A Comprehensive Energy Management Tool for Renewable Energy Communities: Modeling PV Production, Building Demand, and Shiftable DHW Scenarios

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***Abstract*—Subsidized Renewable Energy Communities (RECs) are perceived as an effective framework to enhance the diffusion of distributed Renewable Energy solutions. This work presents a streamlined model for estimating energy balances within RECs, and applies it to a comparative case study aimed at evaluating the benefits of integrating Domestic Hot Water (DHW) as a fully time-shiftable load. A urban community based in Milan is chosen as reference for the simulations. Simulation results demonstrate that electric production of DHW significantly reduces environmental impact and improves overall community self-consumption. The best results are achieved when DHW demand is fully shiftable and each building is equipped with a storage tank, as this configuration maximizes system flexibility. Finally, a sensitivity analysis, based on varying the ratio of prosumers (i.e., buildings equipped with PV systems) to consumers in the REC, shows that as more photovoltaic capacity is installed, the community becomes better at consuming its own energy locally (higher physical self-consumption). However, this also leads to a reduction in virtual self-consumption, since the surplus energy injected into the grid exceeds what other members can absorb at the same time.**

***Index Terms*—Renewable Energy Communities, Virtual Self-Consumption, Distributed Energy Resources, Energy Modeling, Heat Pumps, PV Systems**

NOMENCLATURE

COP	Coefficient of Performance (of the heat pump)
CSC	Community self-consumption
CSS	Community self-sufficiency
DHW	Domestic Hot Water
KPI	Key Performance Indicator
POD	Point of Delivery (unique identifier for an energy user/producer)
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
REC	Renewable Energy Community
SHGC	Solar Heat Gain Coefficient
TMY	Typical Meteorological Year

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I. INTRODUCTION

The European Union *(EU)* has placed a significant emphasis on Renewable Energy Communities *(REC)* as a way to accelerate the energy transition and meet long-term decarbonization targets. Within the broader legislative package "Clean Energy for All Europeans", the Renewable Energy Directive *(RED II, 2018/2001/EU)* formally recognized RECs as a key instrument to facilitate citizen participation in the energy market, reduce CO_2 emissions, and improve system flexibility. In this framework, a renewable energy community is allowed to generate, consume, store and sell renewable energy at the local level, encouraging a more efficient and equitable use of distributed energy resources.

In Italy, the transposition of RED II Directive paved the way for the introduction of the "Comunità Energetica Rinnovabile" *concept*. National legislation, such as Legislative Decree 199/2021, has defined operational and fiscal guidelines for these communities, while ARERA (the Italian Regulatory Authority for Energy) issued regulations on metering and tariff structures that support share energy models. Under this Italian regulatory framework, RECs receive incentives through a community manager, who is then responsible for distributing the benefits according to an internal sharing mechanism.

By pooling local resources such as as photovoltaic (PV) systems and storage, Italian RECs can foster community self-consumption of generated electricity and reduce the usage of the transmission networks. Moreover, incentive mechanisms (e.g. feed-in tariffs or non-metering arrangements) can further boost local renewable production and promote prosumers, end users who both produce and consume energy.

In Italy, the incentive mechanism is the "Virtual self-consumption", where the withdrawn energy is paid on a retail basis, while the community self-consumed energy, called shared energy, is incentivized at a price set by the national authorities [1] . The share energy incentive currently ranges from €60/MWh to €120/MWh, depending on the system size and the hourly zonal electricity price (Pz), as established by [2]. This corresponds to the economic value assigned to each megawatt-hour that is self-consumed within the community virtually, i.e. by exploiting the distribution network. More precisely, this virtual self-consumption is defined as:

$$\textit{Virt. self-cons}_{REC,t} = \min(En.Injected_t, En.Withdrawn_t) \quad (1)$$

From a technical standpoint, RECs offer an ideal setting to integrate time-shiftable loads (e.g., heat pumps, battery systems, or electric vehicle chargers) that can be scheduled to match local renewable generation profiles. In doing so, they address key grid and market challenges:

- smoothing out consumption/generation peaks by coordinating flexible demands;
- ensuring that local renewables are effectively utilized;
- lowering reliance on fossil-based imports by maximizing community-level self-consumption.

Consequently, subsidized RECs have emerged across Europe, incentivized by national grants or tax deductions to boost local investment in distributed renewable energy sources [3] The final aim is to empower citizens, local authorities and small business activities to jointly produce and share clean energy at lower costs, while reinforcing energy autonomy and grid resilience at the community scale.

