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Design and Modeling Renewable Energy Communities: A Case Study in Cagliari (Italy)

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ABSTRACT

Renewable energy communities (RECs) are non-profit organizations made up of members who join to produce and exchange clean energy for sustainable development. This work analyzes different REC scenarios, considering energetic, economic, and environmental perspectives. The case study is a typical condominium of eight apartments with a low energy class in Cagliari (Italy). This study considers the condominium with different energy efficiency levels before and after retrofit interventions together with solar technologies to produce energy. Future scenarios include both the share of energy between the eight apartments within the condominium and a REC composed of two neighboring condominiums. At condominium scale, results showed better outcomes in aggregating the energy share from the PV generation into a single point of sharing (PoS). In the REC scenario with a neighboring building, and after retrofit interventions, the self-sufficiency index was increased by 26% with a decrease of 23% in GHG emissions, which shows the importance of having retrofitted and smart buildings boosting the renewable energy sources in achieving a more sustainable built environment. The methodology of this work with a new software can be a useful decision-making tool to test the effectiveness of RECs and it can be applied to building, neighborhood, or district scales.

1. INTRODUCTION

In the last decades, European countries shifted towards decentralized energy generation, a crucial step for enhancing the diffusion from centralized power systems to smaller-scale distributed systems. The distributed energy and on-site generation reduce the transportation costs and losses since the production is close to the consumption. This in turn has both environmental and economic benefits. It also has social benefits since it involves small-scale producers, providing new employment and small-scale businesses. This action was strengthened with the Clean Energy for all Europeans Package [1] underlying its benefits concerning energy independence, environmental and economic perspectives. The aim is to achieve the energy independence of territories, reducing consumption and exploiting all the renewable energy sources available locally too. The European Union (EU) has a target by 2030 of reaching the 32.5% of energy savings (Energy Efficiency Directive, 2018 [2]) and the 40% of Renewable Energy Sources (Renewable Energy Directive II, [3]).

These policies shift towards decentralized energy generation led to the active involvement of citizens, public, and private entities in this practice, which allowed their inclusion in local communities. The Energy Communities (ECs) assumed a significant role over the last years, proposing new opportunities for stakeholders to be involved as actors in the energy transition. The ECs could also become one of the urban planning practices to solve energy, social and environmental problems. In literature, the meaning of energy community differs slightly [4]: Local (LEC), Citizen (CEC), and Renewable Energy Community (REC).

In 2022, Javadi et al. presented a trading model which allows the prosumers to share their surplus energy generation in a local energy community through a conceptual model, following a rule-based market, both to limit the power injection and to reduce the peak power procurement from the main network [5]. The results showed a cost reduction of 16.63% for the small-scale scenario and 21.38% for the second scenario. The study shows the importance of a coordination structure between the end-users and their consumption patterns in the local energy communities.

In 2021, Mutani et al. presented a place-based methodology that evaluates the hourly energy consumption of 5 different end-users [6]. The analysis takes into account solar energy production, assesses different energy profiles and optimizes the energy demand and supply. A flexible tool was developed to be adaptable to REC at different scales. Amar et al. in 2021 presented an experimental investigation on Solar Water Heaters (SWH) in southern Algeria. The study includes the daily performance of SWH in different time periods. The aim is to encourage rural families to use solar energy for domestic hot water (DHW) production by providing solar collectors manufactured with local materials [7]. Kherbiche et al. in 2021 determine the suitable technology in collecting solar energy for electricity production from the available technologies in the current market [8]. The evaluation is based on daily temperature and daily solar irradiation data in north Algeria.

In 2021, Laouni et al. analyzed the development of a building material through an experimental campaign by manufacturing two material prototypes of small scales that aim to improve thermal comfort and decrease the energy demand for space cooling during summer [9]. The results showed a decrease in indoor air temperature, which in turn reduced the energy demand for space cooling. Together with the building materials, the energy consumption of buildings depends on other variables: surface-to-volume ratio, period of construction, inhabitants/m^3. Using these variables, Mutani et al. in 2021 define a place-based bottom-up model, for evaluating the spatial distribution of energy consumption at an urban scale using existing municipal data and considering the actual characteristics of each building [10].

Battery storage systems play an important role in the energy transition by optimizing the use of renewable sources that are, for the most part, discontinuous in energy production. The high costs and the environmental impact of batteries are still a big hurdle in the energy shift, especially for small-sized enterprises. Paul et al. in 2021 provide business models for battery storage to succeed in their market by explaining the different types of batteries since battery chemistry plays a crucial role in deciding the costs [11].

This work aims to test the effectiveness of Renewable Energy Communities (RECs) through modeling and testing different scenarios in a real case study. The analyzed scenarios of energy sharing between the members of a REC were simulated with new software to evaluate the effectiveness of a REC. This work is an ongoing research project which also involves other case studies and the development of new software. The paper is developed with the presentation of the case study in section 2, giving the general overview and the building status quo. It is followed by explaining the methods and the materials used in section 3. The results of the tested scenarios are given in section 4, followed by a conclusion discussing the outcomes and the possible developing assumptions.

2. CASE STUDY

The case study analyzed in this work is one of the five pilot sites of the research project LIGHTNESS in Cagliari, Italy (Figure 1). This pilot site focuses, first, on building-scale analysis and the energy sharing between the common uses and the eight apartments; then, more residential condominiums were analyzed to create a district-scale energy community optimizing the energy production by RES and the energy sharing between members of the community.

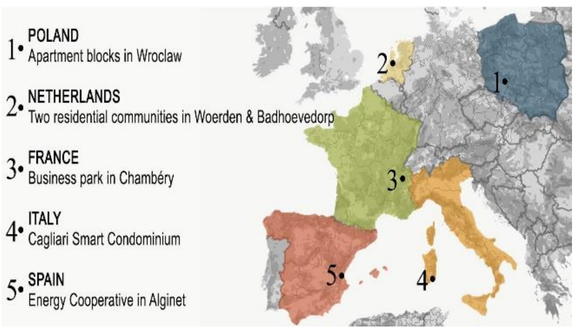


Figure 1. Case studies in the LIGHTNESS research project

2.1 General overview

The pilot site is a condominium located in Cagliari, the capital city of Sardinia and the most populous municipality on the Italian island (Figures 1 and 3). The energy balance of fossil fuels and renewable sources among the total final energy consumption in Sardinia for 2019 is [12]: 0.8% solid fuels, 58.3% Petroleum, 15.4% renewable sources, 0.1% non-renewable wastes, 0.8% derived heat, 24.6% electric energy. The civil sector accounts for 38% of the total energy consumption in Sardinia and 61% of total electricity consumption.

