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Enhancing PV Self-Consumption through Energy Communities in Heating-Dominated Climates

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Abstract: The European Union, in accordance with its decarbonization objectives, has enacted the Directive (EU) 2018/2001 and subsequently the Directive (EU) 2019/944 that legally recognizes and regulates the formation of citizen energy communities. These are believed to be key enablers for reducing buildings' carbon footprint by allowing for a wider diffusion of on-site renewable energy generation and by maximizing renewable energy self-consumption. In this study, the benefits of the energy community are assessed through simulations of average Italian buildings of various sizes, different energy efficiency levels, equipped with a photovoltaic system and a heat pump-driven heating system, and located in heating-dominated climates. The work focuses on energy communities both at the apartment scale—i.e., in a multi-family building—and at the building scale—i.e., in a neighborhood. The net energy consumption, the self-consumption, and the self-sufficiency of all the possible energy communities obtainable by combining the different buildings are compared to the baseline case that is represented by the absence of energy sharing between independent building units. The energy community alone at both the building-scale and the neighborhood-scale increases self-consumption by up to 5% and reduces net energy consumption by up to 10%. However, when the energy community is combined with other maximization strategies such as demand-side management and rule-based control, self-consumption can be raised by 15%. These results quantify the lower bound of the achievable self-consumption in energy communities, which, in the rush towards climate neutrality, and in light of these results, could be considered among the solutions for rationalizing the energy consumption of buildings.

Keywords: energy community; PV; self-consumption; heat pump

1. Introduction

The decarbonization of the building stock is an important step on the path towards a climate-neutral society. According to the International Energy Agency [1], buildings are responsible for 28% of global CO_2 emissions for energy generation, and, in Europe, residential buildings represent the second-most energy-intensive sector with a 26% share of final energy consumption. The main driver for the reduction of buildings CO_2 emissions is the combination of energy efficiency measures with the electrification of building energy consumption [2–4].

The widely regarded most effective approach to pursue the reduction of CO_2 emissions by electrifying the energy demand of buildings is to combine heat pump-driven systems with photovoltaic (PV) panels [5]. However, there is often a time mismatch between power generation and consumption that could lead to an overload of the electric grid, with consequences on the stability and quality of the service. Moreover, the time mismatch could result in buildings still importing the largest fraction of their energy demand from the grid, with no guarantee of it being renewable. To overcome these issues, strategies must be implemented to maximize the self-consumption (*SC*) of onsite generated energy.

According to Luthander et al. [6], there are two ways to increase SC: energy storage (e.g., batteries or water tanks) and demand-side management (DSM) (e.g., peak shaving and appliance scheduling). Energy storage makes part of the unconsumed generation available when there is no generation or during peak demand. On the other hand, the idea behind DSM is to adapt the load to the supply. Both strategies lead to valuable improvements in SC, with DSM being less effective, as reported by J. Widén (2014) [7].

Lopes et al. [8] have suggested also including the sharing of the produced energy among neighboring buildings in the SC maximization strategies . A neighborhood in which the locally generated energy is shared is known as an energy community. The energy community concept is not new and there are several examples in Europe [9], some of which can be dated back to the beginning of the previous century in response to electricity poverty of unindustrialized areas, such as mountain areas [10]. Energy communities could lead to the achievement of net-zero energy neighborhoods rather than buildings by increasing the self-consumption. Marique et al. [11] and Mittal et al. [12] have highlighted the opportunities of achieving zero-energy consumption by developing a framework for net-zero energy neighborhoods. In an energy consumption scenario analysis involving typical central European neighborhood typologies, Nematchoua et al. (2021) have reported a 90% reduction of actual energy consumption at the neighborhood scale. However, as presented by Abbà et al. [13], the simplest energy community is a multi-family house in which energy sharing among the apartments is permitted.

The European Union recently enacted the European Directives EU 2018/2001 and EU 2019/944 [14,15], with which the energy communities become formally recognized. Italy has started an experimental period, which sparked the realization of energy communities, some of which have been the object of research studies (e.g., [16–18]). In Viti et al. [19], energy communities, in comparison to individual consumers, were demonstrated to achieve not only higher *SC* but also higher profitability. Likewise, Fina et al. [20] have shown that the installation of PV-systems in energy communities brings economic benefits. Some studies have compared different SC maximization strategies, concluding that energy communities offer great potential [18,21]. An early study by Baetens et al. (2012) [22], regarding the electrical limitations to self-consumption in single-family houses, reported an increase in self-consumption of 7% at the neighborhood level.

Although the number of studies on the benefits of energy communities to *SC* is rapidly growing [23], there is no common definition of energy communities in the scientific literature [24] and most of the studies often regard specific cases, consisting mainly of single-family houses. In addition, as highlighted by Caramizaru and Uihlein [25], more research is necessary to clarify and quantify the energy community potential benefits for supporting the EU's climate and energy goals. Among the main obstacles, energy communities face technological issues during implementation [23] and the demand mismatch is one of these [26].

To address these aspects and to generalize the results of the benefits of energy communities on the *SC*, this work performs a preliminary general simulation study, focusing on a generic energy community composed of multi-family buildings equipped with heat pump-driven heating systems and with photovoltaic panels. The buildings are representative of the building typologies of Italian heating-dominated climates. Together with the formation of the community, other *SC* maximization strategies are studied to provide an order of magnitude of the achievable levels of *SC* when each or a combination of these strategies is implemented. Specifically, a control algorithm to maximize self-consumption by storing thermal energy (developed by Pinamonti et al. [27]) and appliance load shifting are considered.

2. Materials and Methods

The impact on the *SC* of forming energy communities is evaluated focusing on typical Italian multi-family buildings in mountain and heating-dominated climates. Two kinds of energy communities can be recognized when multi-family buildings are considered: either

a multi-family house itself acts as an energy community if the sharing of energy occurs among its apartments, or a set of multi-family houses can form an energy community. This work first analyzes the benefits of turning a multi-family house into an energy community, then it broadens the perspective considering energy communities at the neighborhood level. The simulation studies were performed in TRNSYS 2018 with a one-minute time-step and the data analysis was performed in MATLAB.

2.1. Case-Study Buildings

The buildings' geometry characteristics and thermal properties were retrieved from [28], which characterizes the main features of Italian residential buildings. This report categorizes the building according to their location, size, and year of construction. However, the construction characteristics are like to much of the European context as demonstrated by the TABULA project [29].

The selected buildings were respectively the medium condominium (MC) and the large condominium (LC) located in the Italian climatic zone "E" i.e., the zone with heating degree days from 2101 Kd to 3000 Kd. According to the report, the average number of floors and apartments in MC are respectively 3 and 12, whereas LC is generally made of 36 apartments subdivided into 6 floors.

