contribution to cover the heating demand. In this context, the yearly cost YC borne by members of the self-consumption scheme can be calculated as

$$YC = E_p \cdot C_p + OPEX_{PV} \cdot P_{PV,size} + OPEX_{HP} \cdot CAPEX_{HP} + \frac{E_b}{\eta_b H_i} \cdot C_m, \tag{29}$$

where $OPEX_{PV}$ and $OPEX_{HP}$ are the per unit operational and maintenance cost for PV and HP as function of PV size and HP installation costs, respectively. C_p and C_m are the average costs for the electricity purchased from the grid and for the natural gas feeding the boiler, while η_b and H_i are the boiler efficiency and the lower heating value of the natural gas, respectively. In particular, according to the Italian rules for collective self-consumption (GSE, 2020), E_p includes both the aggregated demand of all the electric appliances within the building flats and the net electricity demand of the HP, since part of this consumption can be fed by PV.

Instead, the yearly revenues gained by the households within the collective self-consumption scheme are due to a combination of different factors: the incentive on the shared energy, the economic exploitation of the electricity injected into the grid and the tax deductions. Particularly, the PV overproduction injected into the grid is charged at zonal market price through the "dedicated withdrawal" mechanism (GSE, 2018), while the shared energy benefits of incentive as already described in Section 2. As a consequence, the yearly revenues YR are given by

$$YR = \sum_{h=1}^{N_h} E_{sh}(t_h) \cdot C_{sh} + \sum_{h=1}^{N_h} P_{inj}(t_h) \cdot C_s(t_h) \cdot \Delta\tau \tag{30}$$

where C_{sh} and C_s are the incentive for the shared energy and the hourly zonal market price, respectively. However, zonal market price C_s changes according to the location of the residential building (Terna, 2005). In particular, although a new regulatory fragmentation has been recently introduced by the Italian TSO (Terna, 2021) and without loss of generality, six[1] Italian market zones grouping different administrative regions were taken into account, as follows:

- North: Valle D'Aosta, Piemonte, Liguria, Lombardia, Trentino, Veneto, Friuli Venezia Giulia, Emilia Romagna.
- Northern-Central: Toscana, Umbria, Marche.
- Southern-Central: Lazio, Abruzzo, Campania.

[1] There are seven zones in the most recent regulation. The seventh zone is Calabria.

- South: Molise, Puglia, Basilicata, Calabria.
- Sicily: Sicilia.
- Sardinia: Sardegna.

Finally, the yearly cash flows YCF obtained by the collective self-consumption scheme can be computed as

$$YCF = YC_{ref} + YR - YC, \tag{31}$$

where YC_{ref} is the yearly cost to cover energy demand in the reference building when both PV and HP are not installed.

4.2. Economic Indicators

The yearly costs, revenues and yearly cash flow presented in the previous section were used to calculate economic indicators to highlight the potential sustainability of investing in this REC configuration. The Net Present Value (NPV), Internal Rate of Return (IRR) and the Discounted Pay Back Time (DPBT) are the indicators adopted to evaluate the investment. In particular, NPV is defined as

$$NPV = -I_0 + \sum_{y=1}^{N_y} \frac{YCF_y}{(1+d)^y}, \tag{32}$$

where N_y is the technical lifetime of the project and d is the discount rate. Equation (32) is also used to calculate the Discounted Pay Back Time (DPBT), since it represents the period required to recover the initial capital expenditure I_0. The Internal Rate of Return (i.e., the discount rate for which the NPV is equal to zero) is also calculated to evaluate the opportunity of the PV investment, as follows:

$$IRR := d \text{ s.t. } 0 = -I_0 + \sum_{y=1}^{N_y} \frac{YCF_y}{(1+d)^y} \tag{33}$$

Typically, IRR is compared to the discount rate d to reveal how the investment is more attractive than an alternative investment.

Finally, the cost saving indicator Percentage Cost Reduction (PCR) is defined to compare the yearly costs of the collective self-consumption scheme with the ones where this REC configuration is not adopted. In mathematical terms,

$$PCR = \left[1 - \frac{YC}{YC_{ref}}\right] 100. \tag{34}$$

5. Results

In this section, the results of the energy, economic and environmental analyses of a collective self-consumption scheme are pointed out for multi-family residential buildings equipped with PV and HP. The aim is to highlight how the decarbonization of energy consumption by PV and HP is potentially profitable and environmentally sustainable in the Italian context through the implementation of the collective self-consumption scheme.

In this view, the energy, economic and environmental indicators presented in Sections 3 and 4 should be evaluated across the whole country adopting the methodology and the approach proposed in (Lazzeroni et al., 2020, 2021). Substantially, these indicators can be evaluated at different locations (i.e., latitudes) of the reference building, to take into account the variability of weather data (i.e., solar beam and air temperature) which influence the results. To do so, the Italian territory of Fig. 6 is represented by a raster image with a resolution of 2.5 x 2.5 km, where both solar radiation and air temperature hourly data can be extracted from the European Joint Research Centre (JCR) database (JRC, 2018, 2021) for each centroid of the raster cells. Later, these datasets were imported into the MATLAB environment and analyses were performed by exploiting the matrix representation of the data. In this study, however, data processing was avoided for all those centroids located at an altitude higher than 850 m, since most of the municipalities (i.e. around 85%) with multi-family residential buildings are located at lower elevations (ISTAT - Istituto Nazionale di Statistica, 2022). Thus, all the following maps include grey areas representing location at an altitude where data analysis is omitted.

Figure 6: Geographical locations of the 20 administrative Italian regions.

This territorial approach was adopted since the results of the analysis can be easily handled through Geographical Information Systems (GIS) tool to obtain more descriptive maps. In particular, two different possible scenarios were analyzed to consider an incremental implementation of the decarbonization in the residential buildings:

- *Scenario A*: only the PV system is installed in the collective self-consumption configuration;
- *Scenario B*: both PV plant and HP are installed to cover the electricity and heating demand of the building.

In both cases, the main parameters used to perform the energy, economic and environmental analysis are shown in Tables 5 and 6.

Table 5: Energy and economic assumptions used for calculating indicators in each raster cell (Lazzeroni et al., 2020, 2017; ARERA, 2022; Energy & Strategy Group - Politecnico di Milano, 2020; Knobloch et al., 2017, 2021).

C_{PV} (€/kWp)	$OPEX_{PV}$ (€/kWp/y)	C_{HP} (€/kW$_{\mathrm{th}}$)	$OPEX_{HP}$ (%/y)	d (%)	α_y (%/y)	PR	N_y (y)
1350 – 1550	50	750	2	5	0.4	0.8	20

Table 6: Energy and economic assumptions used for calculating indicators in each raster cell (Lazzeroni et al., 2020, 2017; Istituto Superiore per la Protezione e la Ricerca Ambientale, 2021; Kona et al., 2020; Energy & Strategy Group - Politecnico di Milano, 2020; Knobloch et al., 2017).