Considering the year 2019, the reference year for this analysis, the population of the Metropolitan City of Cagliari (17 municipalities) was 422,840, with a population for the municipality of Cagliari of 151,005 inhabitants (according to www.tuttitalia.it).

Cagliari has hot summers and windy mild winters, with an average annual air temperature in 2019 of 17.5°C. The hottest month was July, with an average temperature of 25.8°C, and the coldest was January, with an average air temperature of 9°C. In Italy, there are six climate zones for space heating: A, B, C, D, E, F (A warmest, F coldest). Cagliari is the C climate zone with:

- Heating season: from November 15th till March 31st with the heating system turned on for about 6-10 h/day;
- Heating Degree Days (HDD): 1584 at 20°C and 1240 at 18°C (the highest HDD, the more space heating demand);
- Cooling Degree Days (CDD): 123 at 26°C and 62 at 28°C).

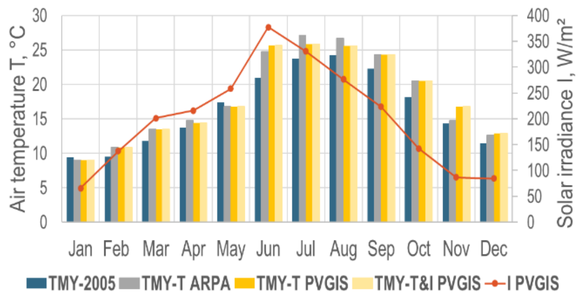


Figure 2. Weather data: Average air temperatures and solar irradiances comparison

The first weather file used for the model simulation was an hourly Typical Meteorological Year related to 2005 (TMY-2005) from Energy Plus database. The average data of daily and monthly air temperatures were not complying with the available climate data related to 2019 recorded by ARPA Sardinia (Regional Agency for the Protection of the Environment). Then, some adjustments were made to the TMY to achieve the average monthly air temperature in 2019 (TMY-T_{ARPA} in Figure 2). The TMY-2005 was also corrected using the PVGIS hourly weather data related to 2019 (TMY-T_{PVGIS} in Figure 2). Finally, the TMY-2005 was further corrected by adjusting both air temperature and solar radiation with PVGIS 2019 data (TMY-T&I_{PVGIS} in Figure 2). In Figure 2, it is possible to observe the monthly differences in air temperatures and solar irradiance with the different weather data. Following the model validation, which is explained in section 4.1, the weather file with the corrected air temperatures and solar irradiance (i.e., TMY-T&I_{PVGIS}) from PVGIS 2019 database showed the closest results with the available energy bills.

2.2 Building's status quo

The building, which is located in the Bonaria neighborhood (Figure 3), is a typical Italian district with condominiums built in 1966 consisting of eight apartments distributed on four floors. The buildings were built before the first Italian law on energy savings (i.e., Law 373/1976) without thermal insulation but with more recent double glasses windows. The vertical opaque structure (exterior and staircase walls) is made of sandstone bricks; a traditional local construction material.

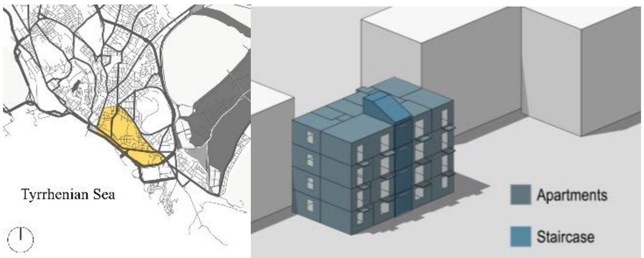


Figure 3. Bonaria neighborhood in Cagliari with a typical condominium with 2 apartments per floor (IES-VE model viewer)

Each apartment has an individual electric heat pump for space heating and cooling, and an electrical boiler for domestic hot water production, DHW (except for apartments 3 and 5). The current energy class of all apartments is G (the worst) and was calculated with IES-VE software (in Figure 3); this result is mainly due to the lack of thermal insulation (except for apartment 6 which has some envelope components with low thermal insulation).

The characteristics of this residential building are described in Table 1 with the types of: opaque and transparent envelope components, technological systems, and users (in the actual scenario). For privacy reasons, the users' description has been omitted in this work and only the number of family members has been indicated; in the model, however, the profile of use for the inhabitants was taken into account considering mainly their age, working activity and habits. IES-iVN was used to simulate a REC between two residential buildings (in Figure 4).

The simulation result of the energy performance of the apartments (before the retrofit intervention) is given in Figure 5. Apartment 7 shows the highest consumption during the whole year, which is explained by the number of users, occupation hours, and location (last floor with a low insulated roof). Apartments 3 and 5 show lower electricity consumption compared to the rest due to the absence of technological systems for space heating, space cooling, and DHW. Apartment 8 shows high consumption during the heating season, even though it has a single-member family and gas boiler for DHW production and low space cooling, this could be explained by its position: north oriented and located on the last floor with a low thermal insulated roof.

