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

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Abstract

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

In this context, the aim of this paper is to perform an energy, economic and environmental assessment of creating a RES-based collective self-consumption community formed by end-users located in the same residential building, taking into account the current available incentive scheme. The energy consumption of an Italian representative building has been estimated and two different potential scenarios have been analysed. Firstly, the photovoltaic generator is assumed to supply only the aggregated electricity demand of the apartments, while an heat pump is introduced in the second scenario for supplying also the space heating demand of the building, that is influenced by the external temperature.

Available temperature and solar irradiance dataset at national level were then used to generalize the analysis to the whole country, at different latitudes. Results highlight how the introduction of RES production by PV and heat pump are economically and environmentally sustainable in the form of the Collective

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Self-Consumption for the residential buildings in Italy.

Keywords: Collective Self-Consumption, PV, Heat Pump, Residential Building

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Nomenclature

α_y degradation rate of PV module (%/y)

β fraction of HP production supplied by PV

ΔCO_2 CO_2 emission savings (%)

η_b efficiency of gas-fired boiler (%)

C_{HP} per unit investment cost for HP (€/kW$_{th}$)

C_m cost of the natural gas (€/m^3)

C_{PV} per unit investment cost for PV (€/kW$_p$)

C_p cost of the electricity purchased from grid (€/kWh)

C_s zonal selling market price of the electricity sold to grid (€/kWh)

$CAPEX_{HP}$ investment cost for HP (€)

$CAPEX_{PV}$ investment cost for PV (€)

COP Coefficient of Performance

d discount rate

$DPBT$ Discounted Pay Back Time (years)

E_p electricity annually purchased 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 from the grid (tCO_2/MWh)

EF_{ng} emission factor of the natural gas (tCO_2/MWh)

G hourly solar irradiance (kW/m^2)

H_i lower heating value of natural gas (kWh/m^3)

HP Heat Pump

IRR Internal Rate of Return (%)

NPV Net Present Value (€)

$OPEX_{HP}$ operational cost for HP (%/y)

$OPEX_{PV}$ operational cost for PV (€/kW_p)

$P_{HP,th,max}$ size of centralized HP system (kW_{th})

P_{inj} PV production injected into the distribution grid (kW)

$P_{PV,size}$ size of PV plant (kW_p)

P_{UE} hourly aggregated electricity demand of the building (kW)

P_{UT} hourly space heating demand (kW_{th})

PCR yearly cost savings (%)

PR Performance Ratio of PV

PV Photovoltaic

SC Self-Consumption (%)

SS Self-Sufficiency (%)

T_a hourly air temperature (°C)

YC yearly costs (€/y)

YCF_y yearly cash flow (€/y)

YR yearly revenues (€/y)

1. Introduction

Europen Union has set ambitious goals for its Member States in terms of sustainability and decarbonization in the next future [1]. Therefore, a drastic change in the paradigm of energy production and consumption is needed in this "energy transition" process. This is particularly true in the residential sector, which accounts for a large part of final energy consumption in Europe [2]. Therefore, the two directives EU 2018/2001 [3] and EU 2019/944 [4] (commonly referred to as RED II and IEM, respectively) addressed the role that citizens can play in this transition process, through the introduction of Energy Communities and Collective Self-Consumption. The underlying concept of *energy sharing* is the enabling factor for decarbonization in the residential sector through increased production and consumption from Renewable Energy Sources (RES). Indeed, energy sharing allows to increase the local consumption of self-produced energy and opens up to self-consumption in context where it was strongly limited in the past (e.g. cities where larger part of the population lives in multi-apartment buildings).

In 2020 the Italian government undertook an experimental phase, which ended with the full transposition of the two Directives in November 2021. In between, a series of regulations were issued to define the framework for end users to join into Renewable Energy Communities (RECs) or as Jointly-Acting Renewable Self-Consumers: [5] and [6] provided the technical and operative rules for these configurations, while [7] defined the incentive structure. Even though the current regulation (hence, all projects currently under development) focuses only on electricity [8], sector coupling can be a viable means to further exploit local RES-production and decarbonize the residential energy consumption. For example, families living in a multi-house residential building can partially replace the centralized fossil-based heating system by means of a heat pump (HP), which is in part powered by the RES-production of a photovoltaic (PV) generator.

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 on the technologies and energy vectors included, the perimeter (e.g. REC or collective self-consumption in a single building) or the approach (with or without optimization).

For example, [9] analyzed the energy and economic performances of residential end-users located in a multi-family building who join together as an energy community and install al PV system on the building's rooftop. The case-study of a REC in Northern Italy is proposed in [10], with multiple PV systems 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. Furthermore, collective self-consumption in energy communities where participants can exchange and trade energy among themselves within a given area is discussed in [11] to highlight the benefits of an optimal resource allocation in a demonstrator located in France. 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 [12] to promote a more efficient management of energy resources. In this case study fixed size of PV and storage unit are considered for a building located in Coimbra (Portugal) to highlight the economic and energy benefits of the initiative maximizing self-consumption and minimizing energy costs. Similarly, a multi-agent simulation of collective self-consumption is analysed in [13] 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. [14] included heating and cooling demand, satisfied by means of HPs, in the model and applied design optimization to a case study of a single building with different users typologies. Similarly, a study for the conversion of a multi-family residential building into an energy community is presented and discussed in [15], where different energy vectors and possible active solutions including PV, HP and storage are considered for a specific case study in the North of Italy. Additionally, the evaluation of the economic profitability of PV systems under collective self-consumption scheme is presented in [16] both for household and non-household electricity self-consumers, but assuming a reference PV installation in a part of Italy with a medium level of insolation.

Despite obtaining interesting results about the energy, environmental and economical sustainability of these initiatives, all these works are limited to single case-studies. Instead, widening the scope of these analyses can be useful to provide insight at larger scales, e.g. regional or national. An attempt in this sense has been made in [17], where the analysis has been extended to 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 repeating the analysis on several case studies. Moreover, the focus was on the potentiality in terms of installed RES capacity, taking into account the phenomenon of reverse power flow.

For these reasons, the present work analyzes the potentiality of collective self-consumption for multi-family residential buildings across the whole Italy, with a smart approach. Two scenarios are considered: in the first one, the families only install a PV system on the building's rooftop to partly fulfill their electricity demand, while the centralized heating demand is fulfilled by means of a gas-fired boiler; in the second one, a heat pump (HP) is installed to partially fulfill the heating demand and at the same time increase the local consumption of renewable electricity. The analysis is repeated over a multitude of points Italy-wide, using a Geographical Information System (GIS) tool to process and visualize the results and open databases, i.e. PVGIS [18], to obtain solar data. Therefore, a reference building is considered, whose energy demands (electricity and heating) are evaluated using statistical and weather data.