η_b (%)	C_{sh} (€/kWh)	C_m (€/m^3)	C_p (€/kWh)	H_i (kWh/m^3)	E_{UE} (MWh/y)	EF_e (tCO_2/MWh)	EF_{ng} (tCO_2/MWh)
0.9	110	85.4 – 95.4	0.22	9.94	108	0.2763	0.202

Although most of the economic parameters can be assumed as fixed, the PV installation cost and the natural gas prices were instead considered variable, since these are strongly influenced both by the PV size and the yearly gas consumption, respectively. In particular, the energy (i.e. electricity and natural gas) prices of 2019 have been used here to avoid further influence related to the current international context., and the PV size was limited to $70\mathrm{kW}_p$ due to the available roof surface of the reference building. Finally, a further simplification in economic assumptions is considered here: the financing of the PV and HP systems is under equity, so both scenarios do not consider loans for the installation of these assets.

5.1. Energy results

An overview of the space heating demand estimated for the reference building considering different possible locations in Italy is presented in Fig. 7. Generally, the heating demand is influenced both by the latitude (i.e. northern regions are climatically coldest than southern ones) and the altitude (i.e. foothill or hilly areas are typically coldest than flatland). In fact, a yearly heating demand exceeding 300 MWh can be easily observed in the North of Italy or close to mountains area (e.g. Alps or Apennine ridge), while lower demand is instead expected in the South where average consumption can be reduced by more than two-thirds, especially in the coastal areas. For these reasons, Fig. 7 is also compliant with the distribution of the climatic zones across the whole country, as described by the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) in (ENEA, 2015).

Instead, the average primary energy consumption estimated for the reference building in the different Italian regions is depicted in Fig. 8, considering

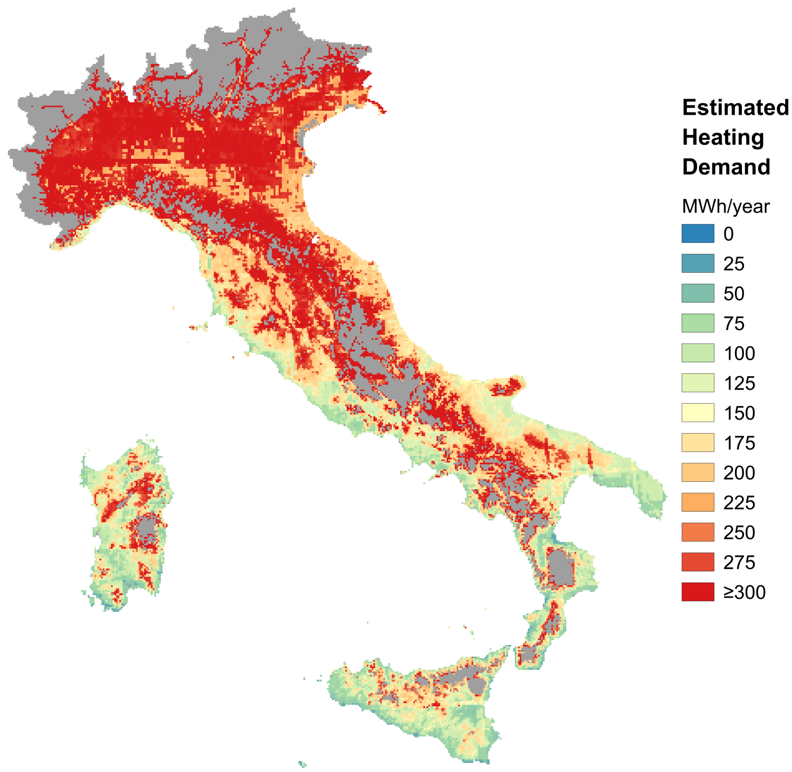

Figure 7: Space heating demand estimated for the reference building across Italy.

a gas-fired boiler as s centralised heating system. It can be noticed that the calculated values fall within the range of 50-400 kWh/m^2/y observed for the Italian residential building stocks, as presented in (Palladino et al., 2019). In particular, higher demand is expected in the northern locations as, for instance, in Valle d'Aosta, Piemonte or Friuli Venezia Giulia where yearly consumption of around 240, 154 and 165 kWh/m^2/y can be pointed out, respectively. Conversely, lower consumptions down to 60-65 kWh/m^2/y are of course estimated for southern regions, like Sicilia or Calabria, thanks to a higher average air temperature. These results are also in line with the ones observed on (Ascione et al., 2022), where the primary energy consumption for a building typology similar to the one adopted in this study was estimated at three different latitudes: Turin, Ancona and Naples which are located in the North, Centre and South of Italy, respectively. The estimated primary energy demand from (Ascione et al., 2022) are 157, 124 and 90 kWh/m^2/y, while values of approximatively 140, 110 and 70 kWh/m^2/y are calculated by the simplified approach adopted here. Of course, differences occur since building typologies and, thus, physical characteristics (e.g., the heat transfer coefficients) are similar, but not coincident. Additionally, (Ascione et al., 2022) considers a different meteorological dataset, and the primary energy demand also includes Domestic Hot Water (DHW) demand. Nevertheless, the energy performance of the reference building is still very low, denoting and confirming the scarce energy efficiency of the Italian residential building stocks.

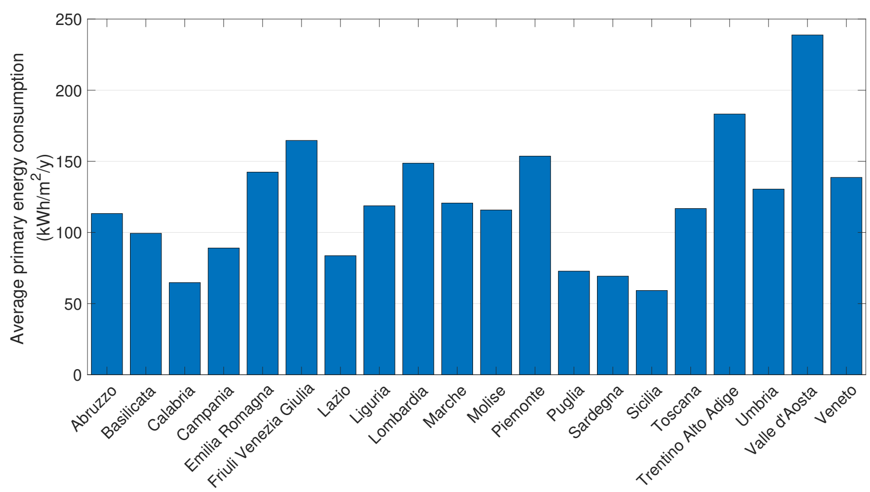

Figure 8: Estimated average primary energy consumption for space heating by regions.