The thermal characteristics were assigned according to the age of the building, considering four envelope quality classes spanning from 1976 to today: class V5 from 1976 to 1990, class V6 from 1990 to 2005, class V7 from 2005 to 2015, and VR after 2015. Class VR also includes all the buildings that were renovated in compliance with the European Energy Performance of Building directive (2010) [30], transposed into the Italian decree 26 June 2015 [31].

The thermal zoning of the buildings subdivided the volume based on the floors and the orientation, splitting the building along the west to the east axis, which resulted in 6 and 12 zones respectively for MC and LC.

Additionally, the single apartments were simulated to evaluate the energy performance of multi-family buildings where each apartment is provided with its heating system. This case represents the actual state of most multi-family houses in Italy. The apartment model was obtained considering the multi-family house volume equally split and simulated by assigning the adiabatic conditions to the adjacent walls of the apartments.

Table 1 presents the geometrical characteristics of the two building typologies considered. Only the glazed surface orientation is reported since the solar gains through walls are negligible. Table 2 presents the thermal properties of the envelope classes.

Table 1. Geometrical characteristics of the typical medium and large Italian multi-family houses and of the apartments composing these buildings. Conditioned volume (V), Floor surface (A_{Floor}), glazed area exposed to south ($A_{w,S}$) and east/west ($A_{w,E-W}$) of the typical medium and large Italian multi-family houses and of the apartments composing these buildings.

Building	# Floors	# Apartments	A_{Floor} (m²)	V (m³)	$A_{w,S}$ (m²)	$A_{w,E-W}$ (m²)
MC	3	12	405.5	3649.5	50.1	37.6
LC	6	36	522.6	9406.5	138.5	103.8

Table 2. Thermal properties of the envelope classes. Heat transfer coefficients of floor (U_{floor}), walls (U_{wall}) and roof (U_{roof}) according to envelope classes.

Envelope Class	U_{floor} (W(m²K))	U_{wall} (W(m²K))	U_{roof} (W(m²K))	Window
V5	1.08	0.78	1.05	Single-pane
V6	0.77	0.62	0.71	Double-pane
V7	0.34	0.34	0.32	Double-glazing
VR	0.24	0.24	0.21	Triple-glazing

2.2. Heating System

Each building and apartment is equipped with the same heating system configuration, which is shown in Figure 1 and consists of an inverter-driven heat pump (HP), a buffer storage (BS) for space heating (SH), and thermal energy storage (TES) for domestic hot water (DHW) preparation.
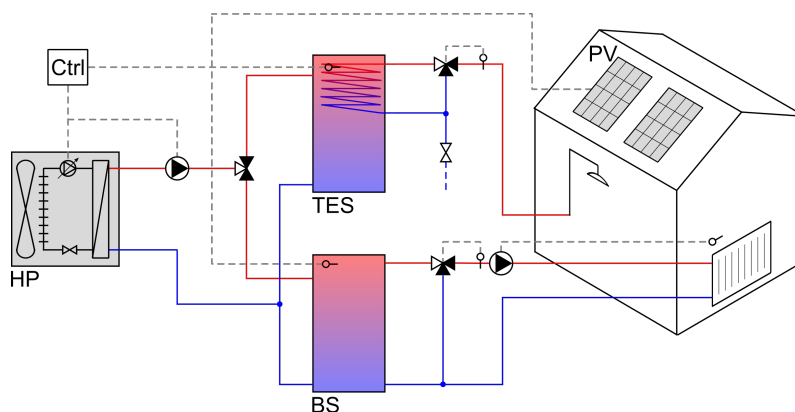
Figure 1. Heating system schematics. BS—buffer storage, TES—thermal energy storage, HP—heat pump.

The DHW is prepared instantaneously via a submerged heat exchanger. Both storage tanks are provided with a double-stage auxiliary electric heater. The terminal units are modeled by *Type 1231* of the TESS library, which models the heat transfer according to the equation

$$\dot{Q} = UA\Delta T^n \tag{1}$$

where U is the heat transfer coefficient of the heating device, A is its area, and ΔT the logarithmic mean temperature of the heating fluid and air temperatures. The exponent n is varied to model either radiators ($n = 1.3$) or radiant panels ($n = 1.1$), depending on the envelope quality class of the building (i.e., radiators for V5 and V6, radiant panels for V7 and VR). The terminal units are fed by the same amount of flow rate, which is bypassed when the temperature set point is reached within the thermal zone. A mixing valve downstream the buffer storage controls the flow temperature to the terminal units, which is particularly useful when not all zones have reached the set point or the buffer storage is loaded at a higher temperature, as explained in the following section.

The buildings are also provided with a PV system installed on the roof. Three levels of roof covering are considered: 50%, 75%, and 100%. The system is made of panels with peak power at nominal operating conditions of $140\,\mathrm{W\,m^{-2}}$, and it assumed to be operated always at the maximum power point, neglecting the losses of the inverter.

2.3. Control Strategy

The control of the system is split into two parts: one controlling the primary loop i.e., the HP, and the other controlling the secondary loop i.e., the terminal units. The first part controls whether the HP needs to be turned on or off according to the temperature level of the storage tanks. As usual, whenever the temperature probe within the TES measures a temperature below the set point of $50\,°\mathrm{C}$, the HP is switched to DHW mode, which consists of running the HP at maximum capacity. The HP in SH mode is controlled based on the BS set point determined by the outdoor temperature reset. Additionally, the working capacity is controlled proportionally to the temperature difference of the BS probe and the set point. The secondary circulation pump is turned on whenever a zone thermostat measures an air temperature lower than the set point. The thermostat implements an on-off control strategy with a centered dead-band of $2\,\mathrm{K}$.

To maximize the *SC* of PV generation, the controller adopts a rule-based control (RBC) strategy for inverter-driven air-to-water heat pumps developed by Pinamonti et al.