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 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, over-generation from some members of the REC (i.e. energy that is produced but not consumed on-site) can be used by other members. In the Italian regulation, a virtual scheme has been defined to allow the sharing of electricity. According to this scheme, electricity over generation is shared when it is simultaneously injected into and withdrawn from the grid by members of the REC. Shared electric energy 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 [19].

2.1. Collective self-consumption scheme in residential buildings

Collective Self-Consumption is a particular method of electricity sharing, where all the end users are located in the same building or apartment block [20]. For instance, Fig. 1, shows a scheme for collective self-consumption in a multi-family residential building. A collectively-owned PV system is installed on the building's rooftop. Electricity generation can be consumed on-site for shared services (e.g., elevator, lighting of common spaces) or injected into the grid. The household users in the building can use this injected energy to fulfill their own electricity demand, thus sharing it. 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, 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. Therefore, coupling of different energy carriers can overcome the limitation of the Regulation about RECs and collective self-consumption, which currently only involve electricity.

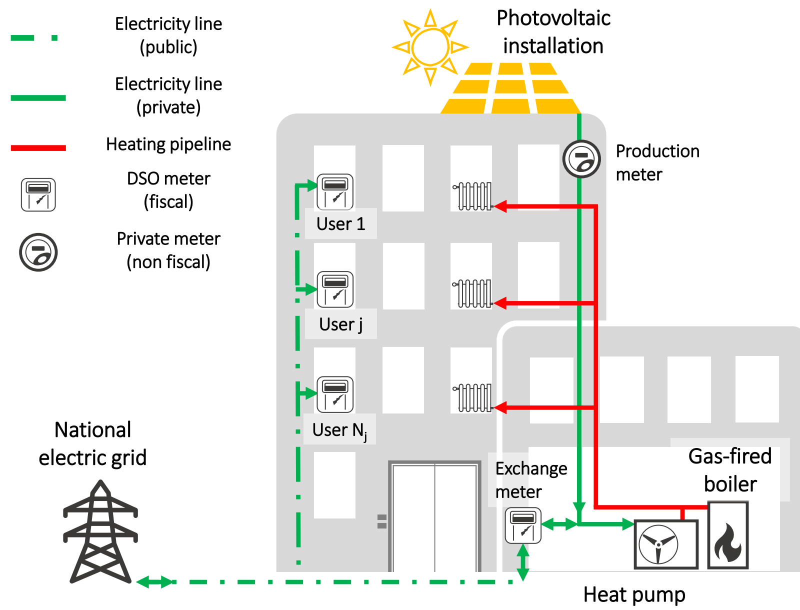

Figure 1: Collective self-consumption in a multi-house residential building with coupling of electricity and heating demand (adapted from [8]).

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.

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 over generation 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

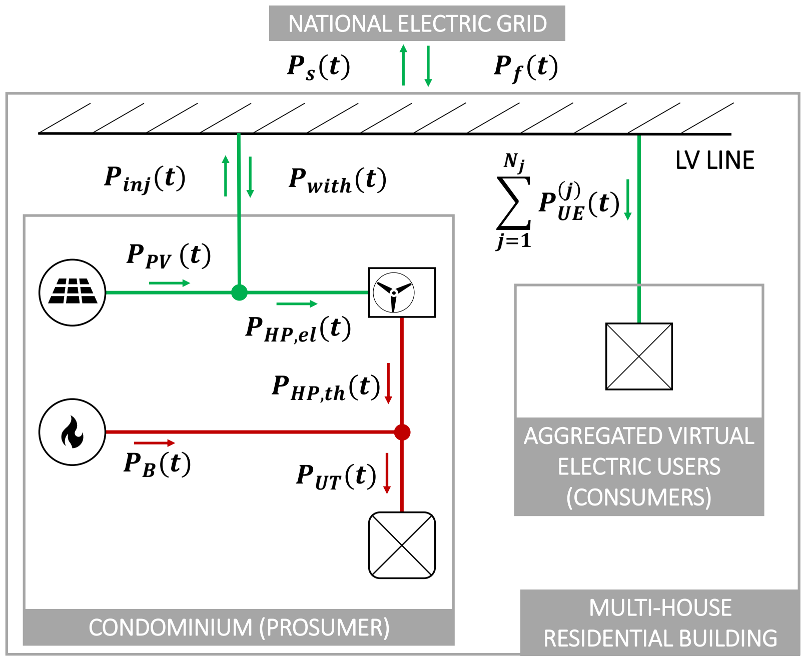

Figure 2: Scheme of the energy flows in the collective self-consumption configuration with a production node and multiple consumption nodes..

time step h, $E_{sh}(t_h)$, is calculated according to [19], 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 [5, 6, 7], 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 economical value of shared energy in collective self-consumption 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 [21], 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

3.1. Heating demand of residential building

The introduction of the collective self-consumption scheme has boosted the interest in the electrification of the energy consumption within the residential Italian context. 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 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 period 1961-1975) was selected as reference, according to the current composition of the Italian building stock [22] shown in Fig. 3.

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 [23], 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 [24], 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:

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

where η_d is the efficiency of the heat distribution system.

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

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

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

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

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

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

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

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 [23].

S/V (m^{-1})	Floors	Apartments	U_{ext} ($\mathrm{W/m^2K}$)	U_r ($\mathrm{W/m^2K}$)	U_g ($\mathrm{W/m^2K}$)	U_i ($\mathrm{W/m^2K}$)	U_w ($\mathrm{W/m^2K}$)	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

Table 2: Other physical characteristics assumed for the reference building [23].

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

According to equations from 4 to 10, the heating load demand can be thus estimated on hourly basis by means of the air temperature data. In this work, data were extracted from the JRC dataset available for all EU countries [25]. Other layout characteristics of reference building, like the walls thickness, were also extracted from [23] and taken into account to 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 [26]. Tables 3 and 4 summarize these seasonal and daily operational limits of the heating system considered in the simplified approach at 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		

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

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

3.2. Heat Pump sizing and operation

The primary energy demand for space heating is still based on fossil fuel within the current Italian residential sector [27]. In particular, natural gas is the main fuel adopted in space heating applications burned in conventional and highly-efficient boilers. However, the increasing performance of alternative solutions like HPs is paving the way for a wider diffusion of this technology, contributing in the electrification and decarbonization of energy consumption in residential buildings. In fact, the heat production by an HP is generally more efficient than a boiler from the primary energy point of view, so that positive effects in terms of energy, costs and emission savings are expected.