In such a context, after performing a literature review, this paper proposes a comprehensive tool to estimate the electrical energy consumption of REC users, by modelling different building archetypes, the production of solar photovoltaic energy and the use of shiftable loads, such as domestic hot water. The approach is then applied to a plausible REC configuration in the Milan urban context. The work flow of this paper is shown in Figure 1

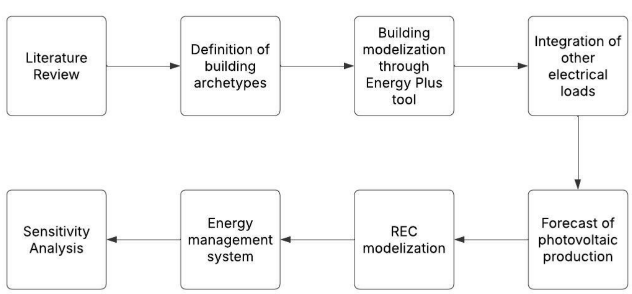


Fig. 1: Work flow chart

II. Literature review

The study of building clusters aimed at promoting efficient and decarbonized energy use is extensive. However, the topic has been approached in various ways. **Vigna et al.** [4] provide a review of different methodologies for analyzing building clusters, along with a set of indicators to measure energy flexibility, defined as the capacity to respond to external factors to maximize the use of renewable energy sources (RES) and minimize CO_2 emissions.

Moghaddam et al. [5] present a mixed-integer nonlinear programming model for scheduling operations within an energy hub, where the goal is to meet the daily cooling, heating, and electricity demands of a hypothetical building while maximizing profit (i.e., surplus energy sales minus energy consumption costs). Their numerical results show that cogeneration operational points and average electrical and thermal efficiency vary significantly between hot and cold days. Additionally, the use of electric heat pumps has a significant effect on meeting heating and cooling loads.

Additionally, the operation and optimization of Renewable Energy Communities (RECs) depend on the legal framework in which they operate. **Taromboli et al.** [6] conducted a quantitative comparison of the impact of different subsidy schemes on energy cost minimization, distinguishing between a virtual scheme (Italy) and a physical scheme (Portugal). Their findings indicate that different regulatory approaches significantly affect energy-sharing strategies and the financial benefits of RECs, emphasizing the role of policy design in optimizing community energy management.

Minuto and Lanzini [1] explore various sharing mechanism algorithms, considering both financing services and self-consumption benefits provided by community members. Their results show that members with low energy demand and poor synchronization with renewable generation benefit more from equal-sharing algorithms, whereas high-energy consumers who are well-synchronized with renewable output gain more from contribution-based mechanisms.

For the portion of energy demand that cannot be met with on-site production, the concept of a community-based Power Purchase Agreement (PPA) has been introduced. **Saari and Vimpari** [7] present a case study in Helsinki to quantify the economic benefits of households participating in such agreements. They found that community PPAs can significantly lower energy costs for participating households.

III. Methodology

The objective of this work is to estimate the electrical energy consumption of REC users, assess the power generated by solar PV systems within the community, model the usage of shiftable loads, such as domestic hot water production through heat pumps, and finally estimate some KPIs.

a) ***Software framework:*** A comprehensive Python-based code framework has been developed to integrate realistic building archetypes simulation for energy demand estimation (heating & cooling, electrical appliances, domestic hot water), compute photovoltaic energy generation and distinguish between Physical and Virtual self-consumption for each REC member, identified by their Point of Deliver (POD) within the distribution network. DHW demand can be either satisfied with natural gas or electricity to evaluate the different impact on the overall CO_2 emissions and on the self-consumption of the community. The tool takes as inputs :

- the REC location
- the number of PODs (e.g. number of REC members)
- DHW management strategy

and for every POD:

- POD type among 6 building archetypes
- m^2 of walkable area
- number of occupants
- m^2 of installed PV panels
- Azimuth and tilt angle of installed PV system

It produces the energy balances of the single PODs and of the REC as output.

Starting from a single-POD analysis, the tool generates the consumption and PV production patterns according to the above-mentioned inputs and merges the two datasets into a unified hourly energy balance. Next, it applies the chosen DHW scheduling method according to the selected scenario to compute Virtual and Physical self-consumption, energy surplus and energy exchanges.

Finally, the tool performs a sensitivity analysis, varying the share of prosumers over the consumers members to assess the impact of key performance indicators.

*b) **Modeling of Building Archetypes' Energy demand**:* The heating and cooling energy demand for predefined building archetypes is estimated using Best Energy — a tool developed at Politecnico di Milano that integrates the EnergyPlus simulation engine [8] with the SketchUp design software. The input parameters include the purpose of the building and typical construction materials properties.