(2020) [27]. This control algorithm, shown in the figure, consists of controlling the frequency of the HP such that the load matches the generation. To allow the HP to work, the excess thermal energy is stored in the TES by raising its temperature set point to 60 °C, and in the thermal mass of the building by increasing the indoor temperature set point of 2 K. When the TES is fully charged, the maximum value of the outdoor temperature reset curve is raised by 10 K to allow for energy-storing within the BS as well. Figure 2 shows the control algorithm flow chart. A comprehensive explanation of the RBC strategy is available in Pinamonti et al. [27].
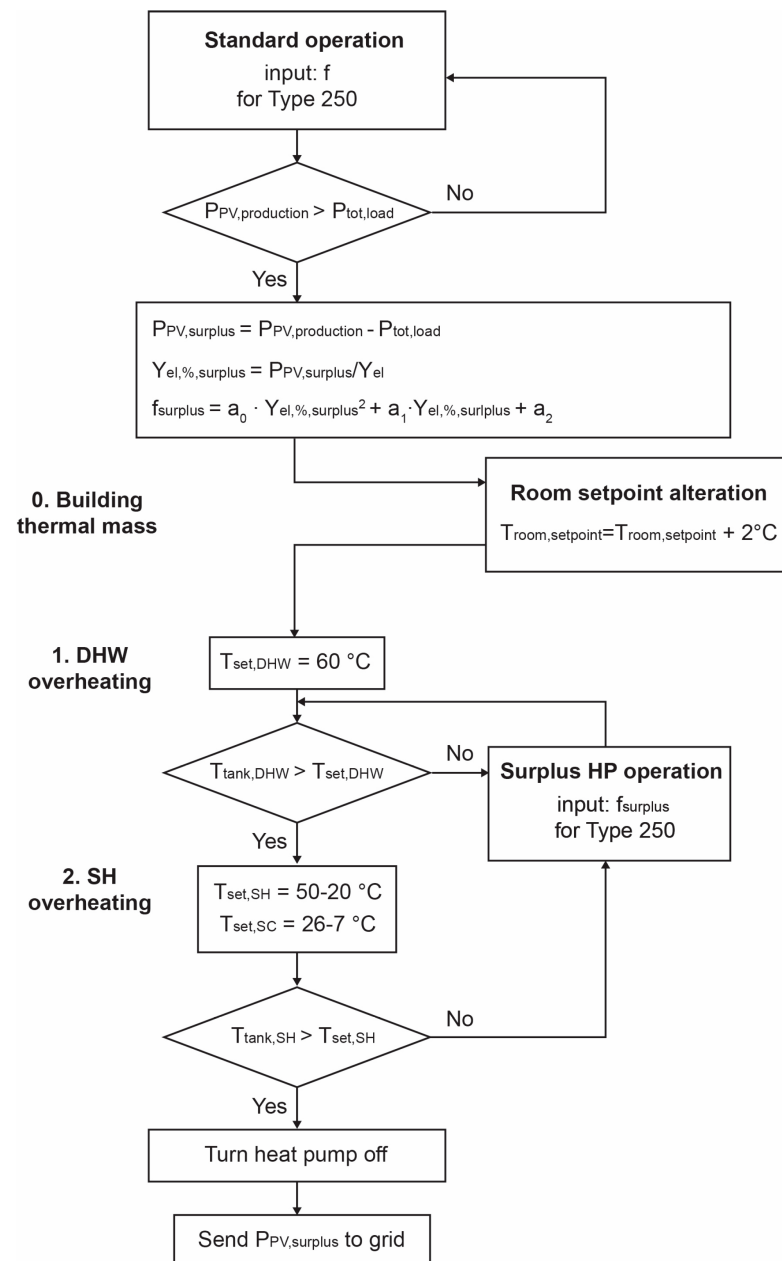

Figure 2. Rule-based control (RBC) strategy, developed by Pinamonti et al. [27], to maximize the self-consumption (*SC*) of the energy generated on-site by photovoltaic (PV) panels.

2.4. Appliance Load Profile

The complete characterization of the electric energy consumption requires the definition of a suitable appliance load profile. For this purpose, the database of monitored annual appliance consumption for residential buildings with a one-minute resolution

provided by Tjaden et al. (2015) [32] was used to generate the load profile. The power consumption profiles in the database were averaged and normalized by the annual energy consumption. Then, in the simulation studies performed for this work, the normalized profile was multiplied by the appliance and lighting energy consumption set to a value of 4 MWh/a per apartment. Figure 3 shows the obtained hourly averaged annual power profile for an apartment. It is interesting to note the decrease of appliances consumption during the summer months, which adds to electric generation-production mismatch of PV panels.
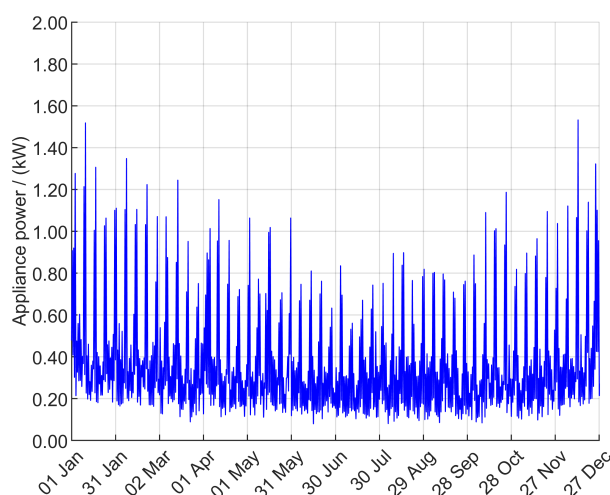
Figure 3. Appliance hourly average load profile for an apartment with annual consumption of 4 MW h, obtained by averaging and normalizing the data provided by Tjaden et al. (2015) [32].

The choice of an average, yet realistic, appliance consumption profile is justified by the purpose of the study. Indeed, the heterogeneous appliance profiles that could be obtained by using stochastic models could lead to better matching of load and PV powers. Thus, a homogeneous profile, representative of average residential consumption, was preferred to provide a lower bound of the achievable levels of *SC* in energy communities.

To evaluate the SC in presence of demand-side management, the appliance power profile was managed assuming to concentrate the power consumption in the central hours of the day, which represents the behavior of smart household appliance connected, for instance, to an energy management system. A baseline consumption of 600 W is subtracted from the profile, in order to identify the peak load. This load is then equally distributed between 10 AM and 3 PM throughout the year. The results of the consumption profile rearrangement for a day in winter are shown in Figure 4.