For these reasons, the adoption of a Air Source Heat Pump (ASHP) is in-

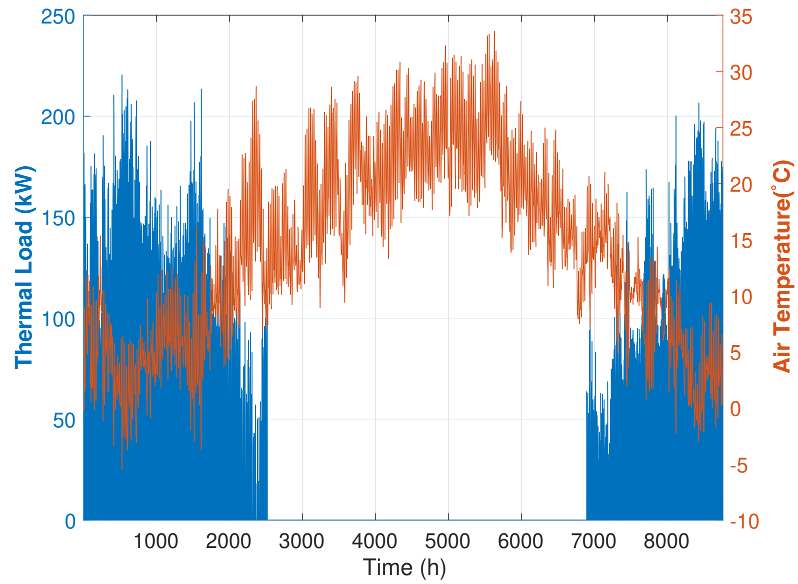

Figure 4: Hourly space heating demand estimated for a residential building located in the North-West of Italy.

troduced 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. 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.

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 function of the air temperature. Thus, according to the simplified model proposed by [28], COP variation for the ASHP can be calculated through the following nonlinear 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. Afterwards, limitations of HP operation were also introduced in order to improve the economic performance of this heating technology, as proposed by [15]. 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

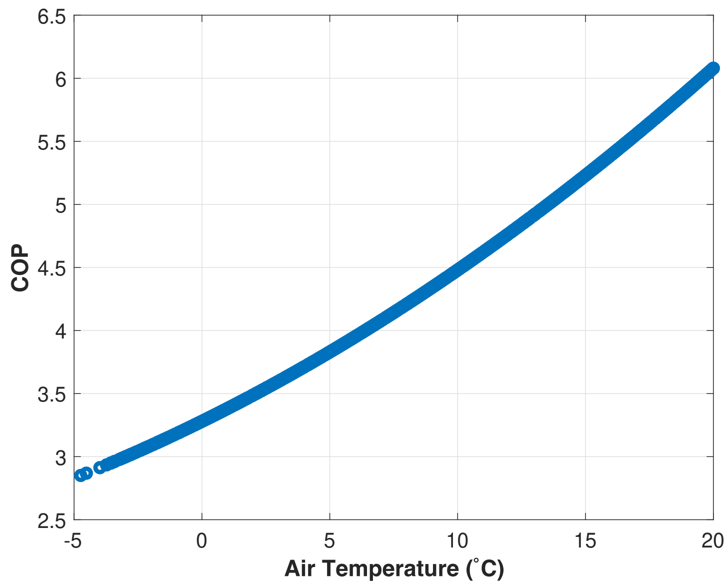

Figure 5: COP as function of the air temperature estimated for a HP in the North-West of Italy.

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 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 assumption that all the households have joined the collective self-consumption agreement, the hourly load profile P_{UE} of the households 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 [29], the hourly load profile P_{UE} has been estimated assuming the yearly demand E_{UE} of all the households appliances and considering a normalized load profile for residential end-users derived by [30, 31]. Then, the normalized load profile was properly scaled to preserve the aggregated yearly electricity demand E_{UE} by means of a scaling factor SF calculated as

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

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) are 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 electricity demand and consequently reduce environmental impact. 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 [32]. Firstly, the PV generation has been estimated according to the approach proposed in [33] where the hourly PV profile is calculated as 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 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 [18]. 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 [32]. 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 energy basis through a parametric approach (i.e. increasing the PV size), as proposed by [10]. 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 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 [34], 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 [35] 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 investment on 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 ($CAPEX$):

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

where C_{PV} and C_{HP} are the per unit installation cost for PV and HP, respectively. However, the Italian government introduced an incentive scheme to promote the diffusion of RES production in the residential sector [36, 37].

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 in cash to reduce the investment costs, as follows:

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

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 [6], 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 [6], 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 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 [21], while the shared energy benefits of the incentive 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 [38]. In particular, although a new regulatory fragmentation has been recently introduced by the Italian TSO [39] 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.

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

- Southern-Central: Lazio, Abruzzo, Campania.
- 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 the 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

The energy, economic and environmental analyses of a collective self-consumption configuration adopted in a multi-family residential building are pointed out in this section. The aim is to highlight how the decarbonization of energy consumption is sustainable in the Italian context.

In this view, the energy, economic and environmental indicators previously presented are evaluated across the whole country adopting the methodology and the approach proposed in [29, 40]. Substantially, the Italian territory of Fig. 6 is represented by a raster with resolution of 2.5 x 2.5 km, where both solar radiation and air temperature hourly data can be extracted from European Joint Research Centre (JCR) database [18, 25] for each centroid of the raster cells. Later, these datasets were imported in the MATLAB environment and analyses were performed by exploiting the matrix representation of the data. 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 building are located at lower elevation [41]. Thus, the following maps include grey areas representing location at altitude greater than 850 m, where data analysis is omitted.

This approach was firstly adopted to explore results taking into account the variation of solar radiation and air temperature at different latitude. Secondly, results can be easily handled through Geographical Information Systems (GIS) to obtain more descriptive maps. In particular, two different possible scenarios

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

were analyzed in this paper to consider a progressive implementation of decarbonization actions:

- *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.

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 by the PV size and the yearly gas consumption,

Table 5: Energy and economic assumptions used for calculating indicators in each raster cell [29, 33, 42, 43, 44, 45].

C_{PV} (€/kWp)	$OPEX_{PV}$ (€/kWp/y)	C_{HP} (€/kW$_{\text{th}}$)	$OPEX_{HP}$ (%/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 [29, 33, 34, 35, 43, 44].