Clearly, the HP sizes calculated for Scenario B with the approach presented in section 3.2 is also influenced by the latitude. In fact, Fig. 9 highlights how HP size increases in the northern regions more than in the southern ones, since the demand for space heating increase correspondingly (see Fig. 7 and 8). An average HP size close to 180-200 kW$_t$ is calculated for all the regions in the North of Italy, while lower sizes near to 110-120 kW$_t$ are calculated in the South as a consequence of increasing average yearly temperature at lower latitude. It is noticeable how PV size is still significant in southern regions, although the operation of the heating systems is required for a shorter period: for instance, according to Table 3, around 2520 hours per year can be calculated in a northern climatic zone E, while around 960 hours for a southern climatic zone B. This could lead to a lower economic sustainability of the HP integration within a configuration with PV production.

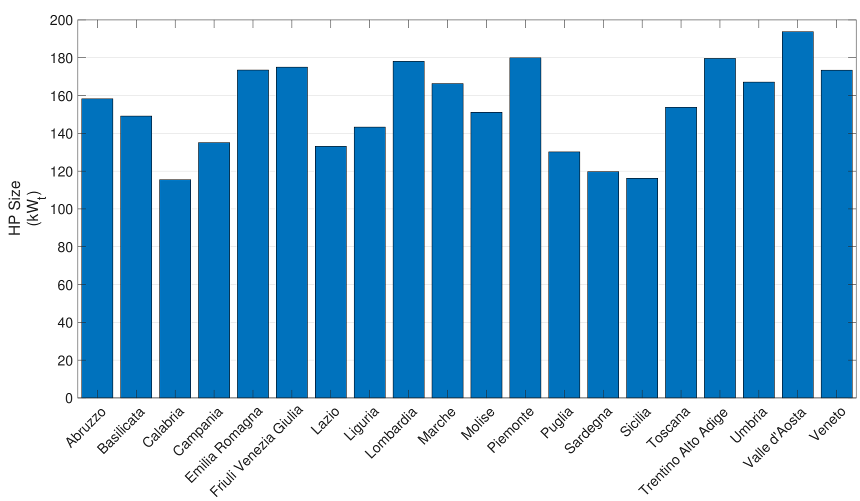

Figure 9: HP size calculated in Scenario B.

Equally, as stated in Fig. 10 and 11, the PV sizes calculated with the approach proposed in section 3.4 is strongly influenced by the latitude where the reference building can be potentially located. The higher the latitude, the higher the calculated PV size in both scenarios. This occurs because the southern regions benefit of higher solar radiation compared to the northern ones. More in detail, according to the PV sizing approach of (Cielo et al., 2021), since Scenario A relies on a fixed yearly electricity demand (only due to the internal appliances) of the building flats, an higher PV size is expected in the North than in the South to maximize both SC and SS and to find the configuration close to the utopia point in the SC-SS plane. In fact, PV size of 28-30 kW$_p$ can be averagely observed in the South while 35-38 kW$_p$ were estimated for the North (see Fig. 11) in Scenario A.

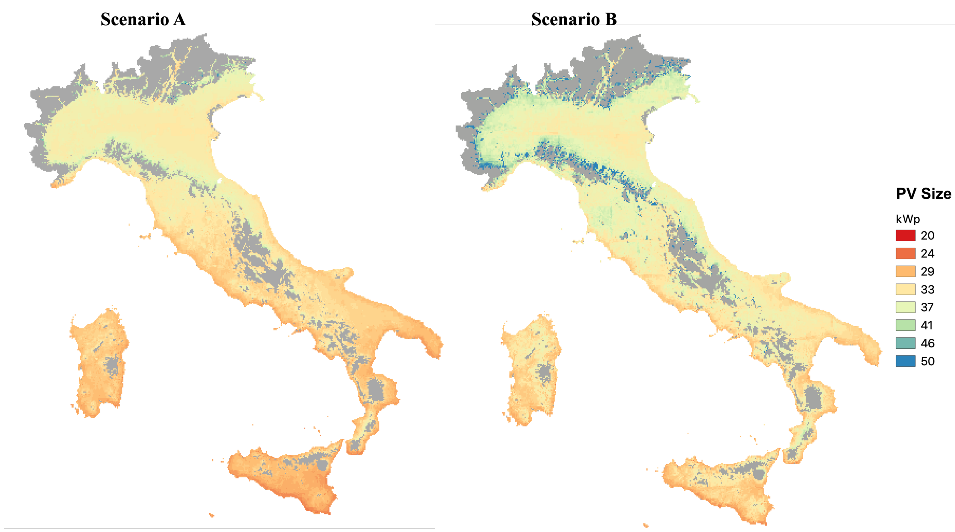

Figure 10: PV size calculated in Scenario A and B.

However, Fig. 10 and 11 reveal how PV size only slightly increases in Scenario B (i.e., generally less than 12% compared to Scenario A), despite the yearly electricity demand of the residential building significantly increases, due to the further integration of the HP and the electrification

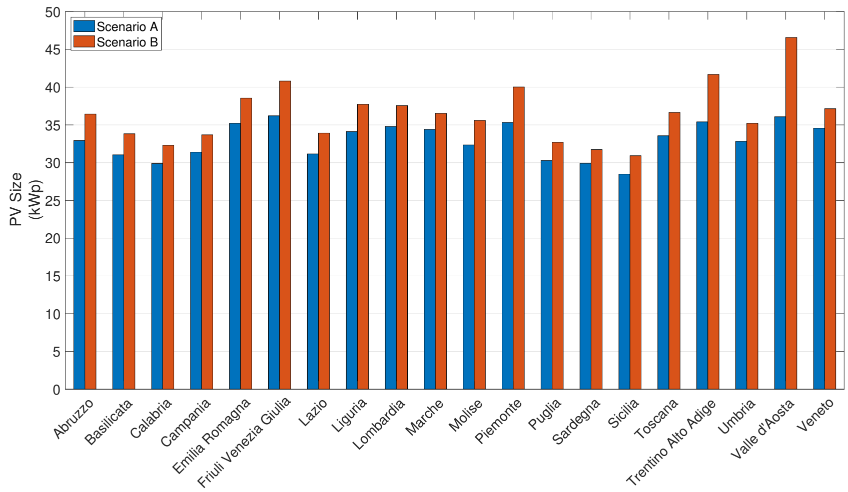

Figure 11: PV size calculated in Scenario A and B.

of the space heating demand. Generally, in fact, higher electricity demand would lead to install bigger PV plants, since SC and SS will increase accordingly. Nevertheless, PV size of Scenario B does not grow as expected because of the characteristic of the electrified heating demand. This energy demand does not increase the building electricity demand constantly along the year, but it is just more concentrated during the cold seasons with lower availability of solar radiation. So, a potential increase in PV size would not improve significantly RES production when needed, but the PV production would be mainly boosted during summer when space heating demand is not needed at all. In other words, a considerable rise in PV size would not grow significantly in both the SC and SS, because of the lack of heating demand during summer with higher solar radiation. Hence, an average size within the range of 32-48 kW$_p$ can be observed in Fig. 11) for Scenario B, pointing out that the proposed PV sizing limits the occupancy of the roof surface of the residential building. It can be noticed that the greatest increase of

PV size can be measured in Valle d'Aosta and Trentino Alto Adige with a growth of 25% and 17%, if compared to Scenario A, since these northern regions are predominantly mountain areas with higher heating demand, but lower available solar radiation.