2.5. Climatic Conditions

The lowest annual *SC* values are expected to be obtained in heating-dominated climates because of the mismatch between peak energy demand of buildings (i.e., in winter) and PV supply (i.e., in summer). Northern Italy encompasses different climatic conditions, ranging from alpine to coastline weathers but, overall, the climate can be considered as heating-dominated. The cities selected as reference climatic conditions were Trento (TN), Belluno (BL), and Padova (PD), which span different levels of heating degree days. According to Koppen classification they are in class *Cfa*, *Dfb*, and *Cfa*, respectively. Moreover, the study included the climate of Strasbourg (SXB) as a reference average European climate classified as *Cfb* according to Koppen (Figure 5). Table 3 reports the annual average air temperature, the design temperature, and the heating degree days of these locations.
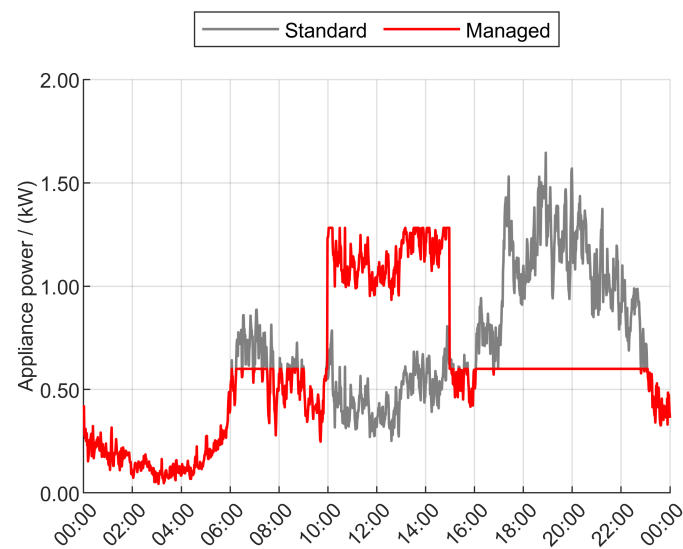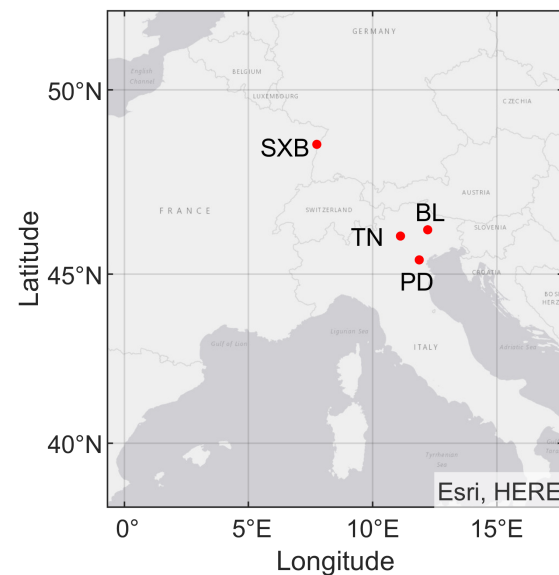
Figure 4. Example of the managed daily appliance load profile for a winter day.

Table 3. Annual average (ϑ_{ave}) and design (ϑ_{des})temperature (°C) and (HDD) heating degree days (°C) and (ASR) annual global solar radiation (kWh/(m²a)) for the studied locations .

Location	ϑ_{ave}	ϑ_{des}	HDD	ASR
(BL)	10.1	−10	3701	1220
(SXB)	10.3	−10	3595	1091
(TN)	12.0	−12	3157	1166
(PD)	13.3	−5	2756	1296

Figure 5. Geographical position of the studied locations.

2.6. The Energy Community

This study focuses on two types of energy communities:

- The multi-family house: Energy sharing taking place among the apartments of the same condominium.
- The neighborhood: Energy sharing taking place among condominiums of the same neighborhood.

Technically, the first kind of community in Italy is known as collective self-consumers. However, for the purpose of the study, there is not a substantial difference between the two options and in the following both will be regarded to as energy communities. The first is also the simplest to implement and could offer greater potential for rationalizing the energy flows within multi-family buildings. Indeed, in Italy, the state-of-the-art in multi-family houses is the decentralized heating system, i.e., each apartment is provided with its heating system, although the best option would be to centralize the heating system.

The neighborhood in this study is built considering all the possible combinations of the analyzed buildings—MC and LC—and envelope qualities, such that the installed PV power does not surpass a threshold value, but neglecting combinations that are too homogeneous (e.g., made of the same building types). The threshold is set according to the Italian law transposing the European directive that, during the experimental phase, is set to 200 kW. The neighborhood was built considering covering 75% of the available roof surface of the buildings and then the 100% and 50% covering of the same neighborhood were assessed. Table 4 reports the composition of the neighborhood together with the number of resulting envelope combinations and the PV power installed for the different roof-covering fractions.

Table 4. The composition of the energy community analyzed together with the number of envelope combinations and PV power installed. .

Community Composition	Installed PV Power (% of Roof Area)	# Combinations
2 × LC + 2 × MC	130 kW (50%) 200 kW (75%) 260 kW (100%)	100

These energy communities were further analyzed considering implementing the previously presented *SC* maximization strategies. Therefore, the obtained scenarios were:

- **Scenario 1**: no implementation of control or load shifting to maximize *SC*.
- **Scenario 2**: RBC strategy presented in the section is implemented.
- **Scenario 3**: load-shifting presented in the section is implemented.
- **Scenario 4**: both RBC and load-shifting are implemented.

These scenarios were all compared to the baseline case, represented by the same type of community (same buildings and envelope qualities) not sharing energy among them and without implementing any maximization strategy.

2.7. Key Performance Indicators

The analysis mainly focuses on net-energy consumption, which is the total energy imported by the buildings during a year, and self-consumption metrics. In the literature there are several metrics quantifying self-consumption. However, as reported in Salom et al. (2011) [33], these metrics can be grouped into two major groups: load-matching and grid interaction indicators. The first group describes the overlap of generation and load profiles, whereas grid interaction targets the unmatched part of these profiles. This study is based on load-matching indicators, specifically, it relies on the metrics adopted also by Luthander et al. (2015) [6]. These are the self-consumption (*SC*), which is the fraction of generated energy that is self-consumed, and self-sufficiency (*SS*), which is the fraction of total energy consumption covered by the onsite generation. These are computed as

$$SC = \frac{W_{SC}}{\int_{t_1}^{t_2} \dot{W}_P dt} = \frac{W_{SC}}{W_P} \tag{2}$$

$$SS = \frac{W_{SC}}{\int_{t_1}^{t_2} \dot{W}_L dt} = \frac{W_{SC}}{W_L} \tag{3}$$

where, $\dot{W}_L$ is the total power consumption, $\dot{W}_P$ is the power generation, and W_{SC} is the self-consumed energy, i.e.,

$$W_{SC} = \int_{t_1}^{t_2} min\{\dot{W}_L(t), \dot{W}_P(t)\}dt \tag{4}$$

In the following, the results report annual *SC*, *SS*, and net-energy consumption, i.e., $W_{net} = W_L - W_{SC}$. By knowing these three quantities, the other two can be determined by

$$W_P = \frac{SS}{SC}\frac{W_{net}}{(1-SS)} \tag{5}$$

$$W_L = \frac{W_{net}}{(1-SS)} \tag{6}$$

As shown by Luthander et al. [34], particularly meaningful is the ratio of *SC* to *SS*, which is

$$\frac{SC}{SS} = \frac{W_P}{W_L} \tag{7}$$

Thus, if both energy generation and total consumption remain unchanged, every measure improving self-consumption will have the same ratio between *SC* and *SS*. On an *SC-SS* chart—known as energy matching chart [34]—this means that a building with a given *SC* and *SS*, after the implementation of, say, load-shifting, all the achievable levels of *SC* and *SS* lies on a line with slope *SC/SS*, unless the load or the generation are changed. The bisector of the quadrant—*SC* = *SS*—represents net-zero energy buildings. Therefore, buildings falling on the left of this line would be net-producer, or plus-energy buildings, whereas those on the right would be net-consumer.