The modeled building archetypes are the following:

- Detached house (old building, non-retrofitted)
- Detached house (new or retrofitted)
- Offices (old building, non-retrofitted)
- Offices (new or retrofitted)
- Condominium (old building, non-retrofitted)
- Condominium (new or retrofitted)

The parameters used for the different buildings are summarized in Table I.

Simulations were conducted for a version of each archetype to obtain a yearly profile of the specific electric heating and cooling demand on a hourly basis in [Wh/m^2], considering a mean value of the COP of the heat pump equal to 3.

These 6 archetypes are then categorized as prosumers (i.e. producing and consuming energy at the same time) or simple consumers. The prosumers buildings are equipped with PV panels with different possible orientations (South, East or West) to optimize energy production and smoothen the energy generation profile. In total, this leads to the definition of 36 types of PODs, each of which characterized by a unique energy demand and production profile.

*c) **Modeling of PV Production**:* Solar PV production was calculated based on the methodology described in Principles of Solar Engineering by Goswami [9], using the system's location, tilt (assumed of 30°) and azimuth as inputs.

Solar time, solar declination, altitude and azimuth angles were determined using the open-access library *pvlib* [10]. The solar radiation incident on a tilted surface was computed as the sum of beam radiation, sky diffuse radiation, and ground-reflected radiation. These values were derived from data processed into a Typical Meteorological Year (TMY) via PVGIS. [11]

Additionally, efficiency losses due to temperature and irradiation were incorporated into the calculations based on standard PV coefficients. [12] Data from three possible different locations are currently implemented in the tool: Milan, Rome and Palermo.

Taking into account the chosen orientation angles and the limited availability of the building's roof surface, it is assumed that the total installed PV surface is 30% of the total ground area covered by the building [13]. In the case of multi-level buildings, such as offices and condominiums, the installed PV surface is assumed to be 6% of the total walkable area, under the hypothesis of an average of 5 floors per building.

*d) **Modeling of DHW management system and scenarios**:* Demand is estimated to be 50 [l/day/person] for residential buildings (i.e. detached houses, condominiums) and 5 [l/day/person] for offices. The occupancy rate of the buildings is assumed to be 1 person per 25 [m^2] of walkable area, both for residential and commercial buildings. It is assumed that each POD/user has the option to heat domestic hot water using either a heat pump or a gas boiler, respectively with an efficiency of 3 and 0,9.

Three different scenarios are proposed to evaluate the impact on the community self-consumption and CO_2 emissions when DHW is considered to be a completely shiftable load. In the first scenario ("Gas"), DHW energy demand is fully covered by natural gas ignoring the possible availability of energy surplus within the community. In the second scenario ("Heat Pump"), demand is instantaneously satisfied through a heat pump, either using self-produced electricity (if available) or withdrawing energy from the grid. DHW consumption is assumed to have a standardized behaviour, varying for residential and commercial buildings as reported below:

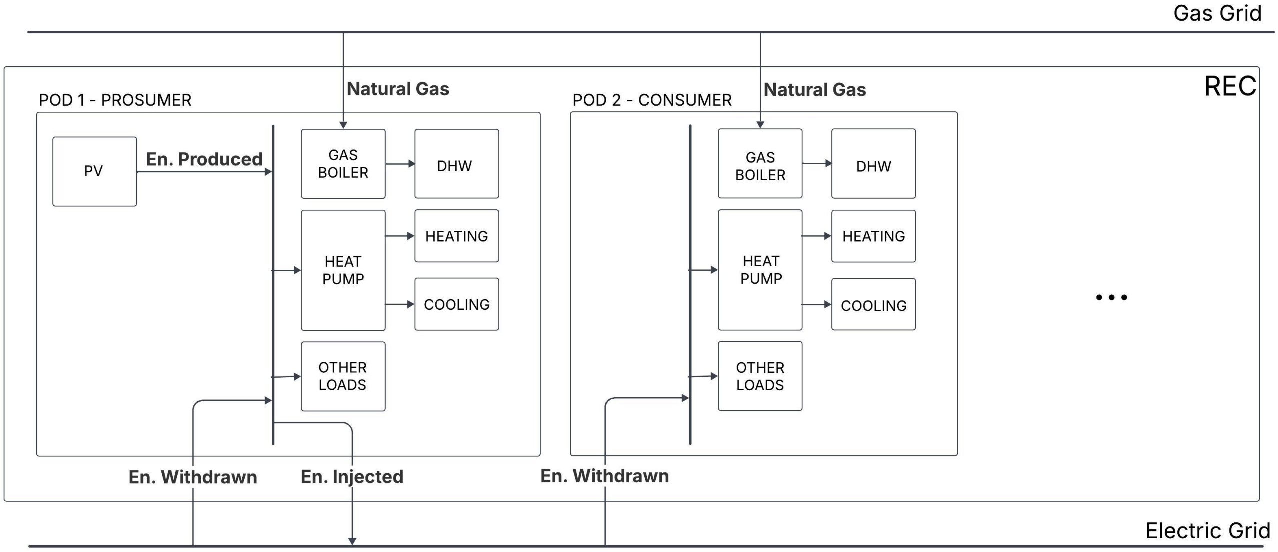
For residential buildings:

- 20% DHW demand between 6 a.m. and 9 a.m.
- 25% DHW demand between 10 a.m. and 6 p.m.
- 55% DHW demand between 7 p.m and 12 a.m.

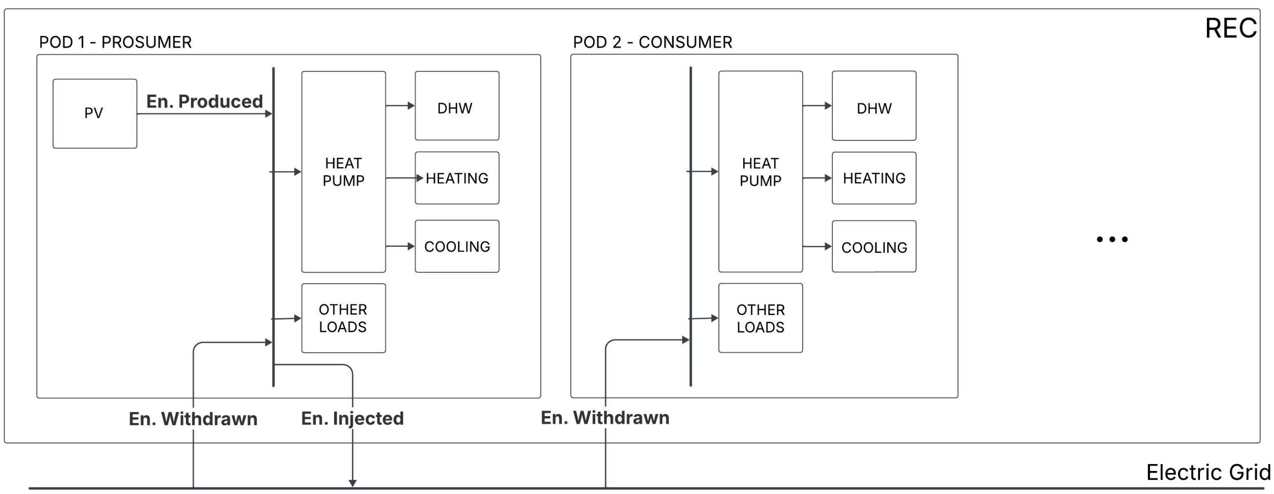
For commercial buildings:

- 100% DHW demand between 8 a.m. and 7 p.m.

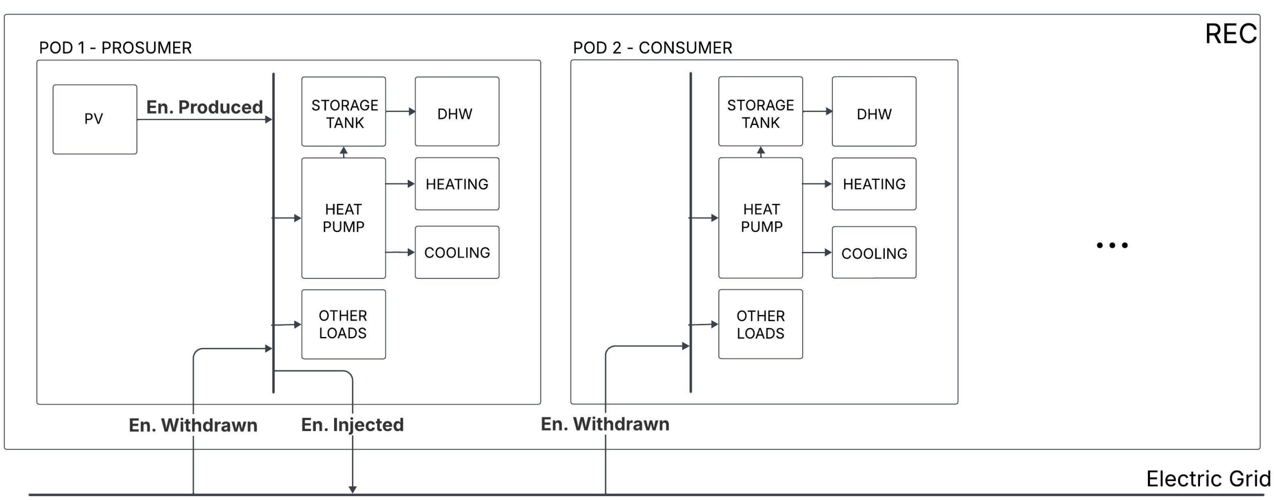
In the third scenario ("Heat-storage"), DHW demand is considered to be completely shiftable to maximize community self-consumption. Each building is provided with an autonomous storage tank and DHW is heated by a heat pump and stored whenever there is a surplus of energy within the community. The tank is dimensioned to store the entire daily DHW demand of the building plus an additional 30% to partially compensate for the unreliability of the sun. Everyday, the demand for DHW is preferably satisfied by the storage tank, relying only on the grid electricity in case of need.