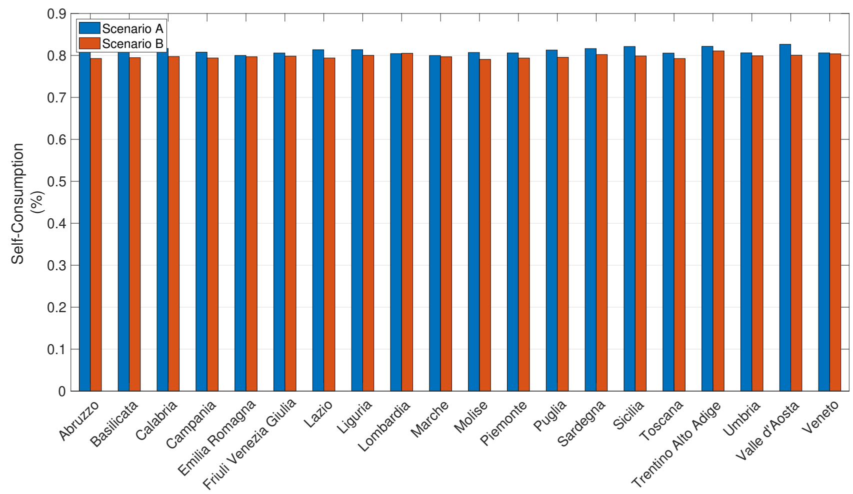

Figure 12: Self-Consumption calculated in Scenario A and B.

For all the above-mentioned reasons, the estimated SC does not remarkably change from Scenario A to Scenario B, but it remains quite constant at around 80% (see Fig. 12). Even if a similar result is also obtained by (Zatti et al., 2021), the PV sizing approach adopted here ensures a particularly high self-consumption level, in contrast to the current average SC value of 36% officially measured by the Italian Energy Service Manager (GSE) for PV installed in the residential sector (GSE, 2022). This result can thus further boost the adoption of the collective self-consumption scheme in the residential multifamily building: a new market opportunity can be achieved for investors as well as end-users can positively evaluate the opportunity to join this scheme. Conversely, Self-Sufficiency (SS) decreases passing from

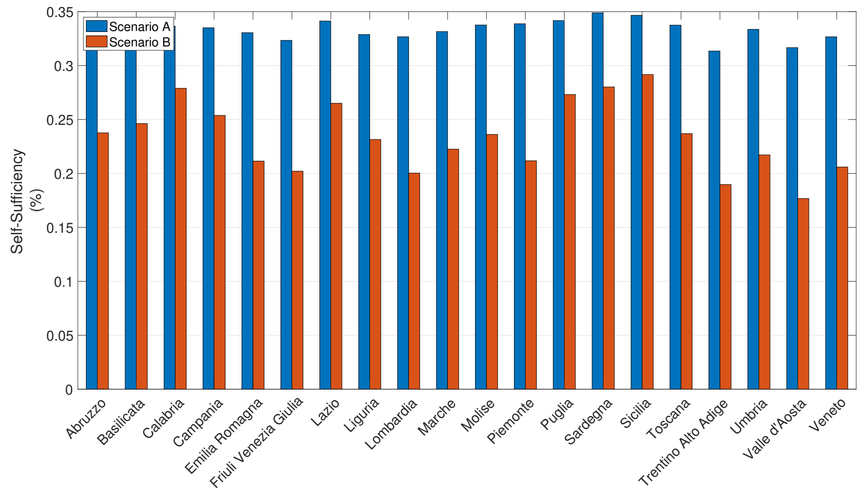

Figure 13: Self-Sufficiency calculated in Scenario A and B.

around 35% in Scenario A to 20-27% in Scenario B (see Fig. 13)). This effect is due to the relevant growth in electricity consumption because of the electrification of space heating demand and PV size changes only marginally in most of the cases compared to Scenario B.

5.2. Economic results

The main economic outcomes of both Scenarios are summarized in Fig. 14 to 20. Firstly, Fig. 14 reports the yearly cost saving achievable by the collective self-consumption configuration in both scenarios. It is clearly noticeable how the introduction of high-efficiency HP significantly improves the cost savings (i.e. improves positive cash flows), since the electrification of the space heating demand has a relevant economic impact. The adoption of HP can in fact drastically reduce the consumption of fossil fuel to supply the boiler that has lower efficiency than the HP. In fact, according to the average electricity and natural gas prices charged to Italian residential end-users in 2019 (see Table 6) and considering the contribution of PV, the per unit cost of producing heat by HP is generally cheaper than the one of the gas-fired boiler. Practically, this means that the COP_{lim} calculated in Eq. 17 is generally higher than the COP estimated in Eq. 12, so HP operates almost all the time.

Consequently, the cost savings with a range from 7% to 14% in Scenario A can potentially increase up to 27-29% in Scenario B. These results are in line with the main findings pointed out in other case studies, most of which are related to northern regions. As already mentioned, in fact, cost savings up to 17% can be achieved by collective self-consumption with only PV (Reis et al., 2022; Negri et al., 2022; Pinto et al., 2022), while cost savings up to 32% can be obtained if HP is further integrated (Zatti et al., 2021; Minuto et al., 2021). In particular, since the estimated cost savings do not include the benefit due to the Italian incentive granted to the collective self-consumption scheme, but are just limited to the saving achievable by the reduction of the billing costs, residential end-users can be significantly attracted by this new regulatory opportunity.

Later, Fig. 15 and 16 highlight how the IRR changes across Italy for Scenario A and B. Generally, a positive IRR is observed in all possible locations of the reference building. This is mainly due to the combined effects of the national incentive on the shared energy and the tax deduction of the installation costs. The latter in particular has the peculiarity of improving economic benefits since the transferability of tax credit to the firm installing the PV and HP can be converted into cash to promptly reduce the investment costs and positively influence all the economic indicators.