Figure 4. The analyzed condominiums for scenario 3 (IES-iVN 3D model view)

Table 1. Apartments' characteristics (actual pre-retrofit scenario)

Apt.	Heating/Cooling system	DWH system	No. of users
1	Air to air heat pump	Electrical boiler	1
2	Air to air heat pump	Electrical boiler	1
3	No installed system		3
4	Air to air heat pump	Electrical boiler	1
5	No installed system		1
6	Air to air heat pump	Natural gas boiler	1
7	Air to air heat pump	Electrical boiler	4
8	Air to air heat pump	Natural gas boiler	1
Roof	Layers (outside to inside): • 0.4 cm rubber floor • 4 cm expanded polyurethane • 8 cm perlite and vermiculite • 0.5 cm bitumen for waterproofing • 4 cm concrete mortar • 16 cm reinforced cement concrete (RCC) slab • 1.5 cm gypsum board		
Walls	Layers (outside to inside): • 2 cm plaster • 40 cm sandstone bricks • 5 cm thermal insulation panel (only for apt. 6) • 2 cm plaster		
Windows	**Apt 1:** double glasses, wooden frames with metallic roller window shutters **Apt 2:** double glasses, wooden frames with wooden roller window shutters **Apt 3-4-7:** double glasses, PVC frames with metallic roller window shutters **Apt 5:** double glasses, 2 wooden frames, 2 PVC frames, 1 aluminum frame for the closed veranda with metallic roller window shutters **Apt 6:** double glasses, PVC frames for all rooms except for the closed veranda which has aluminum frames with metallic roller window shutters		

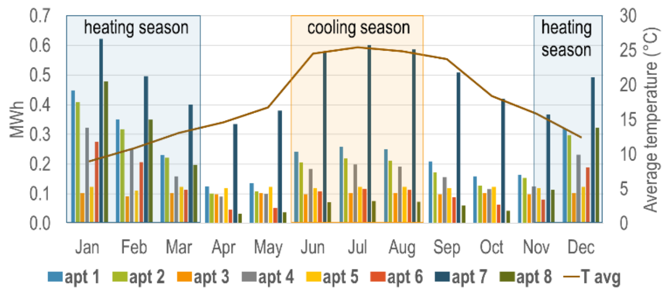


Figure 5. Electricity consumptions per apartment (actual pre-retrofit scenario) in 2019

3. MATERIALS AND METHODS

The methodology of this work was supported by a literature review, applied examples, and in force policies. This analysis was based on an energy audit methodology that starts with analyzing the hourly/monthly consumption profiles of the eight apartments, which will be the members of the energy sharing scenarios within the condominium and between condominiums in the energy community (EC).

The model was verified by comparing the results of energy consumption with the monthly bills; then, the verified model was used for the retrofit scenarios changing the characteristics of the envelope components and technological systems and, finally, for the energy sharing scenarios. The description of this methodology is illustrated in Figure 6.

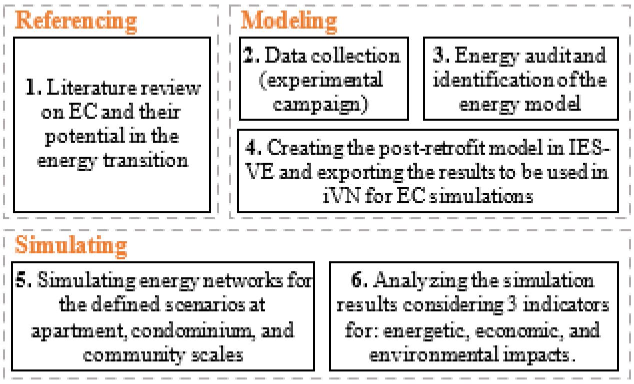


Figure 6. Methodology flow-chart

3.1 Data sources

The data used for modeling the energy performance of buildings are on-site collected data by the company R2M (coordinator of the Italian pilot site). The available electricity bills of four apartments were used to verify the model; this verification was implemented following the energy audit methodology described in the European EN 16247-2:2014 and the Italian UNI CEI/TR 11428:2011 standards. To calculate the energy performance of the apartments the IES-VE software was used, and some adjustments were identified on the input data to reduce the errors and absolute relative errors between calculated and measured energy consumptions.

The aim of the energy audit was to identify the energy consumption/production model for the apartments and then apply the model to find the more effective retrofit interventions from an economic and environmental point of view. All information were used to describe the real use of each apartment and to measure the level of energy efficiency for every energy service within the apartments considering only the electricity consumption.

3.2 New energy modeling tools: From apartment to condominium and community scales

This research project involves some tests on a new software about energy sharing between members of a community. The new software was intended to analyze energy performance both at building and community scales and to describe the energy sharing between users in an energy community (EC) or within a condominium.

The tool used to simulate and analyze the energy performance of a building was IES-VE (Integrated Environmental Solutions – Virtual Environment). VE was used to model the building using detailed input concerning energy consumption (e.g.: building characteristics, space heating/cooling systems, user profiles, internal heat gains, DHW consumption). The obtained simulation results were compared with the available bills and after some adjustments about envelopes and technological elements and family behavior; the model was verified following the energy audit methodology described in the standard EN 16247-2:2014 and UNI CEI/TR 11428:2011, as explained previously.

The simulation data of the verified model were exported using iSCAN (Intelligent Control and Analysis) to be used afterward with iVN (Intelligent Virtual Network) for modeling the energy networks between the eight users/apartments (at condominium scale) and between neighboring users/buildings (within an energy community).

iVN is a new software still under development that was used to create the energy networks between users, to evaluate the energy sharing between users, and the technical-economic feasibility of some scenarios of energy community with an hourly timestep.

Figure 7 illustrates briefly the steps taken for the energy modeling of this work with the different software.

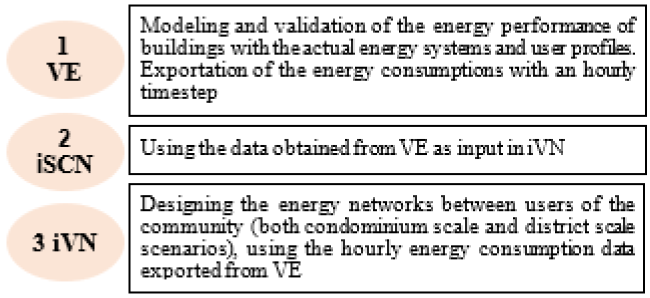


Figure 7. Software workflow

VE has a user-friendly fast interface, and this makes it possible to model a detailed building. Both VE and iVN have short simulation time compared to the detailed inputs used in the modeling, and it is possible to choose the appropriate simulation timesteps for the analysis. The results can be viewed and exported with varied plotting options (e.g., charts, graphs, tables, data).