Energy flows of the PODs inside a REC – DHW produced with gas boilers



Energy flows of the PODs inside a REC – DHW produced with fixed-schedule heat pumps



Energy flows of the PODs inside a REC – DHW produced with tank-equipped smart Heat pumps

Fig. 2: Comparison of DHW scenarios in the REC.

TABLE I: Parameters for thermal model of building archetypes

Parameter	**Detached House (Old)**	**Detached House (New)**	**Offices (Old)**	**Offices (New)**	**Condo (Old)**	**Condo (New)**
Wall transmittance [W/m^2K]	1.00	0.23	1.00	0.23	1.00	0.23
Window transmittance [W/m^2K]	3.00	1.40	3.00	1.40	3.00	1.40
Window-to-wall ratio [-]	0.20	0.20	0.30	0.50	0.20	0.20
SHGC [-]	0.70	0.35	0.70	0.35	0.70	0.35

Figure 2 shows the energy flows of the PODs inside a REC, respectively for the Gas, Heat-pump, and Heat-storage scenario. The community relies on the gas grid only in the Gas scenario, while a full electric configuration is assumed in the other two cases. Moreover, in the Heat-storage scenario, a DHW storage tank is provided to better exploit the flexible consumption of the community.

e) ***REC performance evaluation****:* The application of the tool allows to compare virtual self-consumption, defined as the energy consumed by the PODs while the total energy surplus of the community is positive (Equation 1) and physical self-consumption, defined as the energy consumed by the same POD that produced it. For each POD:

$$Physical\ Self-cons_{POD,t} = \min(En.Injected_t, En.Withdrawn_t) \tag{2}$$

Physical self-consumption is not a subsidized flux, but is linked to the avoided cost of electricity purchase.

To describe the performance of the REC the following KPIs are proposed:

$$\text{CSC} = \frac{Physical\ selfc. + Virtual\ selfc.}{Energy\ Produced} \tag{3}$$

$$\text{CSS} = \frac{Physical\ selfc. + Virtual\ selfc.}{Energy\ Consumed} \tag{4}$$

$$\text{Carbon intensity} = \frac{CO_2\ emissions}{Energy\ Consumed\ (incl.DHW)} \tag{5}$$

where, in the Gas scenario:

$$\begin{aligned} CO_2\ emiss = CO_{2,gas} + \\ (Energy\ Consumed_{(excl.DHW)} - Physical\ selfc. \\ -Virtual\ selfc.) * C.Intensity_{grid} \end{aligned} \tag{6}$$

Natural gas is assumed equivalent to CH_4 with a lower heating value of 50 [MJ/kg].

In the other two scenarios:

$$\begin{aligned} CO_2\ emiss = \\ (Energy\ Consumed_{(incl.DHW)} - Physical\ selfc. \\ -Virtual\ selfc.) * C.Intensity_{grid} \end{aligned} \tag{7}$$

TABLE II: REC Composition by Building Type and Age

Age	**Type**	**sqm**	**%**
New	Detached House	3260	7%
Old	Detached House	3815	8%
New	Condominium	6000	13%
Old	Condominium	16400	35%
New	Offices	7800	17%
Old	Offices	9300	20%

and the Carbon Intensity of the electricity of the grid was considered equal to $257.2 g/kWh$ [14].

IV. Results and discussion

The plausible community that is the object of this case-study is characterised by the composition of archetypes shown in Table II, and joins 60 PODs, 36 of which are prosumers, in Milan.