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

respectively. Otherwise, the PV size was limited by the available roof surface of the reference building and, consequently, the PV sizing presented in section 3.4 adopted a maximum PV size of around 70 kW$_p$.
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.

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 from the latitude (i.e. northern regions are climatically coldest than southern ones) and from the altitude (i.e. foothill or hilly areas are typically coldest than flatland). In fact, an 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 are instead expected in the South where average consumption can 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 [46].
Instead, the average primary energy consumption estimated for the reference

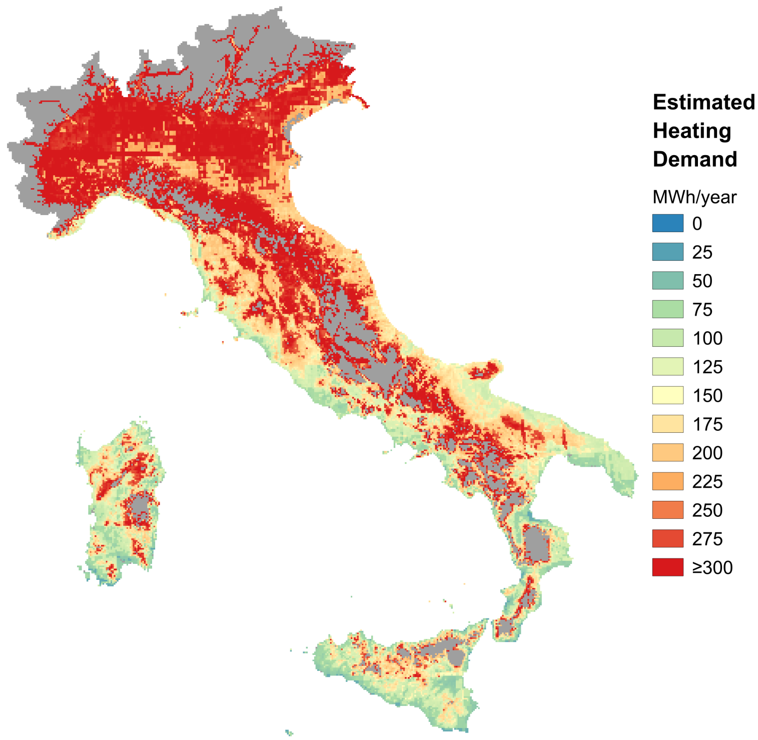

Figure 7: Space heating demand estimated for the reference building across Italy.

building in the different Italian regions is depicted in Fig. 8, considering a gas-fired boiler as 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 [47]. 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 consumption down to 60-65 kWh/m^2/y are of course estimated for southern regions, like Sicilia or Calabria, thanks to an higher average air temperature.

As a consequence, the HP sizes obtained for Scenario B by applying the approach presented in section 3.2 follow this trend. In fact, Fig. 9 highlights how

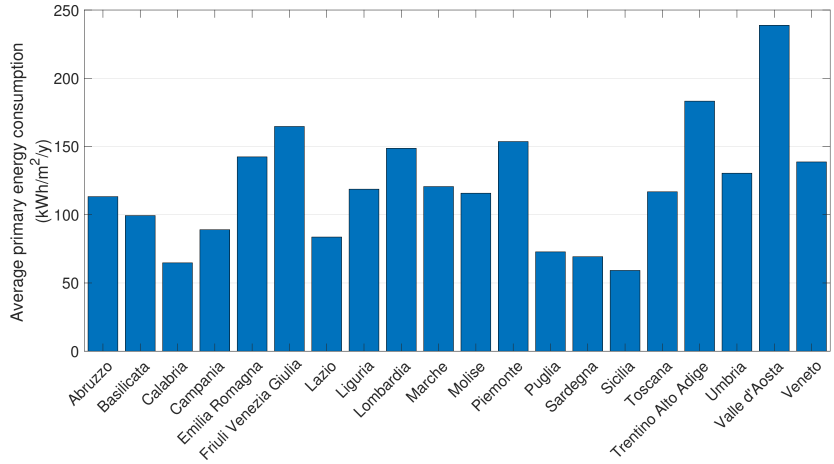

Figure 8: Estimated average primary energy consumption for space heating by regions.

HP size increases with the latitude, since northern regions are typically coldest than the others and peak demand for space heating increase correspondingly (see Fig. 7 and 8). An average size close to 180-200 kW$_t$ is estimated for all the Northern regions, while HP size near to 110-120 kW$_t$ are calculated in the South as a consequence of increasing average yearly temperature at lower latitude.

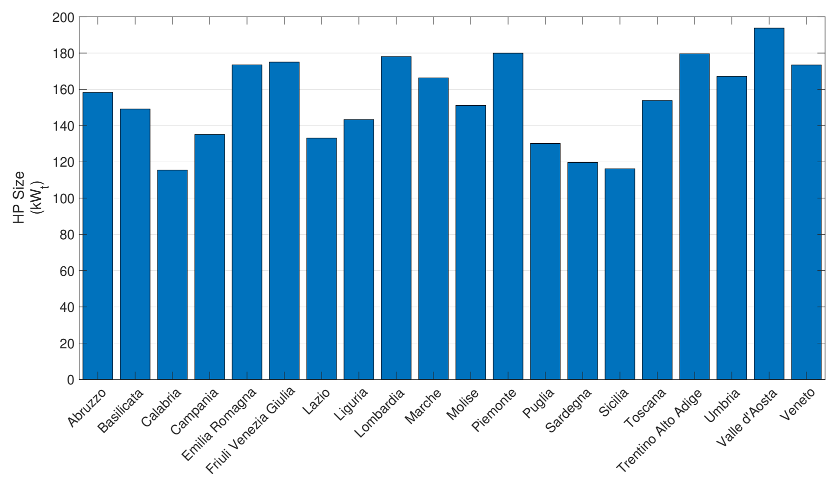

Figure 9: HP size calculated in Scenario B.

Equally, the PV sizes calculated adopting the approach of section 3.4 is strongly influenced by the latitude where the reference building can be potentially located, as stated in Fig. 10 and 11. In fact, the higher the latitude, the higher the calculated PV size in both the scenarios. This occurs since the southern regions benefit of higher solar radiation compared to the northern ones. Thus, since Scenario A relies on a fixed yearly electricity demand of the residential building in all the locations, an higher PV size is expected in the North to maximize both SC and SS than in the South. In fact, average size of 28-30 kW$_p$ can be observed in the South while 35-38 kW$_p$ were calculated for the North (see Fig. 11) in Scenario A.