Ideally, both indicators should be maximized, such that the maximum possible amount of generated energy is locally consumed (i.e., maximum *SC*), and this covers the largest possible fraction of total consumption (i.e., maximum *SS*). Depending on the goal, *SC* should be higher than *SS* when the aim is to reduce the burden on the grid, whereas larger self-sufficiency signifies less dependence on the grid.

3. Results

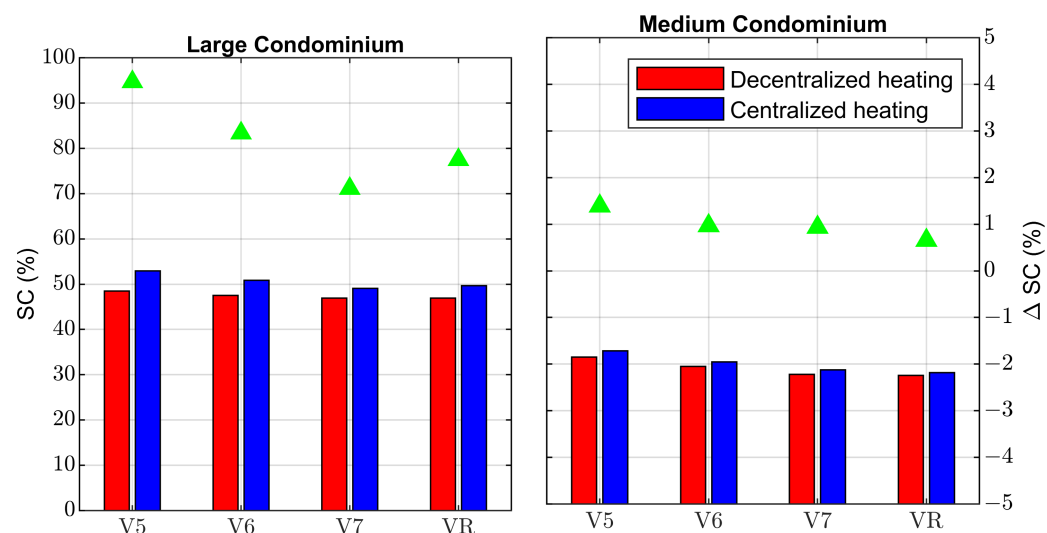### 3.1. Comparison of Decentralized and Centralized System

Figures 6–8 show the comparison of net-energy consumption, self-consumption, and self-sufficiency in multi-family buildings with centralized and decentralized heating systems for Trento, because the other locations showed similar results.
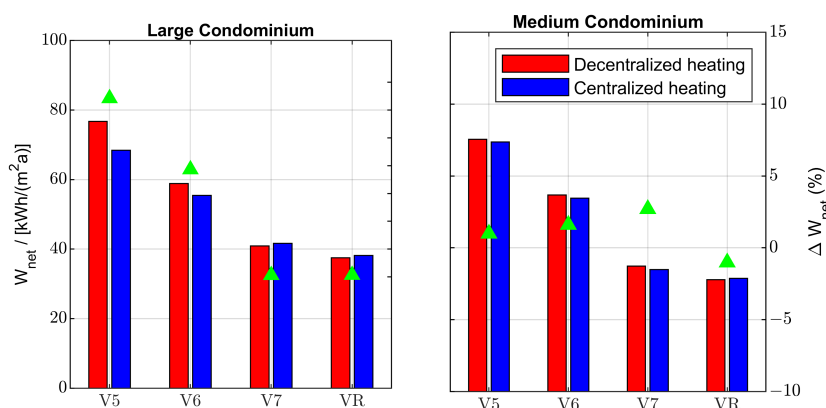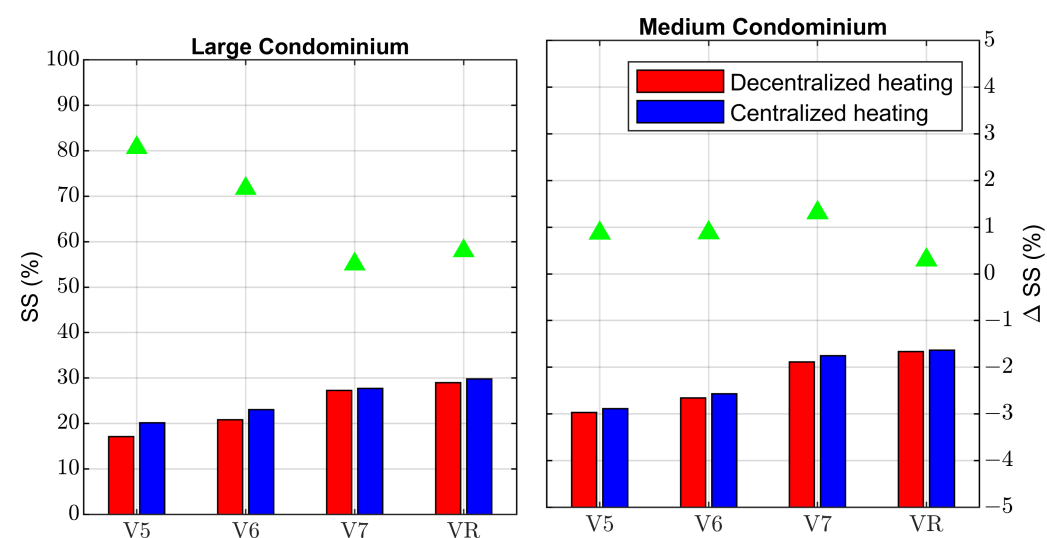

Figure 6. Comparison of net-energy consumption of decentralized and centralized heating system in a large condominium (**left**) and a medium condominium (**right**) for the climate of Trento. ΔW_{net} is highlighted by green triangles and shows the percentage difference of W_{net} between decentralized and centralized heating systems.