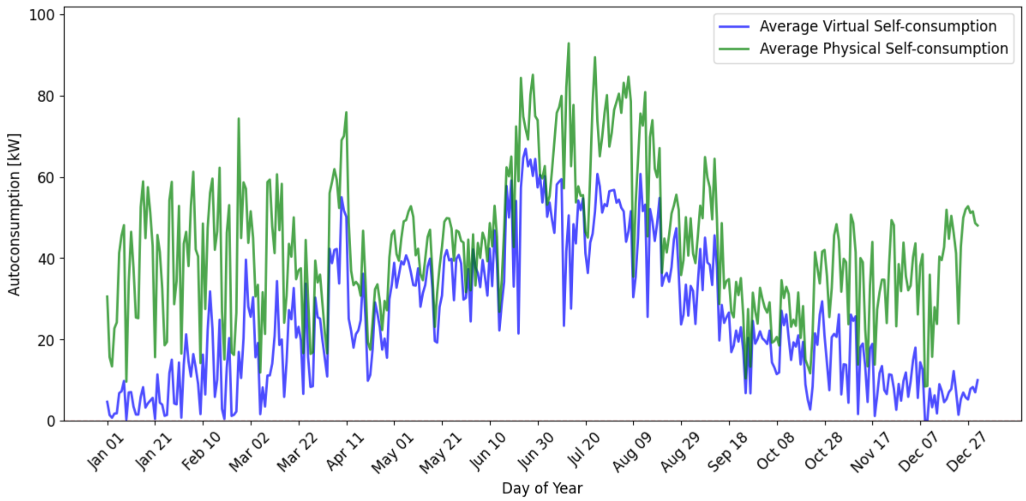
Following the hypothesis presented in the Methodology section, this REC is modelled to have 2740 m^2 of installed solar panels, evenly distributed among facing South, East and West.

With the model proposed it is possible to calculate the energy balances of each POD and therefore estimate the yearly profiles of the Virtual self-consumption and the Physical self-consumption of the REC. Figure 3 represents the daily-averaged profiles of Physical and Virtual self-consumption, respectively in the Gas, the Heat-pump and the Heat-storage scenarios. In all three cases, virtual self-consumption presents a more accentuated seasonal profile than Physical self-consumption. This implies that the revenue streams (subsidies) of the REC will also be seasonal.

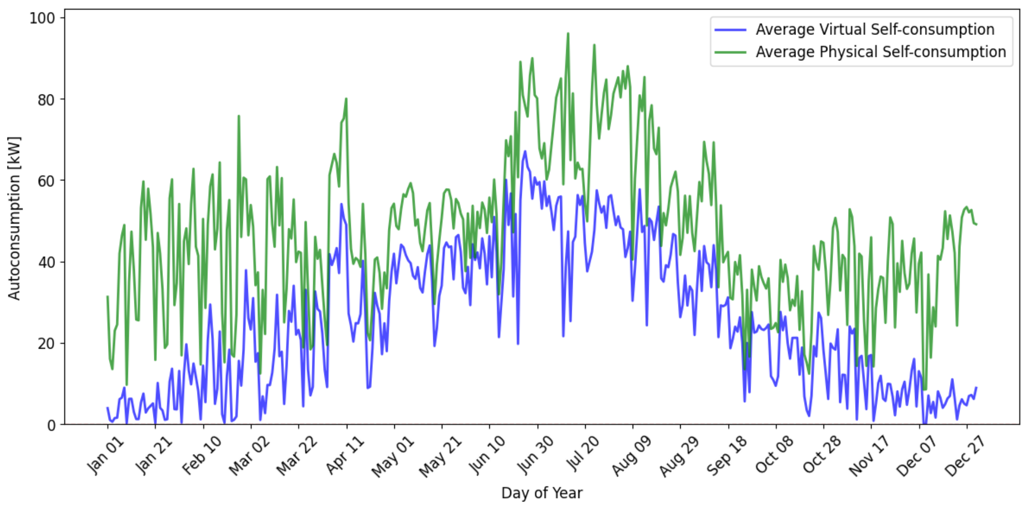
The total yearly energy exchanges and the performance of the REC are shown in Table III. The introduction of shiftable DHW has the following impact: physical self-consumption is increased while virtual self-consumption is decreased with respect to the Gas scenario.

In the Heat-pump scenario, around one-tenth of the DHW demand is satisfied by locally-produced energy, while in the Heat-storage scenario around one-third.