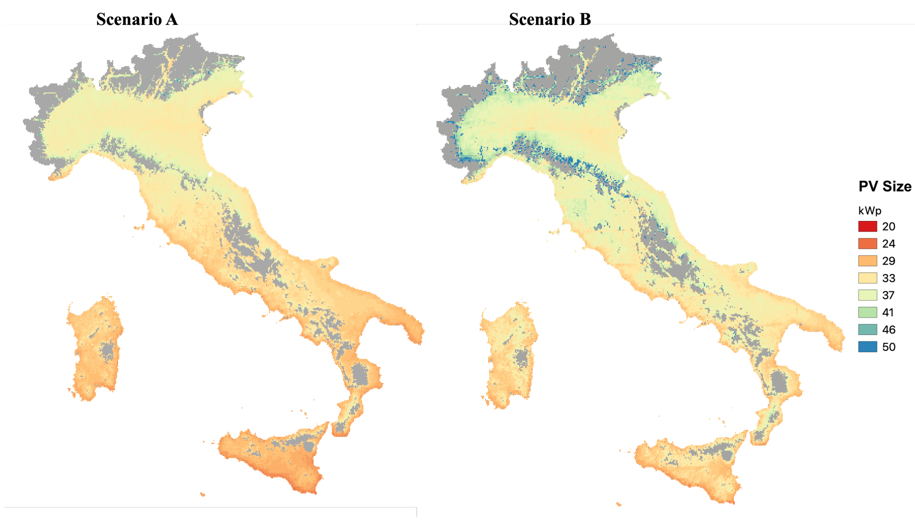

Figure 10: PV size calculated in Scenario A and B.

However, Fig. 10 and 11 reveal how PV size slightly increase 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 HP production. This is mainly due to the characteristic of the heating demand which occurs only during cold seasons with lower solar radiation. So, a considerable rise of PV size would not significantly growth both the SC and SS, because of the lack of heating demand during summer with higher solar radiation. Hence,

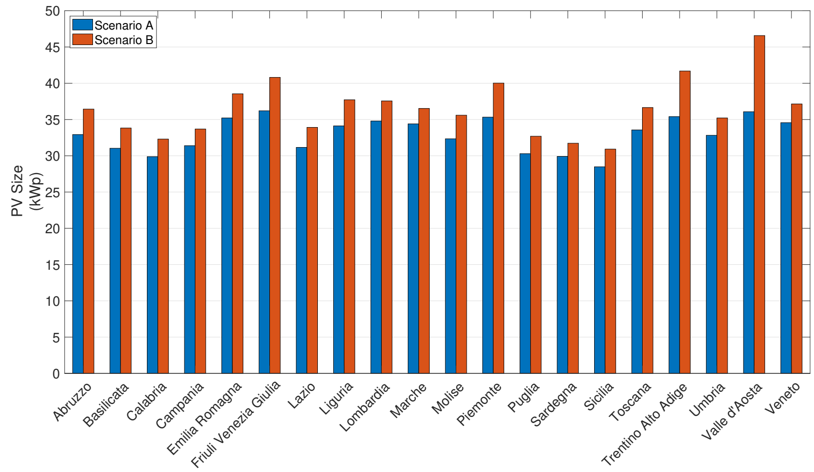

Figure 11: PV size calculated in Scenario A and B.

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.

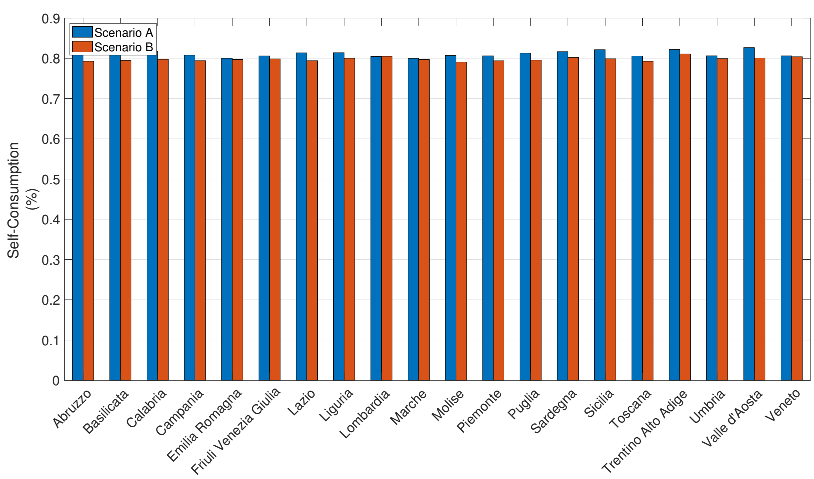

Figure 12: Self-Consumption calculated in Scenario A and B.

For these reasons, the estimated SC does not remarkably change from Scenario A to Scenario B, but it remain quite constant at around 80% (see Fig. 12).

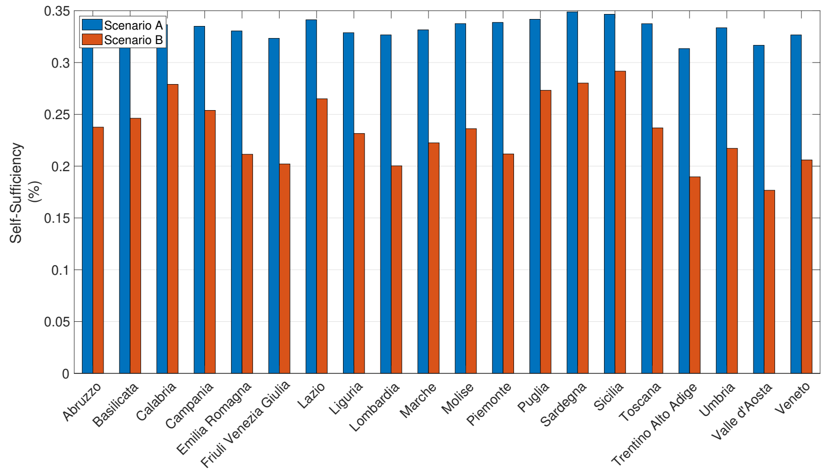

Figure 13: Self-Sufficiency calculated in Scenario A and B.

While the Self-Sufficiency (SS) decreases passing from around 35% in Scenario A to 20-27% in Scenario B (see Fig. 13)), due to the growth in electricity consumption because of HP contributes in covering heating demand and PV size remains quite constant. The main economic outcomes of both Scenarios are instead summarized from 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 reduction of primary energy consumption for space heating has a relevant economic impact. In fact, the cost savings with a range from 7% to 14% in Scenario A can potentially increase up to 27-29% in Scenario B.