A centralized heating system has a positive impact on the net-energy consumption in buildings with low envelope quality according to the results shown in Figure 6. The difference is evident for large condominiums, whereas it is negligible in medium-sized multi-family houses. In a V5 LC, the realization of a centralized heating system with the possibility to share the electric energy generation leads to an improvement of the energy demand of 10%.

A centralized heating system always improves both self-consumption and self-sufficiency. The difference is more significant for buildings with poorer envelope qualities than in newer buildings. Yet the maximum improvements achievable are almost 5% in self-consumption and 3% in self-sufficiency.

Figure 7. Comparison of self-consumption (*SC*) of decentralized and centralized heating system in a large condominium (**left**) and a medium condominium (**right**) for the climate of Trento. Δ*SC* is highlighted by green triangles and shows the percentage difference of *SC* between decentralized and centralized heating systems.

Figure 8. Comparison of self-sufficiency (*SS*) of decentralized and centralized heating system in a large condominium (**left**) and a medium condominium (**right**) for the climate of Trento. Δ*SS* is highlighted by green triangles and shows the percentage difference of *SS* between decentralized and centralized heating systems.

3.2. Comparison of Neighborhood Energy Communities

Table 5 reports a comprehensive overview of the results for all the locations and PV panels roof covering of 75 % for the neighborhood energy communities.

Table 5. Median net energy consumption (W_{net}), self-consumption (*SC*), and self-sufficiency (*SS*) for the locations considered and the scenarios analyzed.

|		Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4
TN	W_{net} [kWh/(m²a)]	72.6	70.2	66.6	66.6	63.9
	SC (%)	40.6	44.4	50.5	50.2	54.7
	SS (%)	26.3	28.8	32.7	32.5	35.4
PD	W_{net} [kWh/(m²a)]	68.8	66.4	63.6	62.2	60.4
	SC (%)	38.1	41.7	46.9	47.7	51.7
	SS (%)	27.7	30.2	33.8	34.5	37.2
BL	W_{net} [kWh/(m²a)]	75.1	72.4	69.0	68.5	66.1
	SC (%)	39.6	43.5	49.4	49.5	54.0
	SS (%)	25.8	28.4	32.1	32.3	35.0
SXB	W_{net} [kWh/(m²a)]	75.3	74.8	72.1	71.7	70.0
	SC (%)	42.5	43.1	48.4	48.3	52.5
	SS (%)	24.2	25.6	28.7	28.7	31.0

The results of the neighborhood energy community for the locations selected with 75% roof surface occupied by PV panels are further represented in Figures 9–11. The net energy consumption, as can be seen in Figure 9, presents a large dispersion around the median value, which is due to the different combination of envelope qualities. Overall, there is no considerable difference among the locations, though Belluno and Strasbourg have larger energy consumption because of the cooler climate. The improvement between the baseline—represented by the same neighborhood of Table 4 without the sharing of energy—and the first scenario is 3% for the Italian cities, whereas it is negligible in Strasbourg as a consequence of the lower PV energy generation. By applying any of the maximization strategies presented in Sections 2.3 and 2.4, the energy consumption decreases by 8% in all the Italian locations and by 4% in Strasbourg. The lowest median net consumption is achieved when all the strategies are applied together, with an average energy savings of 11%.
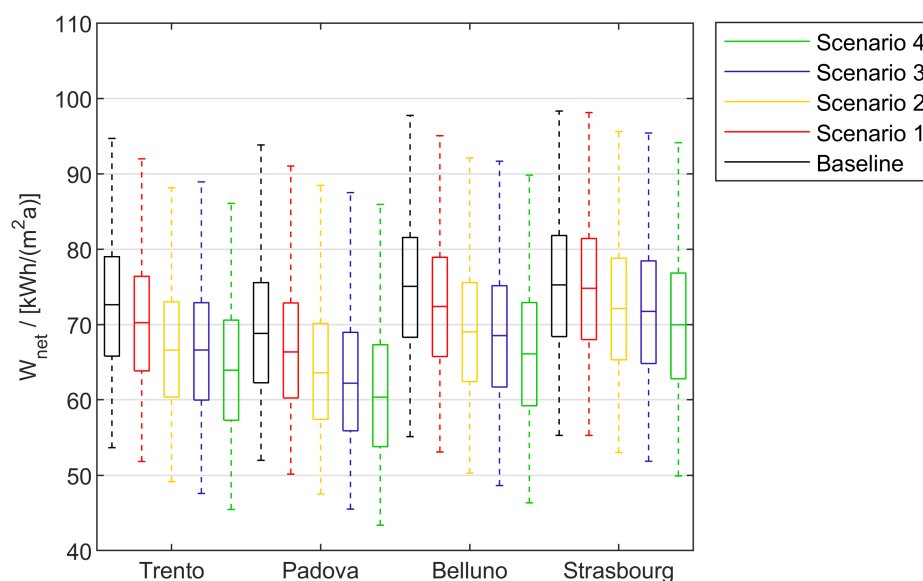
Figure 9. Box plot of the net-energy consumption (W_{net}) for the energy communities in the four locations and with 75% roof coverage by PV panels.

In Figure 10 the self-consumption (*SC*) is shown. The data dispersion is limited, mean-

ing that the envelope quality has a small impact on the achievable values of *SC*. Forming an energy community leads to almost a 5% increase in (*SC*) at the Italian latitudes. Similarly to the net-energy consumption, the maximization strategies lead to an improvement in *SC*, with appliance load profile management being slightly less effective in all the locations, except for Padova.
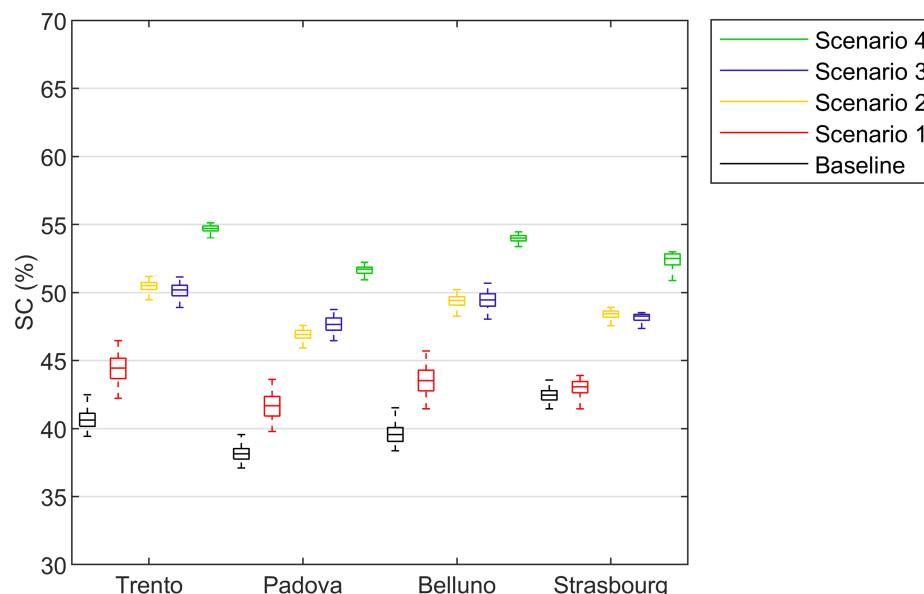
Figure 10. Box plot of the self-consumption (*SC*) for the energy communities in the four locations and with 75% roof coverage by PV panels.