VE tool can be helpful not only for evaluating the energy performance of a building or the share of energy between buildings but as a decision-making tool for various end-users:

- Policy makers to define economic incentives and energy-climate targets;
- Citizens for dimensioning the more efficient renewable energy systems considering the energy demand of users, buildings or communities;
- Municipalities to check the reachable requirement for greenhouse gas (GHG) emissions to reduce environmental impacts of energy production considering all constraints at the territorial level.

The data used for modeling the building are both on-site collected data and data acquired from related references. The input data used for the model in VE are:

- Climate hourly data (for 2019 year)
- Energy consumption monthly data: for types of energy service, energy system and operating hours.
- People occupancy data: user profiles.

The available data regarding the above-mentioned inputs are adapted to be used in VE as described below:

- Climate data:

Weather file: the weather file used for the model validation is related to 2019, the year in which the electricity bills were available. Due to the absence of hourly weather data for 2019, a reference TMY file from PVGIS related to 2019 was used. The hourly data of this file was adapted to meet the average daily air temperature and solar radiation available from ARPA Sardegna for the 2019 year. This step is taken to use the closest weather data for the intended year (2019), which helped in achieving realistic results compared to the available reference bills for energy consumption.

After the model verification for 2019, TMY weather data from EnergyPlus tool was used too for simulating EC scenarios in iVN. The TMY data are related to a long period of several years which makes the analysis more adaptive compared to simulations considering a specific year; about Italian weather data, Energy plus TMY-2005 is quite old but still is widely used.

- Energy production data:

Type of systems: the characteristics of the system were evaluated after a site inspection and by photographic material and technical data sheets. The space heating/cooling and DHW systems are the main focus points for energy consumption in this work (Table 1). In the simulations, the apartments which have missing data about the installed heating/cooling and DHW systems are considered to have the same system as the other apartments with available data.

- Energy consumption data:

Energy consumption: This data was verified with the reference annual consumption trends in Sardinia, which are: 2659.7 kWh_{el}/inhabitant/year (for the year 2018) and 5940.3 kWh_{el}/family/year (for the year 2017). The reference for the electricity consumption is taken from the available energy monthly bills of 4 apartments in 2019 (i.e., apartments 1, 6, 7, and 8). The other 4 apartments are considered to be within the average consumption in Sardinia. However, the verified model showed close results both to the available bills and average consumption reference.

User profiles: the number of users in each apartment available from the on-site survey is assigned to the related apartments (in Table 1). The occupation hours follow a realistic profile considering the type of work performed by the individuals. The DHW demand input follows the average range of 35–88 l/day/person found in the literature [13, 14] (in Italy, this range is 50-70 l/day/person). The mentioned variables were adjusted until the simulation results had similar values to the energy bills considering the monthly consumption trends.

Operating system: The space heating system was assigned to be turned on according to the climatic classification of Cagliari: about 6-10 h/day during November 15th-March 31st (according to the Italian heating seasons, Decree DPR 412/1993). The regulation control system for heating is set for all apartments to be switched on between 7-9am / 12am-2pm / 6-10 pm, with a setpoint degree of 20℃ and setback degree of 16℃: the heating system will operate to reach 20℃ inside the rooms in ON hours and will be triggered to switch on again during the OFF hours when the room temperature drops below 16℃.

Finally, the output data analyzed in this work were hourly timesteps considering the annual energy consumption for each analyzed apartment.

3.3 Result indicators

The hourly results of the analyzed scenarios were used to evaluate the hourly energy consumption, production and sharing and to calculate the following 3 annual indicators as the sum of hourly data:

- Energy performance indicators:

SCI= ∑(*SC*+*CSC*)/ ∑*TP*
SSI= ∑(*SC*+*CSC*)/ ∑*TC*

where:

SCI (Self-Consumption Index): the share of locally self-consumed energy out of the total energy production by RES.

SSI (Self-Sufficiency Index): the share of locally self-consumed energy out of the total energy consumption.

SC (Self-Consumption): instantly self-consumed energy.

CSC (Collective Self-Consumption): the share of energy that is exchanged among the renewable energy community members, which is the minimum between energy fed into the grid (Over-Production, *OP*) and the minimum between energy withdrawn from the grid (Uncovered Demand, *UD*) by all members in each hour: *min (OP:UD)*.

TC and *TP* are the total consumption and total production.

These indicators were evaluated for every hour of the year, for each typical summer and winter day, and considering each member of the REC and all members together of the community.

- Economic benefits:

The Net Present Value (NPV) was used to determine the economic benefits of the various scenarios, considering the time value of the money. It includes the positive cash flows (benefits due to energy savings and incentives), negative cash flows (costs due to energy consumptions) and considers the period of the incentives of 20 years. In general, each user has different energy withdrawal and injection costs. The economic incentive on the energy exchanged for the members, on the other hand, is the same.

The NPV was calculated for each scenario:

$$NPV = \sum_{t=0}^{N} \frac{R_t}{(1+r)^t} \tag{1}$$

where: R_t is the sum of the relevant cash flows or net cash flow (i.e., cash inflow – cash outflow), at time t, N is the number of considered years, t is the time of cash flow, r is the discount rate (e.g., 2%).

The investment costs used for the economic calculation are provided in Table 2. These costs can consider the presence of "Ecobonus 50%" incentive too: a tax reduction of 50% for the first 10 years which applies both for the costs of the installed PV and battery system. The payback time of each analyzed scenario is provided in section 4.3 both with and without the presence of "Ecobonus 50%" incentive, to emphasize the importance of government policies in supporting these investments.

Table 2. Investment costs used for retrofitted scenarios [15]

PV cost (6≤kWp≤20)	1600 €/kWp
Battery investment cost	500 €/kWh
Battery replacement cost	250 €/kWh
Battery lifetime	10 years

About retrofit interventions on the opaque and transparent envelope components, the costs were not considered in this work because of an excessive increase in the material costs, so this retrofit intervention was postponed.

The economic incentives for energy sharing provided by the Italian MISE Decree 09/2020 are reported in Table 3 and can be applied to 2 configurations of energy sharing considering the energy produced by the RES plants within a condominium (C) and between members of a REC connected to the same electric substation MV-LV. The energy fed into the National grid is paid on the basis of Italian zonal prices and considering the incentives with a reimbursement given for the missing distribution losses (MDL) and a premium on the energy exchanged between users (EEU).