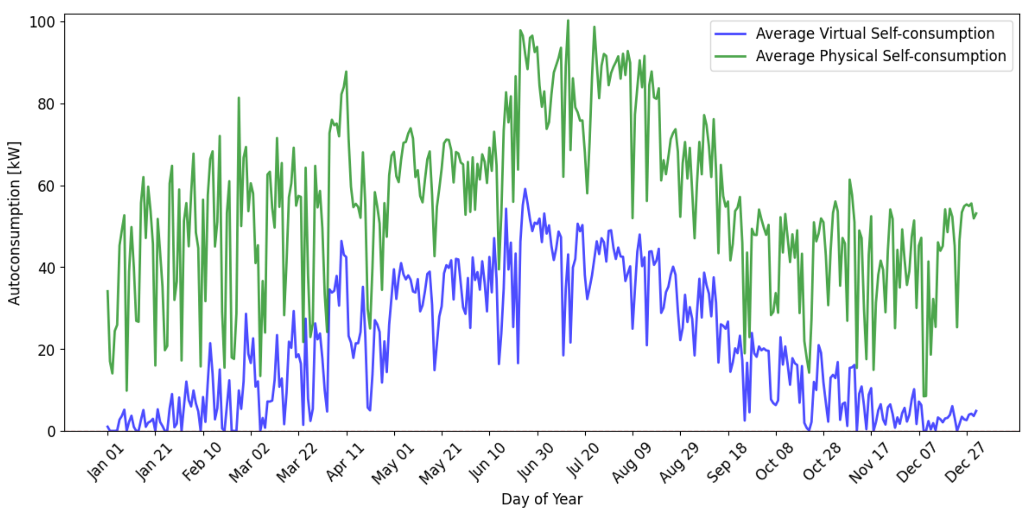
The overall impact of the introduction of DHW produced by the heat pumps on the REC KPIs is notably positive with respect to the Gas case. The energy injected in the grid is reduced because it is locally consumed (Physical self-consumption is increased). A further improvement can be achieved moving from the Heat-pump to the Heat-storage scenario, where the community self-consumption increases of



REC self-consumption profiles (daily averaged), Gas scenario



REC self-consumption profiles (daily averaged), Heat-pump scenario



Self-consumption profiles (daily averaged), Heat-storage scenario

Fig. 3: REC self-consumption profiles under different DHW scenarios.

TABLE III: Simulation results

REC Energy Flux	Gas	Heat-pump	Heat-storage	Unit
Gas for DHW	1537.5	0.00	0.00	MWh_{th}
CO_2 emissions	1228.1	910.1	881.9	tons
DHW self-produced	0.00	35.6	109.6	MWh
DHW electric demand	0.00	310.1	310.1	MWh
Virtual Self-consumption	221.0	221.7	182.4	MWh
Physical Self-consumption	381.0	415.9	490.6	MWh
Energy Injected	370.2	335.3	260.6	MWh
Energy Produced	751.2	751.2	751.2	MWh
Energy Withdrawn	3210.3	3485.5	3410.8	MWh
E. Consumed (excl. DHW)	3591.3	3591.3	3591.3	MWh
KPI				
Community self-consumption	80.14%	84.87%	89.59%	-
Community self-sufficiency	16.76%	16.34%	17.25%	-
Carbon intensity	314.79	233.26	226.05	$g(CO_2)/kWh$

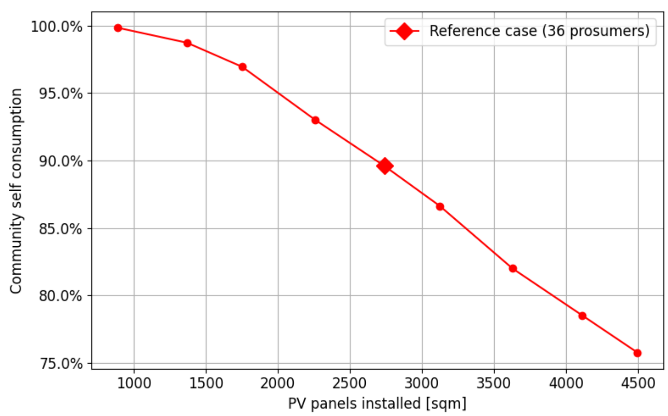


Fig. 4: Sensitivity analysis of CSC varying the number of prosumers

an additional 35 MWh thanks to the higher flexibility of the system.

On the other hand, the low CSS values in all scenarios are due to two main factors:

- only a fraction of the buildings are retrofitted
- a low PV penetration was assumed due to non-optimised roof layouts.

Finally, a sensitivity analysis on the number of prosumers in the REC is performed. The share of prosumers over consumers in the community is gradually varied, keeping unchanged the building share composition of the urban context (Table II) to assess the impact on Physical and Virtual self-consumption. Starting from the reference case of 36 prosumers, where PV panels cover 2740 sqm, Figure 4, Figure 5 and Figure 6 show respectively the variation in the community self-consumption, self-sufficiency and in the amount of energy shared within the REC under the Heat-storage scenario.