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

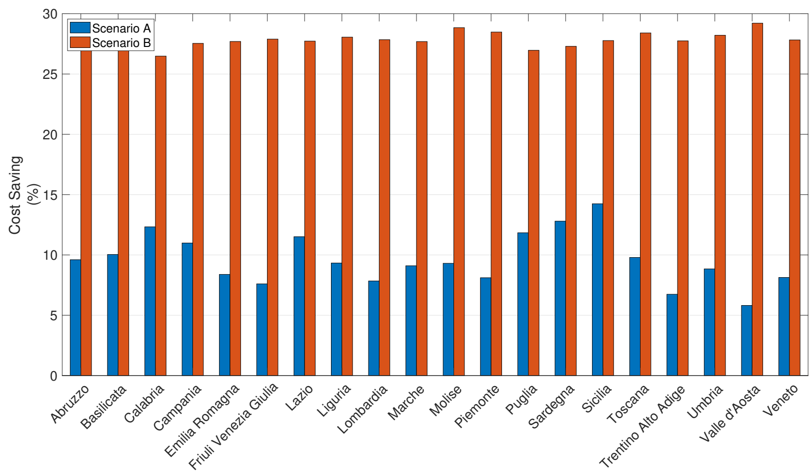

Figure 14: Cost-Saving calculated in Scenario A and B.

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, although 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.

In particular, better IRR can be observed when HP is installed in residential building 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 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 worsened if compared to one of the North in Scenario B.

Fig. 17 and 18 describe 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

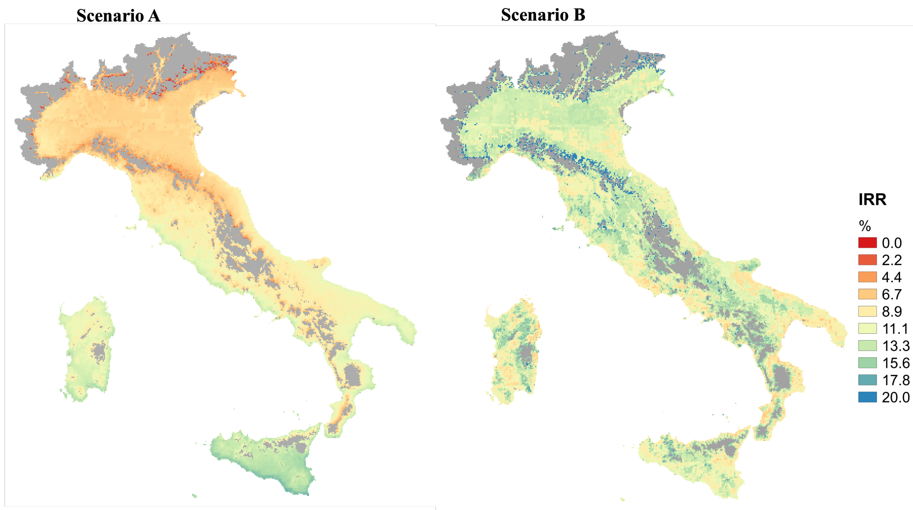

Figure 15: Internal Rate of Return (IRR) calculated in Scenario A and B.

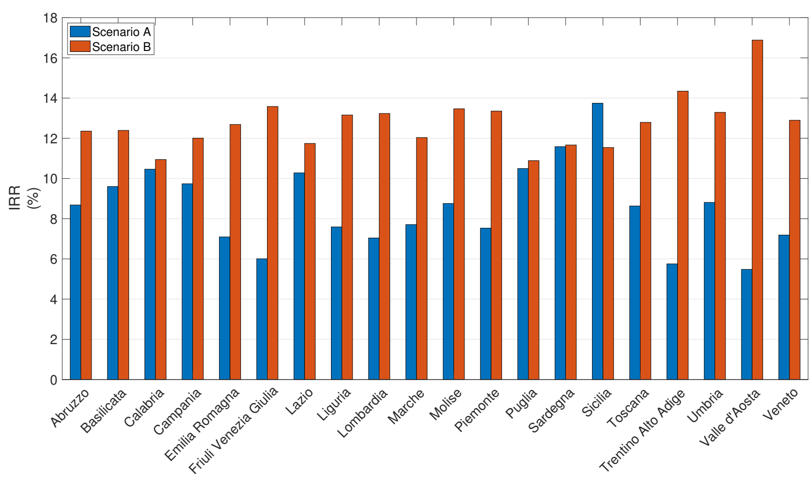

Figure 16: Internal Rate of Return (IRR) calculated in Scenario A and B.

reduction of primary energy demand for space heating. NPV range in fact from 20 to 30 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 suffer of lower NPV since installation cost decreases less than operational cost savings.

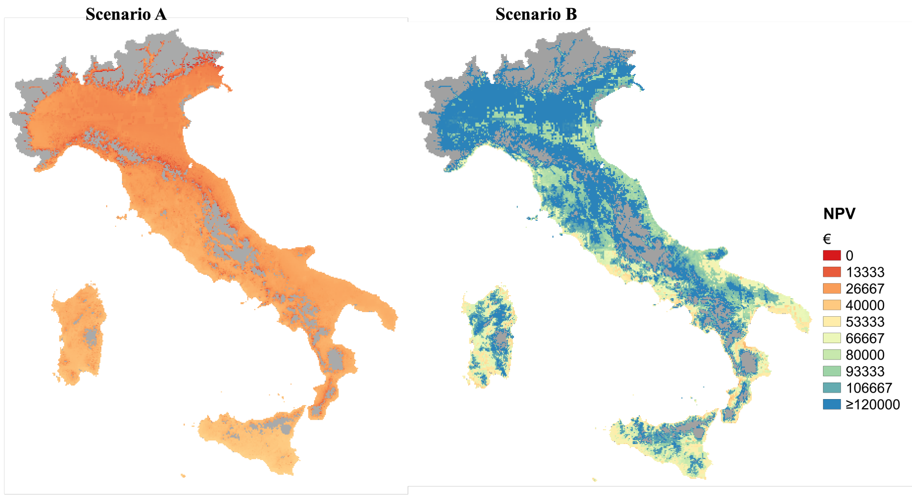

Figure 17: Net Present Value (NPV) calculated in Scenario A and B.