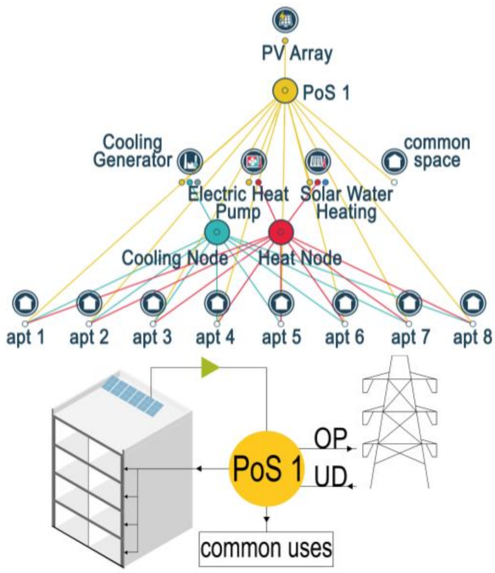
- Environmental impact:

The annual greenhouse gas emissions (GHG, measured in $CO_{2,eq}$) were calculated for each scenario, considering the GHG emissions intensity (gCO_{2e}/kWh) of electricity production in Italian country [16].

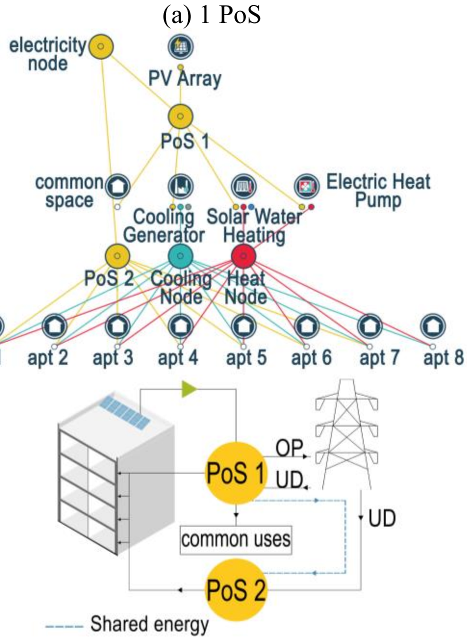
Table 3. Economic incentives about typologies of energy sharing

	Injection prices (Sardinia zonal prices)	Reimbursement on MDL	Premium on EED
C	https://www.gse.it/servizi-per-te/fotovoltaico/ritiro-dedicato/documenti (in Italian)	9.56 €/MWh	100 €/MWh
REC		8.22 €/MWh	110 €/MWh

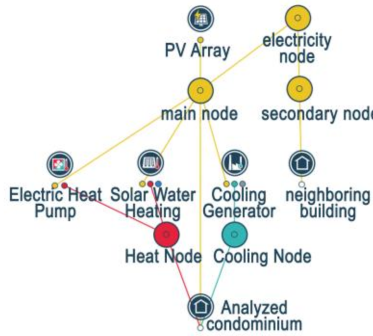
3.4 Case-study scenarios



(a) 1 PoS



(b) 2 PoS



(c) REC with 2 neighboring buildings (one PV array)

Figure 8. Electrical network diagram for the various case-studies: a) 1 PoS, b) 2 PoS and c) REC

The first two scenarios are regarding the condominium scale (C), where energy demands of each of the 8 apartments and the common services are considered nine users, producers and prosumers. Scenario 3 analyzes the share of energy between the renewable energy community (REC) consisting of two neighboring buildings, with the same characteristics. The different users can be named technically as PoS (Point of Sharing):

1) **1 PoS:** This scenario has no energy sharing and no incentives (Figure 8a). The common uses include the space heating/cooling and DHW system (i.e., with solar collectors), photovoltaic modules (PV) on the rooftop, and the energy demand of the common areas (e.g., entrance and staircase).
2) **2 PoS:** In this scenario, the main PoS (PoS 1) is connected to the common uses, PoS 2 is connected to the 8 apartments. In this case, there is the economic incentive for the energy shared within the condominium (Figure 8b).
3) **REC with 2 neighboring buildings (one PV array):** This scenario aims to understand the sharing of energy between different users in neighboring buildings but connected to the same electrical substation (Figure 8c).

The simulations of these three scenarios will test different case studies to demonstrate the economic, energetic, and environmental effects of:

a. Non-retrofitted buildings
b. Retrofitted buildings
c. Retrofitted buildings with storage system (batteries BT).

4. RESULTS AND DISCUSSIONS

4.1 Model validation

The input details of the analyzed building were provided by the project coordinator R2M company and used to define the first energy consumption model. Due to the use of the standard TMY weather file and the uncertainty of the user behavior, the first results were not close enough to validate the model, so adjustments were made to obtain lower errors considering the provided bills.

In this verification, the hourly weather file was corrected considering the daily air temperatures and solar irradiations for the year in which the bills were provided (2019). Following this analysis, 4 weather files were created based on 2019 weather data from PVGIS and the data collected by ARPA

Sardinia.

The model was simulated using these 4 weather files to compare and define the closest weather file when comparing the data from the available bills with each simulation result.

Figure 9 illustrates briefly the steps followed in the adjustment of the inserted inputs.