However, better economic performances are exploitable in Scenario B where the installation of the high-efficiency HP is considered. In fact, al-

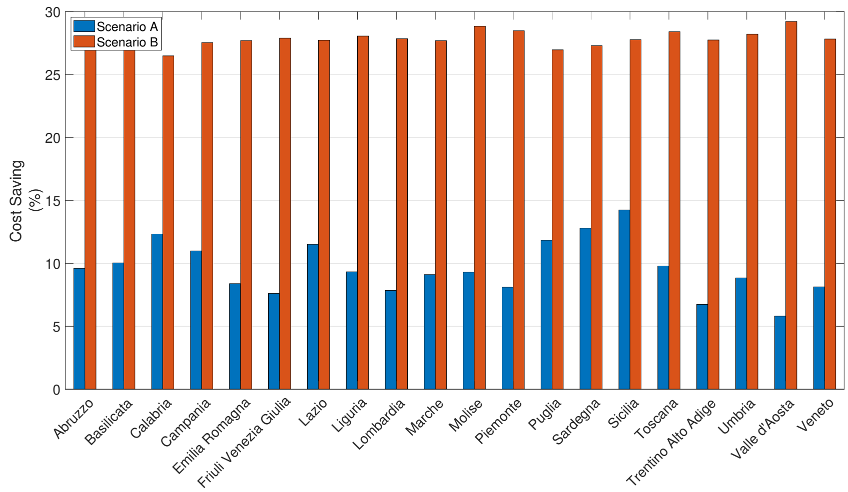

Figure 14: Cost-Saving calculated in Scenario A and B.

though the HP needs of a quite significant investment cost, the tax deduction and the reduction of primary energy consumption contribute to gain this positive result by cutting down both installation and operational costs, respectively. As a consequence, IRR ranges from 6% to 14% in Scenario A, while a range from 11% to 17% can be measured in Scenario B. Also these results are in line with other case studies. In particular, the one presented in (Viti et al., 2020) demonstrates how an IRR close to 18-20% can be achieved in a similar application of the collective self-consumption scheme.

From Figures 15 and 16, better IRR can be observed when HP is installed in residential buildings located in northern regions, instead of southern ones. Indeed, the yearly heating demand of South regions is around one-third of the North ones (see Fig. 7), while the average HP size in the South is around two third of the one in the North (see 9). This means that, if compared to the North, installation cost decreases less than operational cost savings in southern Italy, so the IRR of southern regions (like in Sicilia

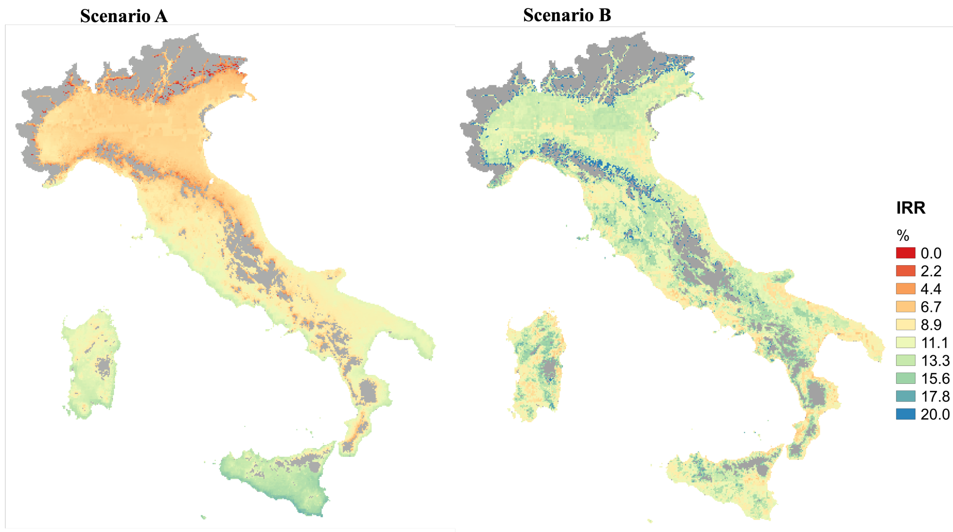

Figure 15: Internal Rate of Return (IRR) calculated in Scenario A and B.

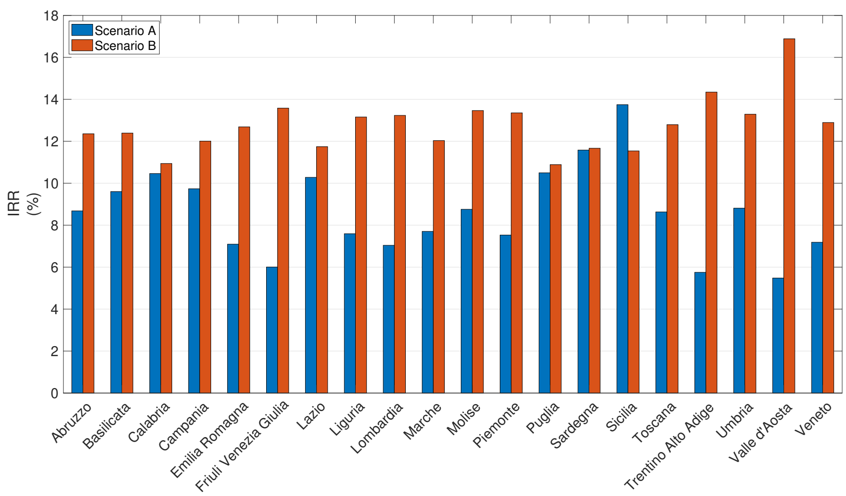

Figure 16: Internal Rate of Return (IRR) calculated in Scenario A and B.

or Calabria) either worsened or unchanged if compared to one of the North in Scenario B.

Fig. 17 and 18 describe instead the geographical distribution of the NPV

considering both Scenarios. Again, the introduction of high-efficiency HP in Scenario B shows improved economic performances compared to Scenario A, due to the reduction of primary energy demand for space heating. NPV ranges in fact from 20 to 35 k€ in Scenario A, while greater values ranging from 80 to 200 k€ are estimated in Scenario B. However, as already stated for IRR in Scenario B, southern regions have lower NPV since installation cost decreases less than operational cost savings.