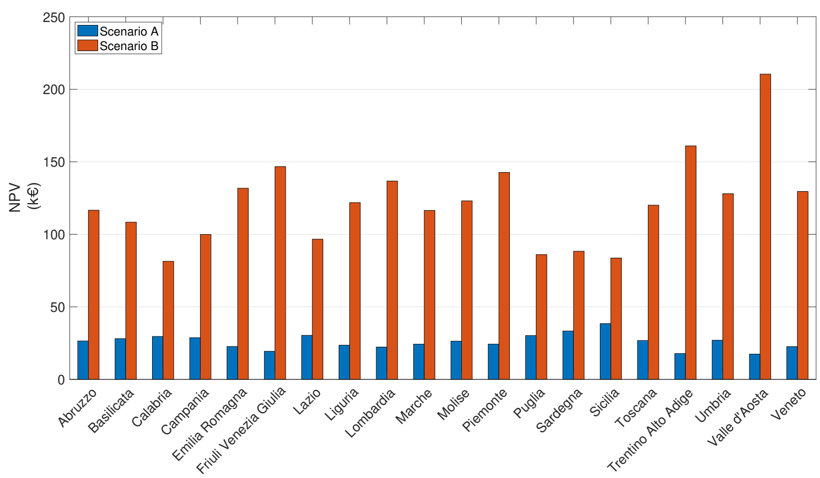

Figure 18: Net Present Value (NPV) calculated in Scenario A and B..

These preliminary 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 reflect 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 low solar radiation (where

$DBPT$ can be over 10 years in some cases), while southern areas benefit of the combined effect of improved solar beam with tax deduction and National incentive on the shared energy. Thus, $DPBT$ 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).

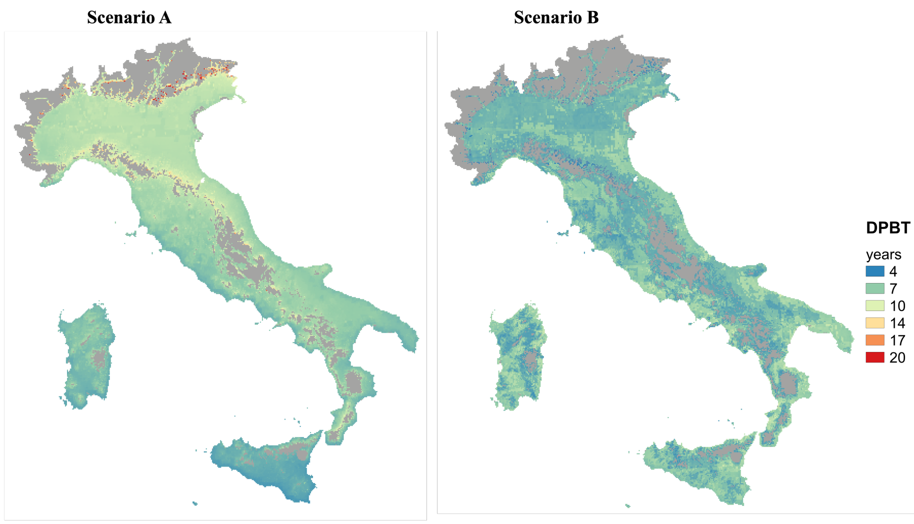

Figure 19: Discounted PayBack Time (DPBT) calculated in Scenario A and B.

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 boost this Scenario to be potentially more attractive in all those northern regions affected by low solar radiation. However, some of southern regions, with lower heating demand, appear to have better economic performance in Scenario A, although the increase of $DPBT$ is not very significant in Scenario B.

Finally, Fig. 21 and 22 instead depict the environmental impact of the adoption of decarbonization actions within the collective self-consumption scheme. Scenario A relies with the introduction of PV to only supply the electricity de-

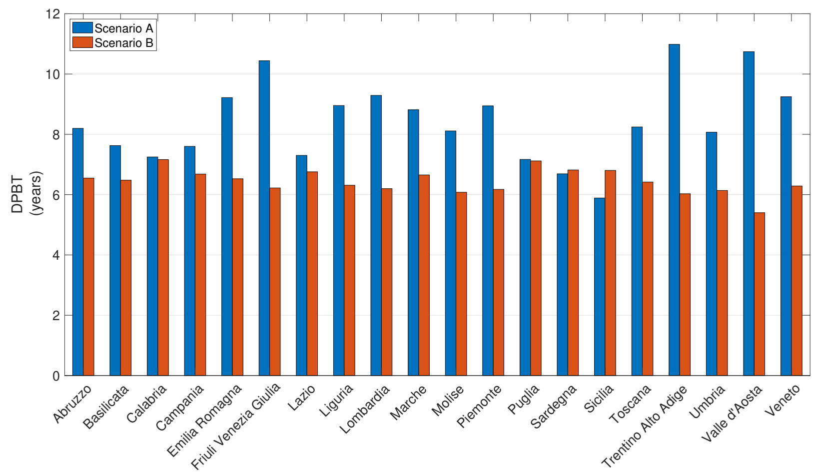

Figure 20: Discounted PayBack Time (DPBT) calculated in Scenario A and B.

mand of residential building flats, 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. 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 and the gas-fired boiler is used just a back-up. Hence, the reduction of CO_2 emission is improved up to 60% in almost all the locations.

This environmental result is 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 up 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 for sustainably promote the electrification of the heating demand, avoiding the direct use and combustion of fossil fuels.

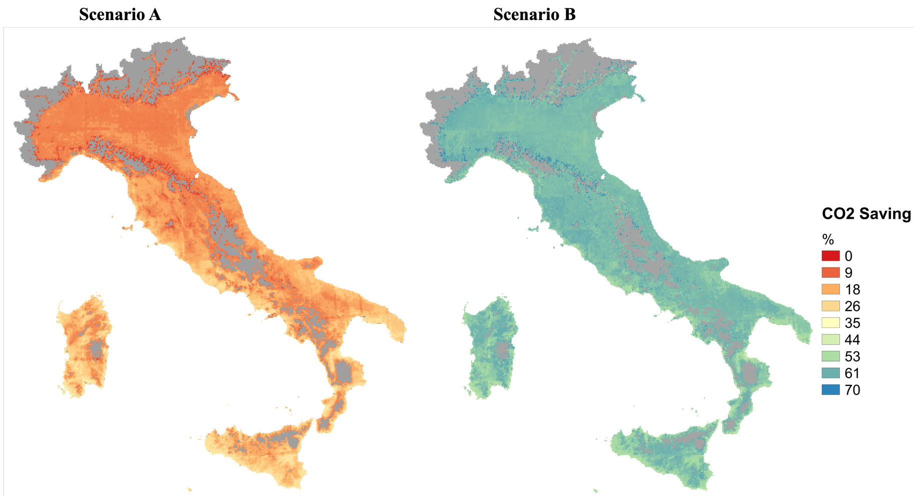

Figure 21: CO_2 saving calculated in Scenario A and B.