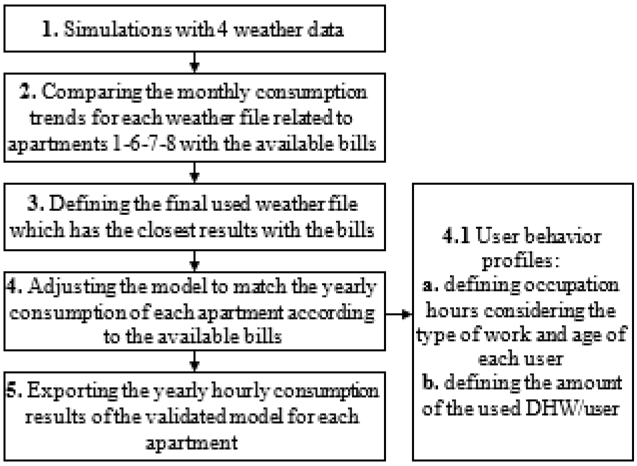


Figure 9. Model validation workflow

Table 4. Absolute relative errors comparing the bills with simulation results

Apt.	n. users	Yearly consumption kWh (simulation)	Absolute relative error %
1	1	2892	2.1
6	1	1453	3.3
7	4	5933	0.2
8	1	1856	70.5 (18.2 in the cooling season)

In Table 4, it can be observed that the simulation results obtained are close to the total yearly consumption of the three apartments with available bills (apt. 1-6-7). These results, for apartment 1 and apartment 7 that have typical electric boilers, are quite close to the average consumptions in Sardinia too, which are: 2659.7 kWh/inh/year (2018) and 5940.3/fam/year (2017). However, the results of apartment 8 show a high relative error compared to the other three apartments. This can be related to the different use especially of the heating system because there is a single old woman that operates manually.

4.2 After retrofit interventions

The characteristics of retrofit interventions were identified according to the minimum requirements of buildings components of actual Italian standards and laws. The intervention includes thermal insulation, windows substitution, the entire renovation of the heating and cooling systems (from individual to centralized), and the installation of solar technologies, solar thermal ST, and PV panels.

In Table 5 are reported the main interventions about thermal insulation of the envelope that can be summarized with an external thermal insulation with 12 cm of synthetic material and the substitution of windows with PVC frame and double low-e glasses with Argon.

Moreover, the autonomous space heating/cooling and DHW systems were transformed into a centralized system with a PV generation of 20 kWp and 14.4 m² of solar collectors for DHW with 910 liters of storage tank capacity.

Table 5. Thermal transmittances before and after retrofit interventions (input values for the simulations with VE)

Building component	Thermal transmittance (U-value, W/m²/K) Pre-retrofit	Post- retrofit
Walls	1.57	0.25
Ground slab	2.15	0.65
Roof	2.40	0.28
Windows (avg.)	2.9	1.4

The results after the above-mentioned intervention inputs showed an average decrease in energy consumptions of about 28% (in Figures 10 and 11): 29% for apartment 1, 25% apartment 2, 32% apartment 4, 26% apartment 6, 18% apartment 7, and 42% for apartment 8. Apartments 3 and 5 show higher results in the post-renovation case, which is explained by the lack of an HVAC system in the pre-retrofit phase.

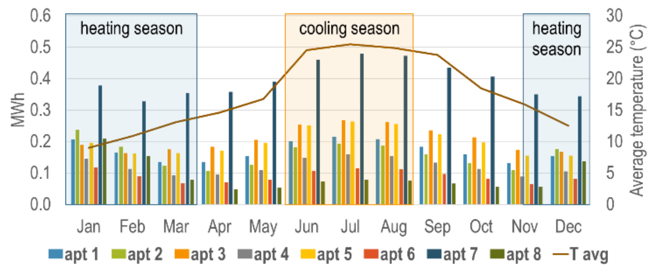


Figure 10. Electricity consumptions per apartment (after-retrofit interventions)

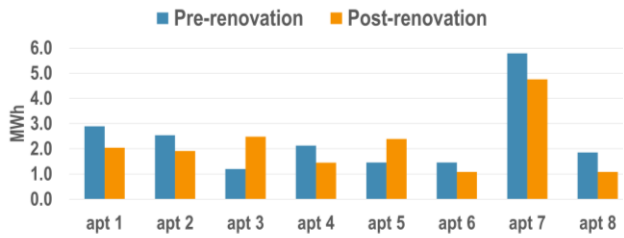


Figure 11. Comparison of electricity consumptions per apartment (yearly data) pre- and post-retrofit interventions

4.3 Scenario results

The typical weekdays of the four seasons were analyzed to understand the energy production and consumption trends considering the installed photovoltaic (PV) system of 20 kWp (Figure 12).

The installed PV has a system efficiency of 20% and for the batteries, a theoretical capacity and an optimal discharge rate were considered. The inclination was identified optimizing the energetic indexes: higher SCI and SSI. The SCI and SSI for a range of inclination of 30-38° were analyzed. The results showed that the optimal inclination was 34° when considering the energetic indicators.

The highest self-consumption index (SCI) was observed in summer when the high space cooling around noon has the same trend of the PV production; while the high energy consumptions in the morning and in the evening cause a high uncovered demand (UD) and a low self-sufficiency (SS) as well. The SC in spring is low due to the high over-production (OP) compared to the low energy demand, which is explained by the minimum use of the heating and cooling system in spring.

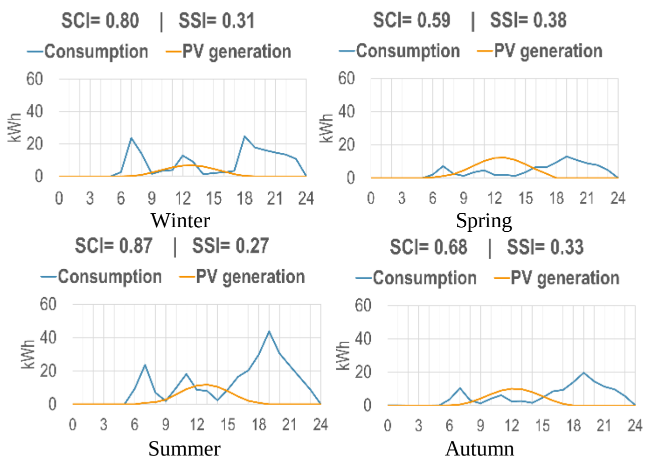


Figure 12. Electricity consumption and production trends for typical weekdays during the four seasons

In Figure 13, the installation of a storage-battery system was tested to improve the self-consumption and self-sufficiency. Overall, the results of the daily generation trend for the installed PV system show that the system is under-dimensioned, compared to the consumption trend. The proper sizing of the installed PV system will result in better SCI and SSI values, thus playing a role in improving the energy sharing between users.