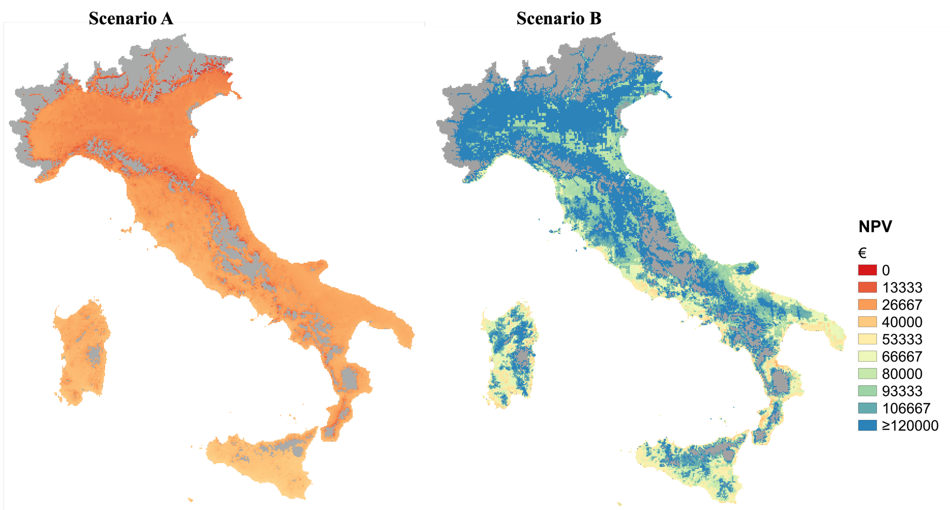

Figure 17: Net Present Value (NPV) calculated in Scenario A and B.

These economic results are also supported by the $DPBT$ shown in Fig. 19 and 20. The location with lower IRR and NPV observed for Scenario A reflects in fact higher payback time compared to Scenario B. In particular, when only PV is installed (i.e. Scenario A), the economic profitability of the investment appears limited for northern regions with lower available solar radiation (where $DBPT$ can be over 10 years in some cases), while southern areas benefit of the combined effect of an improved solar beam with tax deduction and national incentive on the shared energy. Thus,

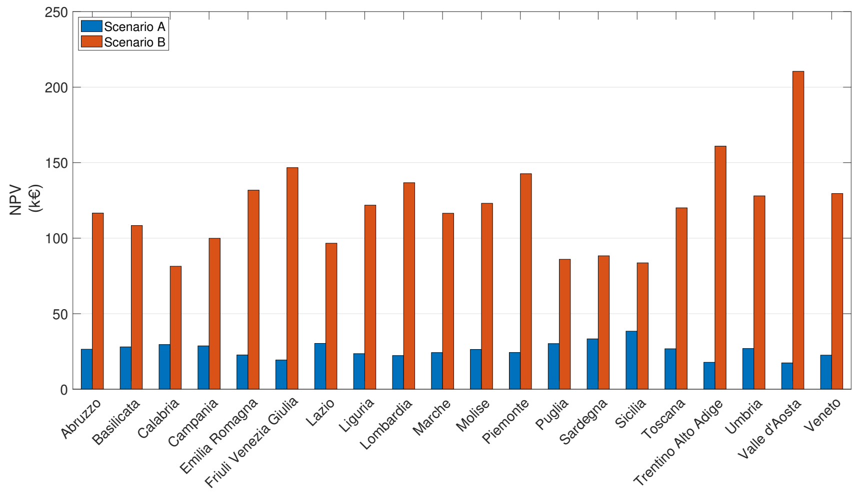

Figure 18: Net Present Value (NPV) calculated in Scenario A and B..

$DPBT$ in Scenario A can decrease down to 6-7 years on average for some of the Italian regions located in the South (e.g. Sicilia and Calabria).

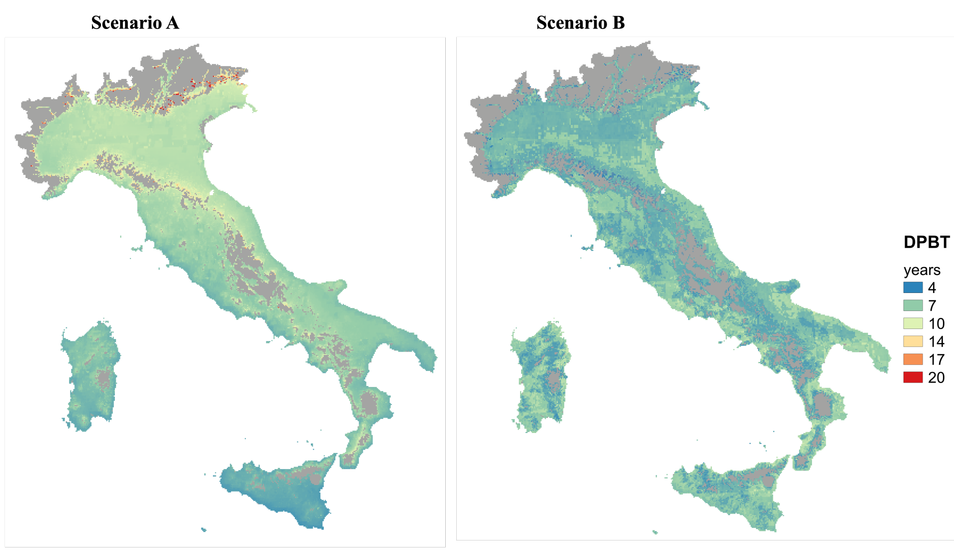

Figure 19: Discounted PayBack Time (DPBT) calculated in Scenario A and B.

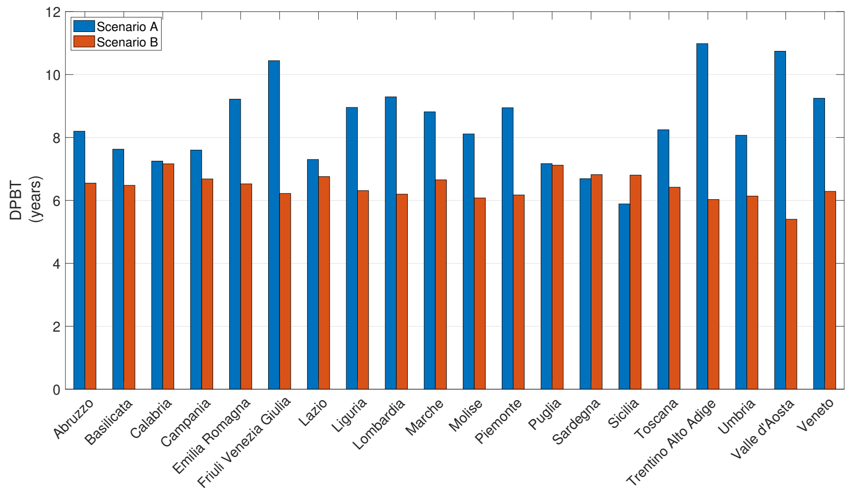

Figure 20: Discounted PayBack Time (DPBT) calculated in Scenario A and B.