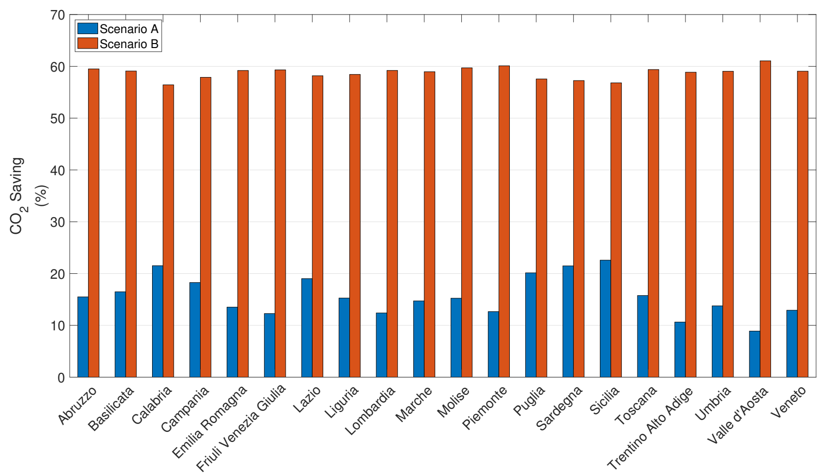

Figure 22: CO_2 saving calculated in Scenario A and B.

6. Conclusion

This paper presents an overview of the energy, economic and environmental benefits potentially achievable by residential multi-family buildings adopting the collective Self-Consumption scheme currently available in Italy. Two different scenarios were evaluated with increasing potential decarbonization effects:

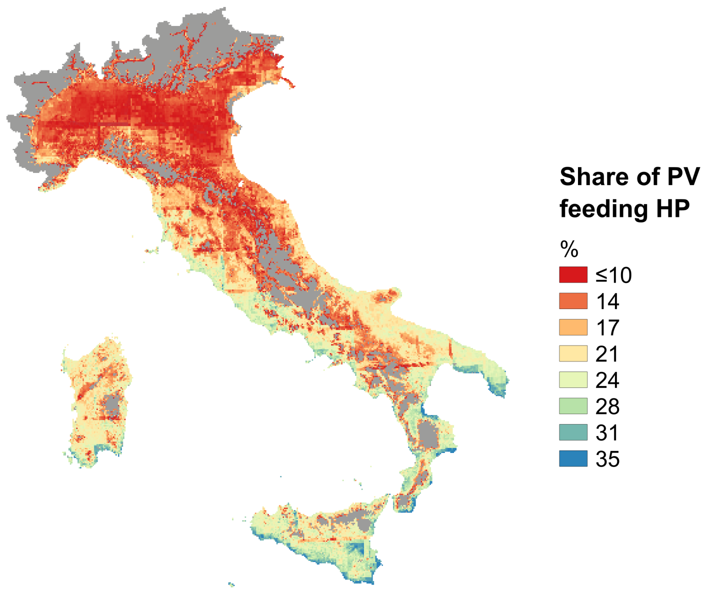

Figure 23: Share of PV production feeding the HP in Scenario B.

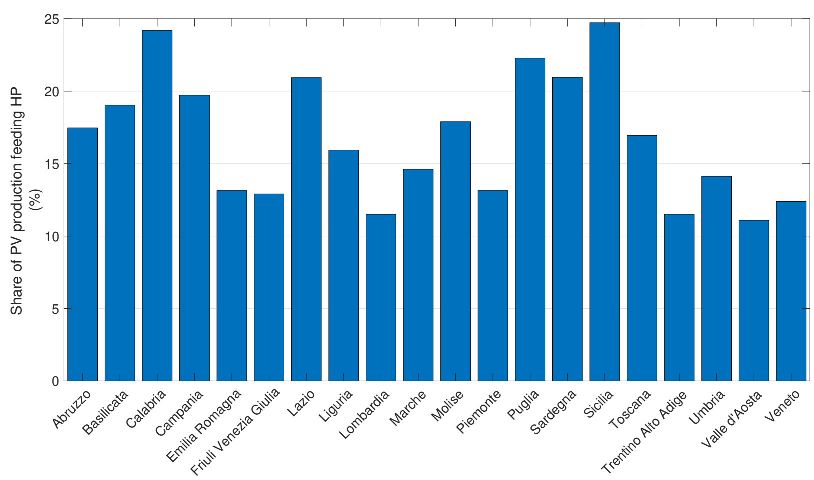

Figure 24: Share of PV production feeding the HP in Scenario B.

firstly the installation of a PV systems to supply the electricity demand of the residential end-users is considered (Scenario A), then the further introduction of a centralised 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 over-sizing and reduce extra-costs.

The analysis were performed by means of spatial data of solar radiation and air temperature in order to estimate both PV production and heating demand on hourly basis. In this context, the analysis were clearly influenced by the location (i.e. the latitude) of the reference building assumed for modeling residential thermal demand. Additionally, the economic analysis takes into account the current Italian regulatory framework promoting the adoption of the collective self-consumption schemes using incentives applied on the shared energy (i.e. on the energy produced by the PV and locally self-consumed within the building) and through tax deduction for the installation costs of PV and HP.

Energy, economic and environmental indicators were then identified to present the main outcomes of the analysis and to spread these results across the whole country (Italy) through GIS tools as valuable support both for policymakers and investors. The economic results highlight as both scenarios under study are profitable, basically because of the incentive schemes on the shared energy and the transferability of tax credit to the firm installing the assets (i.e. PV and HP), so that tax credit can be converted into cash to reduce the investment costs and 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. Conversely, Scenario A is more attractive for southern regions where lower space heating demand does not significantly benefit HP installation.

Energy results pointed out instead how a relatively high level of PV self-consumption can be ensured in most of the cases in both scenarios. Thus, most of the PV production can be locally consumed with lower injection into the distribution grid, but clearly a relevant increase in the electricity demand should be expected for the introduction of HP. Similarly, the environmental indicator highlights how both scenarios are clearly capable to contribute in the decarbonization of the energy consumption in residential buildings. In fact, the installation of RES assets, like the PV and the HP, are surely the way for promoting the energy transition also through the electrification of the heating demand.

Finally, further development of the presented approach can be introduced to improve and overcome potential limitation of the study. In particular, since analysis 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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