The choice of the battery size for the retrofitted building was identified by an economic point of view. The economic convenience of the various batteries' capacity was calculated with the net present value (NPV) starting from 5 kWh and increasing the size until there is no over-production (around 55 kWh). The battery with storage capacity of 20 kWh shows the highest NPV among the other sizes, which is used for simulating the scenarios that considers a battery storage system. Batteries with lower storage capacities have low NPV since the energy cost savings from storing the OP is not high enough, so having higher storage capacities helps in storing the surplus production and therefore increasing the profitability of the investment. Batteries with a capacity higher than 20 kWh are no longer profitable due to the increasing cost of investment (about 500 €/kWh) and the low energy savings, because the PV system is under-dimensioned and the OP available is already low and doesn't need a high storage capacity. This explains the increasing trend in NPV until 20 kWh storage capacity and the decreasing trend in NPV after 20 kWh storage capacity. However, the results could show different trends with more end-users.

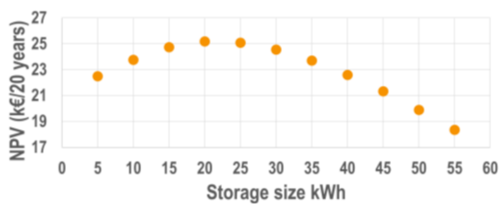


Figure 13. NPV of simulated storage sizes for the retrofitted condominium with 8 residential users

4.3.1 1 PoS – 2 PoS (retrofitted building)

Figure 14 illustrates the SCI and SSI values for both 1 PoS and 2 PoS case studies, considering the difference when a battery system (BT) is installed with a capacity of 20 kWh. The installation of a BT system results in higher SCI and SSI values since it increases the share of energy by decreasing the mismatch between production and consumption, making the over-production available to the members of the community.

Figure 15a compares both cases from the energetic perspective, showing that in PoS 1 scenario, aggregating all the end users with one BT, higher SCI and SSI values can be reached. The main aim is to achieve higher SC, because with the PV energy production, the SS will be lower than 40% due to the winter months with low solar irradiation and high space heating consumptions. In Figures 15b-c considering the economic and environmental perspectives, 1 PoS+BT shows higher NPV, higher SS, and lower GHG emissions compared to the other cases.

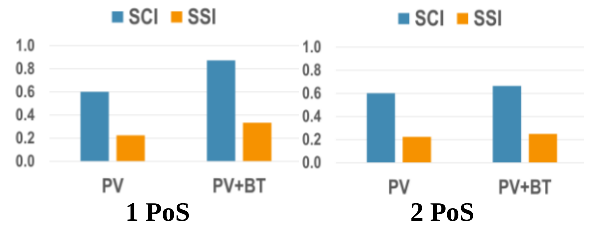


Figure 14. Self-consumption and self-sufficiency indexes (SCI and SSI) for 1 PoS and 2 PoS scenarios

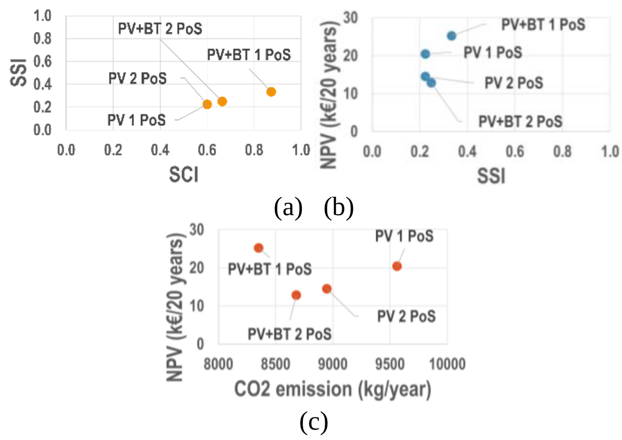


Figure 15. Comparing the energetic, environmental, and economic results (within a condominium)

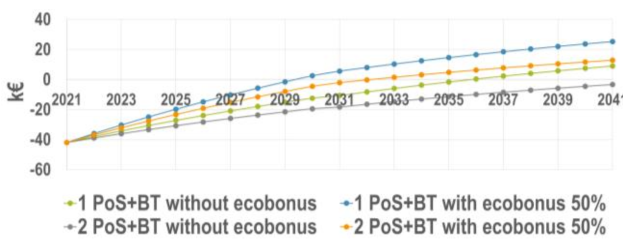


Figure 16. Payback time with a battery storage system (BT) within a condominium

In Figure 16, the payback time of each case study 1 PoS and 2 PoS was analyzed considering and not considering the existing tax deduction "Ecobonus 50%" for residential buildings (incentive on buildings' retrofit measures). This graph shows the importance of government policies in supporting these investments on energy savings. The 1 PoS case has better results, both with and without the incentive;

overall, it takes 8 years to pay back the investment costs with the presence of "Ecobonus 50%" incentive for 1 PoS+BT, while it takes 11 years for 2 PoS+BT scenario.

4.3.2 REC with a neighboring building

This scenario will consider the impact of energy retrofit measures and the presence of batteries of different capacities in a renewable energy community.

The following scenarios have been considered:

- A: actual buildings
- B: retrofitted buildings
- B+BT*X*: retrofitted buildings with a *X* kWh capacity battery BT (i.e., *X* varied from 20 to 40 and 60 kWh).

Considering the energetic indexes, Figure 17 shows the effects of retrofit measures for the energy community (case A and B), which results in 11% of increase in the SCI. Adding a storage system "+BT" improves the self-consumption level by utilizing better the over-production. The SSI cannot reach 0.3 due to the low solar irradiation, low energy production by PV and high consumptions during the heating season. This problem is also due to the residential user who consumes electricity mainly in the late afternoon and evening. With a different user, like commercial or industrial ones with prevailing daily consumptions (not residential users), this result could be partially amended.

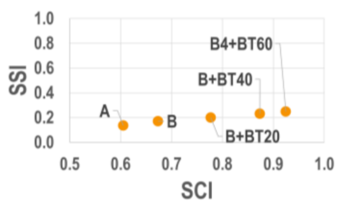


Figure 17. Energy indicators for REC scenario with a neighboring building

From an economic point of view, B+BT40 has the highest revenues with a payback time of 8.5 years (Figure 18) using the "Ecobonus 50%" incentive.