Differently, the further introduction of the high-efficiency HP in Scenario B brings economical benefits to the collective self-consumption scheme in almost all the Italian regions, with a $DPBT$ close to 6-7 years. In fact, the relevant primary energy savings provided by the HP, together with the fiscal and energy incentives and the local PV production, boost this Scenario to be potentially more attractive in all those northern regions affected by low solar radiation. Nevertheless, some of the southern regions, with lower heating demand, appear to have still better economic performance in Scenario A, because the increase of $DPBT$ is not very significant in Scenario B.

In summary, although Scenario B is generally more attractive (from the economic point of view) for northern or central Italian regions where space heating demand is higher, Scenario A could be still more profitable for some of the southern regions. Of course, all these results are influenced by the energy prices assumed in the analysis, so an energy framework with higher energy prices could potentially lead to better economic performances of the collective self-consumption scheme.

5.3. Environmental results

Finally, Fig. 21 and 22 depict the environmental impact of the RES production and the electrification of space heating demand in residential buildings adopting the collective self-consumption scheme. Scenario A relies on the introduction of PV to only supply the electricity demand of residential building flats, and, consequently, this leads the CO_2 emission savings to be in line with the self-sufficiency (SS) presented in Fig. 13. Thus, emission savings appear within the range of 10% to 21% for Scenario A, with higher environmental benefits in the southern regions due to the higher available solar radiation. This result is confirmed by the analysis presented in (Negri et al., 2022) for an Italian multi-flat building with PV, adopting the collective self-consumption scheme, where the CO_2 emission can be reduced up to 24.7%.

The introduction of high-efficiency HP in Scenario B boosts the reduction of carbon emissions, since lower primary energy consumption is also needed to cover the space heating demand. As already mentioned, in fact, the average energy prices charged to Italian residential end-users and the weather conditions, lead HP to operate almost all the time, so the gas-fired boiler is used as just a backup. In this situation, where lower consumption of fossil fuel is expected, the reduction of CO_2 emission is greatly improved up to 60% in almost all the locations, making the integration of HP attractive also from an environmental point of view. Particularly, these emission reductions are in line with the ones already presented in (Zatti et al., 2021), where the integration of PV and HP under the collective self-consumption scheme in a small/medium condominium can achieve carbon emission savings up to 65%.

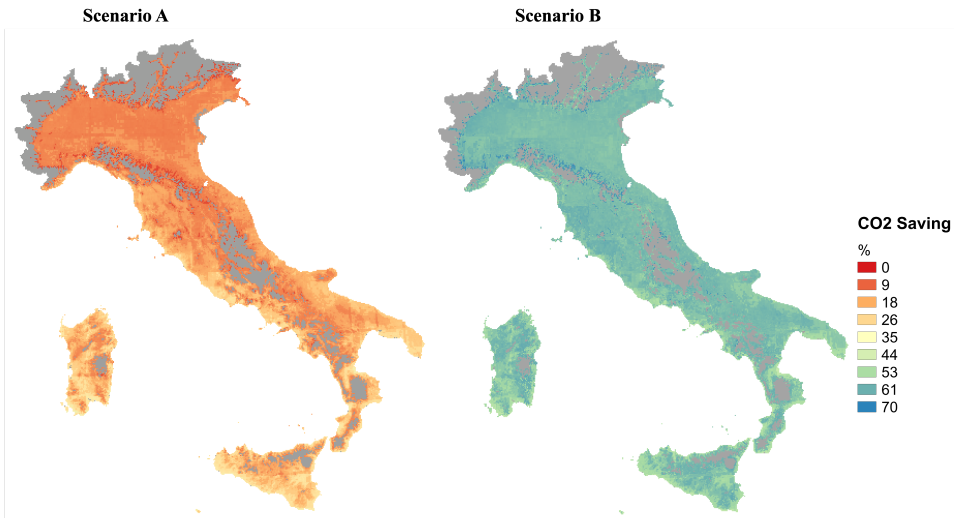

Figure 21: CO_2 saving calculated in Scenario A and B.

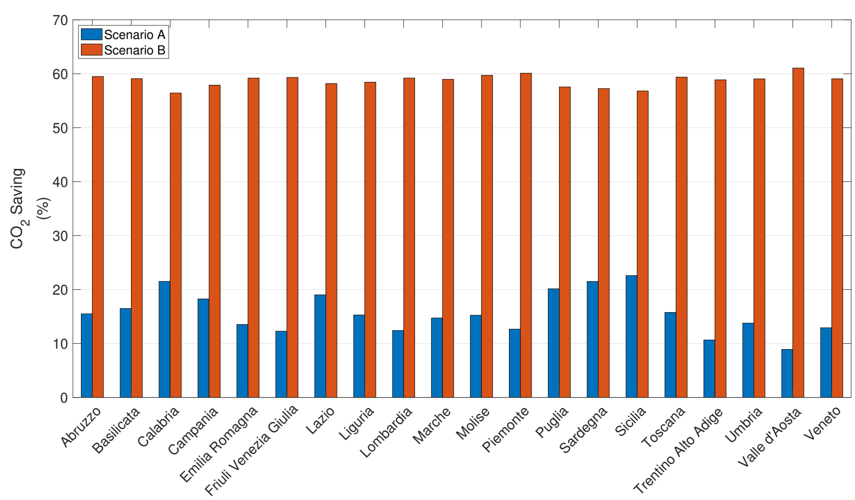

Figure 22: CO_2 saving calculated in Scenario A and B.

The environmental results observed for Scenario B are also supported by the fact that part of the electricity used to feed the HP is produced by the PV systems, as reported in Fig. 23 and 24. Both reveal how, averagely, more than 10% of the PV production can be potentially used to supply the HP. Clearly, better results are expected in the South of Italy where the share of PV feeding the HP can raise to 25%, since space heating demand is lower (see Fig. 7 and 8) while the solar radiation is higher. Nevertheless, Scenario B still represents an opportunity to sustainably promote the electrification of the heating demand, avoiding the direct use and combustion of fossil fuels.