Self-sufficiency (*SS*) presents the same trend as the *SC*. The energy community combined with the maximization strategies improves the self-sufficiency by almost 10%. As previously observed, Strasbourg presents the lowest improvements as a consequence of the lower energy generation.
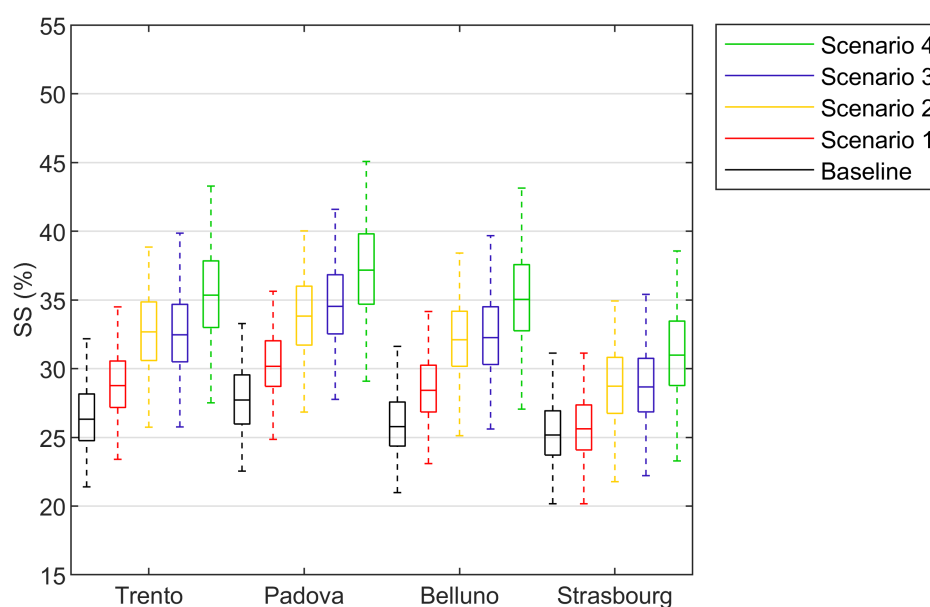
Figure 11. Box plot of the self-sufficiency (*SS*) for the energy communities in the four locations and with 75% roof coverage by PV panels.

A more detailed representation of the results can be seen on the *energy-matching* chart [34] shown in Figure 12 for the energy communities with 75% roof covered by

PV panels and located in Trento, which was chosen coherently with the choice made in Section 3.1 and because its results are more significant than those obtained for Strasbourg. The dispersion of the results is immediately clear and, as observed in Figure 10, the *SC* is tightly concentrated around its median value. The community with the best envelope qualities are located in the upper part of the plot, as shown by the color scale gradient—which represents the net energy consumption—that fades upwards from red to yellow. The Baseline and Scenario 1 cases for increasing SS levels also present slightly decreasing *SC* values. This trend can be inverted by applying the maximization strategies, which allow better insulated buildings to improve both the SC and the SS, with respect to more poorly insulated buildings.
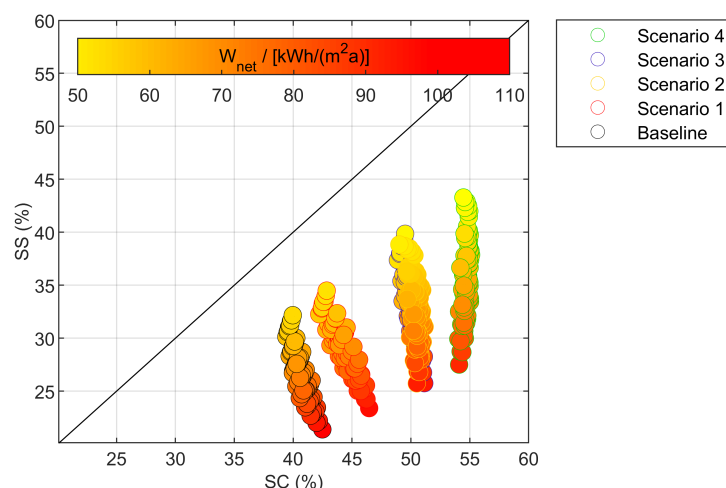
Figure 12. Energy matching chart for the energy communities in Trento and with 75% roof coverage by PV panels.

At 75% PV panel coverage, none of the energy community combinations is a net-zero energy community. As discussed in Section 2.7, unless the total energy consumption or the total energy generation were changed, no SC maximization strategy could make a neighborhood (or a building) that is not already net-zero, or better, become it. However, by increasing the covering to 100%, some communities with the best envelope quantities become even plus-energy communities on an annual balance, as shown in Figure 13. Scenario 4 presents *SS* and *SC* as high as 48%, which means that almost half of the energy generated is consumed onsite, and this self-consumption satisfies half of the energy needs of the community.
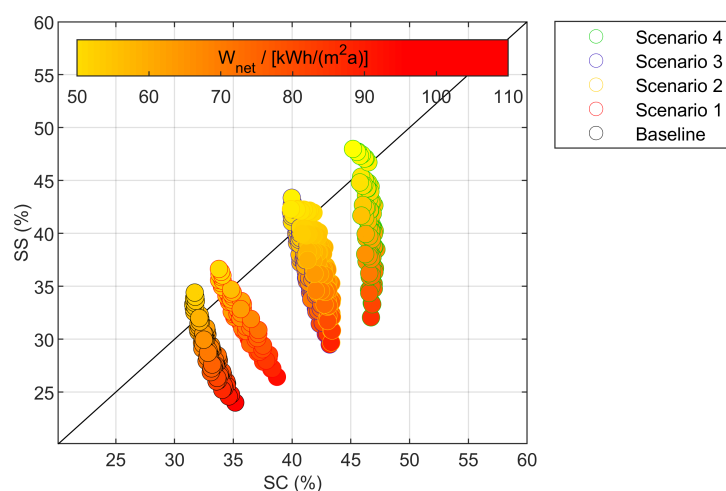
Figure 13. Energy matching chart for the energy communities in Trento and with 100% roof coverage by PV panels.