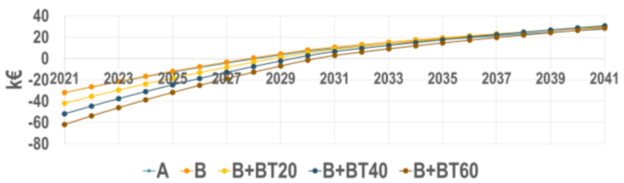


Figure 18. Payback time with the Ecobonus 50% incentive for REC with a neighboring building scenario

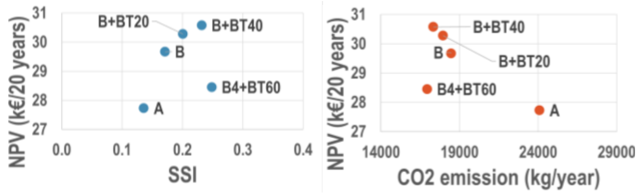
In Figure 19 it is possible to observe the summary of the energetic (SSI), economic (NPV), and environmental (GHG emissions) results. Comparing the 5 case studies, this summary helps in optimizing the choice of the investment considering the energy, economic, and environmental perspectives. From Figure 19a is it possible to observe that using a battery storage system of 40 kWh results in the highest NPV and 0.23 for SSI. B+BT60 shows a slightly higher SSI (0.25) but considering the NPV difference between the two storage sizes (40 and 60 kWh), 40 kWh is more advantageous. Considering the environmental impacts, B+BT40 has the most profitable and eco-friendly results.

Overall, the results of this scenario point out the importance of the following inputs for an EC:

- a renovated envelope results in better energy efficiency/savings;
- a BT storage system increases the energetic, economic, and environmental indexes;
- optimizing the storage capacity properly (with a cost/benefit analysis) is important to improve the results.

From the energetic perspective, the results of both scenarios analyze the energy efficiency and the potential EC scenarios for the studied building.

From the architectural point of view, it is seen that improving the envelope materials contributes to decreasing the energy needed for space heating and cooling, which in turn affects the results of the REC. Hence, this work shows the importance of having a collaboration between different designers (i.e., architects, engineers, and urban planners) and the use of new tools like iVN can allow the implementation of these analyzes more easily to achieve sustainable districts.



(a) (b)

Figure 19. Comparison between economic, energetic, and environmental results for REC with a neighboring building

5. CONCLUSION

This work aimed to illustrate a comprehensive analysis of the energy consumption profiles starting from a typical apartment, which was used later for the design of a REC, both at condominium and community scale. The findings can answer two different energy concerns: 1) how the building envelope and the technological systems can play an important role in the total building energy performance, 2) how to test the effectiveness of RECs at different scales with a comprehensive tool like iVN.

Analyzing the retrofit interventions, an average decrease of 28% in the total energy consumption was observed, which points to the importance of having an energy-efficient building stock in urban environments. Especially in the cities first it is necessary to reduce the energy consumption, given the great intensity of energy consumption and the limited availability of renewable energy sources.

Considering the case studies on RECs, both scenarios show that battery storage systems have an effective role in increasing the self-consumption levels of the community since solar energy is intermittent and needs to be optimized for its usage by storing the surplus of production. The batteries are also important in avoiding the high peak of energy demand and in improving grid flexibility, which results in more resilient energy grids.

The tested scenarios consider:

- PV of 20 kWp and 20% efficiency as the renewable energy source (RES) with and without batteries,
- ST (14.4 m²) for domestic hot water production,
- the residential families as the end-users (other typologies of users could be more effective with solar technologies).

Summarizing the analyzed retrofitted scenarios, in 1 PoS case of the condominium scenario, adding batteries showed an increase of 45% in the SCI, 49% in the SSI and 23% of NPV, with a payback time of 8 years. Considering the 2 PoS case, the increase in SCI and SSI showed a constant value of 11% with the presence of a battery, and a decrease of 12% in the NPV with a payback time of 11 years; concluding that aggregating the energy demand of the condominium into 1 PoS results in better values than having 2 PoS. This assumption also corresponds with the analysis of the project coordinator regarding the analyzed Italian pilot site.

In REC scenario with a neighboring building and one PV array, retrofitting resulted in a 26% increase in SSI, and a decrease of 23% in GHG emissions, which shows the importance of having renovated and high-efficient buildings in achieving more sustainable districts. In this case, adding a battery of 40 kWh to the retrofitted building showed an increase of 36% in SSI and 30% in SCI, and a payback period of 8.5 years. Overall, the GHG emissions decreased by 28% when having renovated buildings with a battery of 40 kWh (comparing case A and B+BT40).

In this work, a small-scale energy community was analyzed. To reach the goals the climate and energy targets of lowering global emissions and achieving more sustainable cities, the recasts of the related directives must be considered. To achieve more robust results meeting the current and future energy demand, it is then important to include different RES and involve mixed end-users. Considering the location of the case study, wind and wave technologies can be included and tested for future REC scenarios; in addition to the use of waste which is a common resource for all cities (without air quality problems).

The economic analysis is important for the implementation of the examined scenarios. It helps in highlighting the advantage of each scenario and ensuring the economic benefit for all the end-users. The representation of the various results from energy, economic and environmental point of view, shows the importance of having incentives that encourage the end-users to implement a REC. The energy prices used in this work consider the domestic market in 2019 with about 20.67 c€/kWh but they are varying especially lately: +53% at the end of 2021 and +121% in 2022 [17]. The increasing price of electricity underlines the importance of investing in REC with greater motivation.

This work has contributed also to testing new software that is intended to achieve sustainable design goals by providing integrated tools that work collaboratively to represent the network of users, producers and prosumers connected to an electrical grid. The aim is to measure the effectiveness and flexibility of the tool in designing and analyzing energy-sharing models. Understanding the logic behind the iVN network structure was important to model the right energy network for the analyzed scenario. The numerous simulations revealed some useful strategies to construct the right energy network. The methodology of this work can give useful information about the management/representation of data in an energy community to test the effectiveness of RECs on different scales.

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