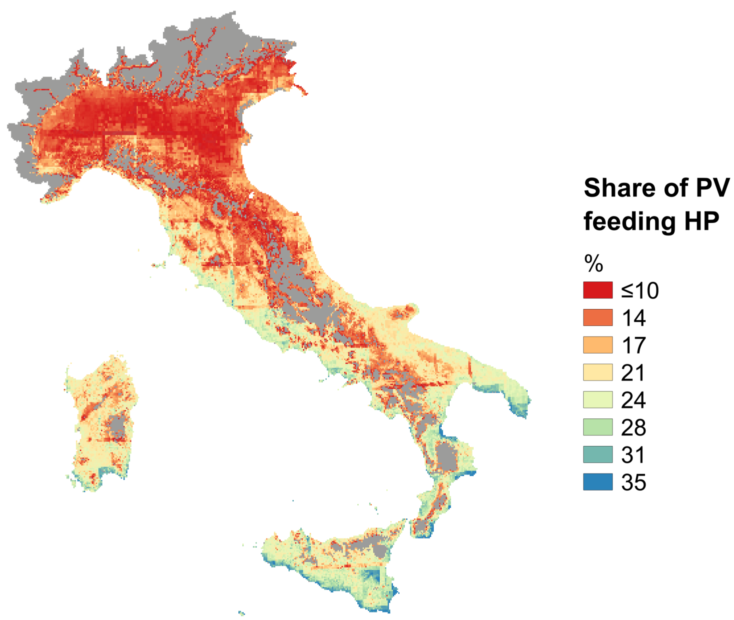

Figure 23: Share of PV production feeding the HP in Scenario B.

6. Conclusion

This paper presents an overview of the energy, economic and environmental benefits potentially achievable by residential multi-family buildings adopting PV and HP under the collective Self-Consumption scheme cur-

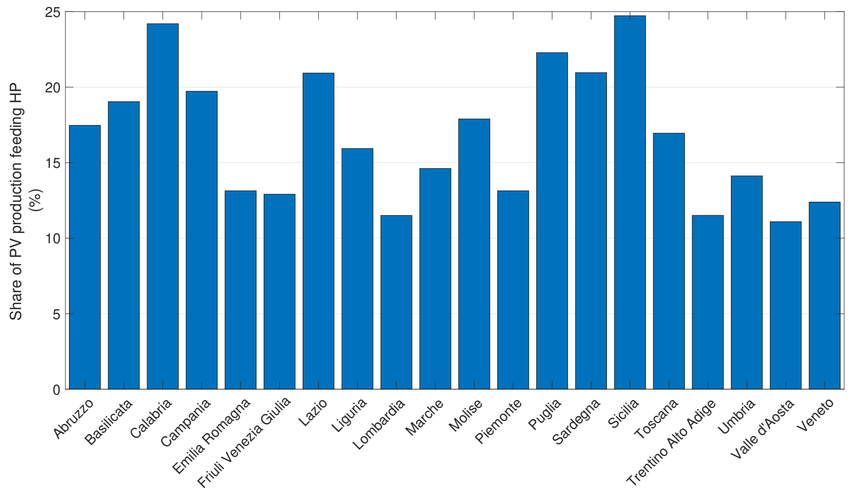

Figure 24: Share of PV production feeding the HP in Scenario B.

rently available in Italy. Two different scenarios were evaluated with increasing potential decarbonization effects: firstly the installation of a PV system to supply the electricity demand of the residential end-users is considered (Scenario A), then the further introduction of a centralized HP is assumed to cover space heating demand of the building (Scenario B). Simplified approaches for sizing of PV and HP were also considered to maximize both PV self-consumption and self-sufficiency as well as to prevent HP oversizing and reduce extra costs.

Indeed, the potential benefits can be different across the whole country, even if incentives on the shared energy (i.e. on the energy produced by the PV and consumed within the building) are currently available for all the residential end-users regardless of building location. However, weather conditions, like solar radiation and air temperature, change with latitude. Thus, the PV production, the space heating demand of the residential building and the corresponding economic and environmental impacts change accordingly.

For this reason, a simplified approach based on the characterization of a reference and representative residential building was adopted to estimate the space heating demand as a function of the weather data (i.e. the latitude).

Energy, economic and environmental indicators were then identified to present the main outcomes of the analysis. These results were finally spread across the whole country (Italy) by using GIS tool to highlight results at national level, offering an interesting general point of view as a support for policymakers, private investors and residential end-users in the promotion of PV and HP under the collective self-consumption scheme.

From the economic point of view, both scenarios being studied are profitable, basically because of the incentive schemes on the shared energy and thanks to the tax credit available in Italy for the installation of the active assets (i.e. PV and HP). In particular, the tax credit can be converted into cash to reduce the investment costs, while incentives for shared energy can improve the yearly cash-flows to positively influence all the economic indicators. However, Scenario B appears more competitive for northern regions with higher heating demand and lower yearly PV production, since higher cost savings are expected thanks to high-efficiency HP reducing primary energy consumption. An IRR within a range of 12% to 17% can be calculated for almost all the northern and central Italian regions, while lower values around 10-11% can be observed in the southern part of Italy. Similarly, the NPV varies within the range of 150 to 210k€ in the North, but values fall down to 90 k€ in the South. As a consequence, also the payback time of the investment for Scenario B is a little bit more favourable in North regions than in the South.

Conversely, Scenario A is more attractive for southern regions where lower space heating demand does not significantly benefit of HP installation. In this scenario, all the economic indicators either rest unchanged or worsened in southern regions passing from Scenario A and B. Hence, from the investors/policymakers' point of view, electrification of the space heating demand through the installation of HP should be priorly boosted in the North than in the South of Italy. From the end-users perspective, instead, Scenario B is always the best option, regardless of the latitude, since the integration of PV and HP can significantly increase the yearly cost saving in the energy bill up to 26-29%, while Scenario A would have a limited impact on households with lower cost saving (around 10%). The electrification of space heating demand can thus significantly reduce the primary energy consumption in the residential sector.

Energy results pointed out how a relatively high level of PV self-consumption can be ensured in most of the cases in both scenarios. Thanks to the PV sizing approach adopted here, most of the PV production (around 80% on average) can be locally consumed (both on-site and virtually) with lower injection into the distribution grid in both scenarios. Consequently, most of the energy produced by RES can benefit of the incentive for the shared energy and contribute in reducing yearly energy costs for the end-users joining the collective self-consumption scheme.

From the environmental point of view, the carbon saving indicator highlights how both scenarios are clearly capable to contribute in the decarbonization of the energy consumption in residential buildings. CO_2 emission savings up to 20% can be easily reached in Scenario A where most of the PV production is used to supply the electricity demand of households in the residential building. The further integration of HP in Scenario B can instead significantly contribute to reduce the environmental impact of the space heating demand in residential building. The electrification of heat demand and the consequent reduction of fossil fuel consumption can improve the emission saving up to around 60%, since part of the HP yearly electricity demand can be also covered by PV production (around 14-15% on average).

As a consequence, all the above-mentioned aspects highlight how the integration of PV and HP under the collective Self-Consumption scheme is surely the way for promoting the energy transition in the Italian residential sector. Nevertheless, further development of the presented approach can be introduced in the future to improve and overcome the potential limitations of the study. In particular, since analyses were performed on hourly basis, the introduction of electric and thermal storage elements could be evaluated in future work to highlight their impact in sizing the active assets through the adoption of multi-criteria optimization considering economic, energy and environmental aspects as a whole.

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