In Figure 4 a lower photovoltaic capacity maximizes the self-consumption due to the disparity between energy demand and energy production. Hence, all the energy generated by the REC is immediately used to satisfy the community demand. On the contrary, when the installed photovoltaic capacity arises, the energy generated by the REC exceeds its instantaneous requirements and is partially sent back to the grid instead of being locally consumed.

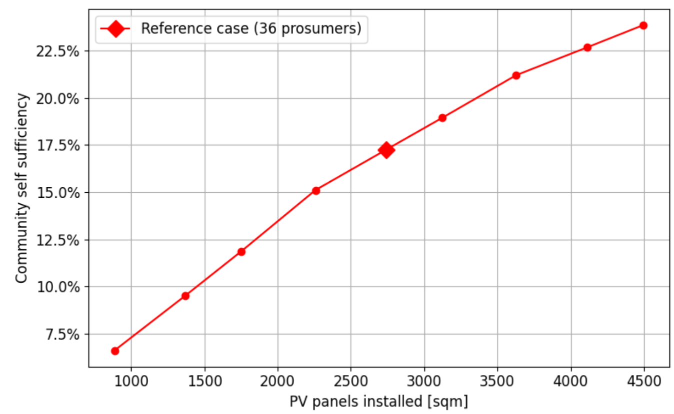


Fig. 5: Sensitivity analysis of CSS varying the number of prosumers

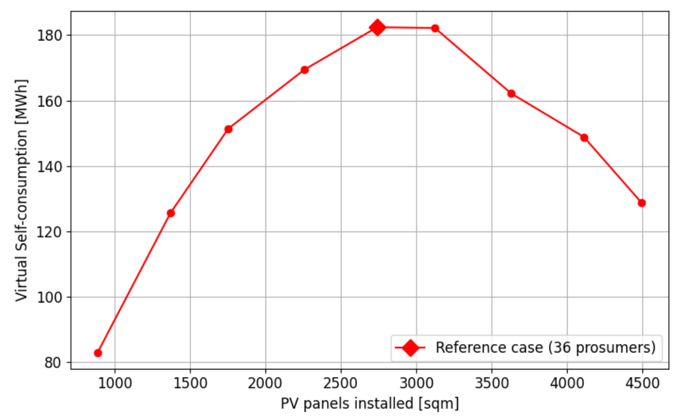


Fig. 6: Sensitivity analysis of the community Virtual self-consumption

Being aware that the physical self-consumption of the community increases according to the amount of installed PV panels, it is important to notice that the same relations are not valid for the virtual self-consumption. As a matter of fact, even if the rise of photovoltaic production increases the community energetic independence and lowers the amount of energy withdrawn from the grid (Figure 5), the amount of energy injected back into the grid globally increases and the virtual self-consumption (Equation 1) faces a peak when the installed PV capacity covers 70% of the maximum available surface, as shown in Figure 6.

V. Conclusion

Renewable Energy Communities can play a key role in urban decarbonization, fostering the deployment of renewable energy sources and decentralized energy production. However, the modeling and forecasting of performance and effective grid integration are crucial to assess the techno-economic feasibility of RECs and support the widespread adoption of energy communities in the market. A tool has been developed to estimate the energy production and demand of the community based on the composition of the urban context, geographical location, and available surface for photovoltaic installation. Energy management strategies are defined in the tool to maximize grid independence and energy self-consumption. In this paper, a case study of a likely renewable energy community in Milan is presented, comparing three different technical configurations where different solutions to produce DHW are evaluated. The Gas scenario, in which the DHW demand is exclusively covered by natural gas, shows the highest environmental impact and the lowest community self-consumption, due to the limited utilization of photovoltaic energy. The Heat-pump scenario proposes a full electric configuration for the community, whose energy demand is either covered by self-produced energy (if available) or withdrawing energy from the electric grid, and shows significant improvements with respect to the Gas scenario in terms of CO_2 emissions (-26%) and community self-consumption (+4.73%). However, the best results are achieved in the Heat-storage scenario, where DHW is considered a shiftable load and coupled with a storage tank in order to maximize the community self-consumption (-28% CO_2, +9.45% CSC, with respect to the Gas scenario). Finally, a sensitivity analysis is performed on the Heat-storage scenario to assess the influence of different shares of prosumers and consumers on the community performances. The sensitivity analysis reveals that a higher installed photovoltaic capacity leads to higher energy self-consumption in terms of absolute value, but also to a lower self-consumption ratio and to the reduction of Virtual self-consumption within the community, requiring a deeper economic analysis to assess which configuration performs better.

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