4. Discussion

The analysis performed in this paper allows assessing the benefits to self-consumption of forming energy communities together with other maximization strategies.

The simplest energy community is represented by the multi-family building. The results presented in Section 3.1 show a marginal improvement in net-energy consumption, particularly for buildings with good envelope qualities. Nevertheless, the energy generation is always rationalized, leading to improvements in both *SC* and *SS*. Furthermore, according to this study, larger buildings with centralized heating system benefits more than medium-sized ones. As a result, switching to a centralized heating system and allowing for the sharing of energy generation might be particularly effective to reduce the consumption of old large condominiums.

An energy community at the neighborhood scale is proven to reduce the energy consumption with respect to the baseline case, albeit by a small amount, especially in locations with lower solar energy availability. However, the benefits are evident when the *SC* and *SS* are considered. Neighborhoods of buildings with low envelope quality could experience the largest improvement in *SC* and *SS*. The implementation of maximization strategies together with the formation of an energy community leads to further improvements in all the metrics considered. Despite the somehow small improvement in net-energy consumption, the exploitation of the onsite energy generation can be improved up to 15% when all the strategies are applied together, leading to an increase in the self-sufficiency of up to 10%. Communities located in climates with lower solar availability—such as Strasbourg—present lower improvements, specifically when only the energy community is formed and no other self-consumption strategies are implemented.

The formation of an energy community alone leads to a marginal reduction of energy needs and an improvement in *SC* and SS metrics that varies between 5% and 3% respectively, both in multi-family houses and in neighborhoods. Nevertheless, the study focused on heating-dominated climates, which is the worst scenario for analyzing the self-consumption of PV energy. Moreover, the standard and invariable appliance load profile makes the energy demand of the buildings or the apartments less heterogeneous, which is also a factor that penalizes self-consumption. Additionally, considering that there is room for system sizing optimization (e.g., PV power based on real needs, storage volumes, etc.), the results presented here can be regarded as the lowest bound of improvements achievable by energy communities. The implementation of DSM and RBC for maximizing self-consumption in energy communities leads to larger improvements. Therefore, energy communities can be considered as an interesting solution for reducing the burden of distributed energy generation on the electricity grid, but it is not the ultimate solution to the problem, and it should be considered together with other strategies.

In this study, electric storage was not considered. From the technical point of view, there is no doubt about its benefits, whereas its contribution should be analyzed from an economical perspective. In general, an approach integrating different technologies and strategies seems to be the right choice, as also presented by Battaglia et al. [5].

Although in a not-so-far future electric vehicles (EVs) will represent a significant load for buildings, considering them in the computation of the achievable levels of self-consumption in energy communities of residential buildings might not be appropriate. Indeed, considering the standard usage of cars, it is unlikely that several vehicles would be connected to residential buildings during the daytime. On the other hand, the load of EVs becomes relevant in energy communities comprising residential office and commercial buildings.

5. Conclusions

This paper contributes to the discussion on the benefits of energy communities to the self-consumption of on-site generated energy from PV panels. The focus is on energy communities located in heating-dominated climates, which represent the most difficult situation for the maximization of PV energy self-consumption. To enable the largest share

of self-consumption the heating system must be electric-driven, hence heat pump-based heating systems. The study focuses on air-to-water heat pumps.

The obtained results quantify the contribution to the self-consumption of energy communities, demand-side management, and RBC control. In multi-family buildings with decentralized heating systems, switching to a centralized heating system and enabling the share of on-site generated energy improves the *SC* and *SS* by almost 5% and 3% respectively. The formation of such a community was particularly effective in poorly insulated large condominiums, enabling also an energy savings of 10%. These results could be further improved by applying RBC, DSM, or both strategies. In general, an energy community at the multi-family building level ensures better levels of *SC* and *SS* that—considering also the financial convenience demonstrated by Abbà et al. (2021) [13]—makes this kind of community attractive and easy to implement.

Communities at the neighborhood level ensure an increase in self-consumption up to 5% at the Italian latitudes. Locations with lower solar availability—such as Strasbourg—are affected by lower energy generation. Combining the formation of the energy communities with DSM and RBC the *SC* can be improved by up to 15% and the *SS* by up to 10%. The energy needs can also be reduced up to 12%.

These results are intended to quantify the lower bound of the achievable self-consumption in energy communities. In an increasingly complex energy system and in the rush towards climate neutrality, there is not a single solution and several alternatives should be combined. According to the results obtained, energy communities are to be considered among the solutions for rationalizing the energy consumption of buildings. By aggregating individual energy demands, communities can offer local flexibility services such as relieving network congestion and avoiding peak withdrawal from the electricity grid. The results of this study can assist local governments in understanding the achievable performance of new energy communities, developing supportive policies, and promoting them to end users.

In future works, commercial and office buildings should be included in the analysis and the presence of electric energy storage should also be considered.

Abbreviations

The following abbreviations are used in this manuscript:

ϑ	Temperature (°C)
A	Surface (m^2)
ASR	Annual global solar radiation on an horizontal plane ($kWh/(m^2 a)$)
ave	Average value
BL	Belluno

ϑ	Temperature (°C)
BS	Buffer storage
des	Design value
DHW	Domestic hot water preparation
DSM	Demand-side management
EV	Electric vehicle
HDD	Heating degree day (°C d)
HP	Heat pump
LC	Large condominium
MC	Medium condominium
PD	Padova
PV	Photovoltaic
Q	Thermal Energy (kWh)
$\dot{Q}$	Thermal Power (kW)
RBC	Rule-based control
SC	Self-consumption
SH	Space heating
SS	Self-sufficiency
SXB	Strasbourg
TES	Thermal energy storage
TN	Trento
U	Heat transfer coefficient (W/(m^{2}a))
V	Conditioned volume (m^3)
W_L	Electricity consumption (kWh)
W_P	Electricity produced on-site (kWh)
W_{SC}	Electricity self-consumed (kWh)
$\dot{W}_L$	Electricity adsorption (kW)
$\dot{W}_P$	PV output (kW)
$\dot{W}_{SC}$	Self-consumed PV power (kW)
w,E-W	East and West oriented windows
w,S	South oriented windows

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