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Development of an Energy Community through semi-dynamic simulation of a urban social housing

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Abstract. Energy communities (ECs) are instrumental in driving the transition to renewable energy in urban areas. This study focuses on implementing ECs in Rome's Tor Bella Monaca district, with a particular focus on linear mass housing. Using the Urban Modeling Interface (UMI) and Simulink, four energy community scenarios were simulated to evaluate their potential outcomes. The scenarios involved integrating photovoltaics and heat pumps into the community's infrastructure to assess their impact on renewable energy production and CO2 reduction. The results demonstrate that higher electrification within an energy community leads to increased self-consumption of renewable energy and reduced reliance on the grid. Furthermore, the integration of heat pumps enhances energy consumption efficiency. This research highlights the significant potential of energy communities and innovative technologies in managing local renewable energy resources effectively. It provides valuable insights for developing sustainable energy models in urban areas. It emphasizes the importance of carefully evaluating technology sizing, integration, and the inclusion of thermal and electrical storage to maximize self-consumption while minimizing CO2 emissions. The study's findings offer practical guidance for policymakers, urban planners, and stakeholders involved in sustainable energy management. They underscore the need for a holistic approach that combines technological advancements, community engagement, and thoughtful integration of renewable energy systems. Ultimately, this research contributes to the adoption of energy communities as crucial elements of a resilient and environmentally-friendly future.

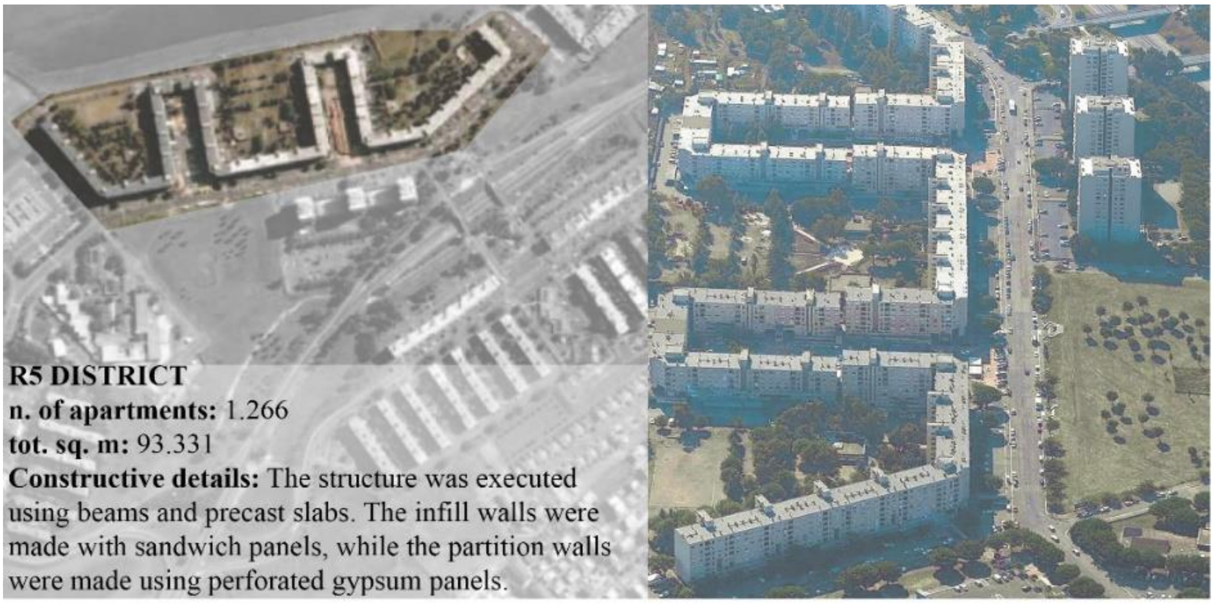
1. Introduction

The Sustainable Development Goals outlined in the European agenda, specifically Goal 7 and Goal 11 [1], place significant emphasis on the energy transition [2-5]. This transition involves a major transformation that societies and urban areas will undergo in the coming decades. It goes beyond simply shifting to renewable energy sources and requires a restructuring of energy systems. The current centralized fossil fuel power plants must be replaced by a new energy model consisting of interconnected distributed energy systems that rely on sustainable self-consumption of renewable energy [6]. This transition requires collective action from communities, particularly among economically disadvantaged individuals. Energy Communities (ECs) are a way to bring households together and enable them to collectively produce, manage, store, and sell renewable energy. The academic literature has recently focused on the debate surrounding ECs, examining their approaches, limitations, and potential [7-12]. The European Union, through the transposition of the European Directive RED II, has legally recognized associations and introduced the role of energy producer/consumer [2]. Italy has made notable progress in implementing renewable energy communities through legislative measures and ongoing development, aiming to establish an innovative energy management model in the country. The most recent step in this process is the proposal of a decree on energy communities, which is being transmitted to the European Union for prompt operationalization. The literature suggests various systems such as Power-to-Power, Power-to-Heat, and Power-to-Gas, which are implemented separately or in combination with residential communities having different renewable energy surpluses. Power-to-Heat and Power-to-Gas strategies are crucial for integrating variable renewable energy sources and increasing system flexibility. The Power-to-Heat approach is cost-effective but has limitations, while the Power-to-Gas configuration, which involves injecting hydrogen into the gas grid and utilizing the local network as a storage system, leads to higher self-consumption. However, the efficiency of electrolyzers in Power-to-Gas systems is lower, resulting in reduced energy and emissions savings. Cost-effectiveness is achieved when low volumetric fractions of hydrogen are used for injection into the gas grid. This study proposes transformative scenarios to facilitate the energy transition of a social housing area in Rome into energy communities. The scenarios are developed using the UBEM tool, which is an Urban Modeling Interface (UMI) [13][14]. Specifically, the focus is on Tor Bella Monaca, R5 compart. The choice of this building typology, which shapes an entire neighbourhood, is twofold. First, it is widespread in the European outskirts. Between the 1950s and 1980s, mass housing developments became common as part of the post-World War II urban expansion. The impetus for this development can be attributed to the rapid growth in housing demand, primarily driven by population growth and the migration of people from rural areas to urban centres. The construction of these buildings was a product of a modern planning paradigm, which relied on standardized and rapid construction methods, aiming to create self-sufficient and experimental urban communities with high-density buildings that integrated all necessary services for residents. It was commonly used for social housing districts. However, despite these ambitions, the haste in construction resulted in a weakness in the durability of the building materials, frequently causing energy inefficiency issues with the building envelope [15]. Secondly, in Rome, around 400,000 residents reside in low-cost social housing projects built during the same time frame as the case being examined, thus providing a rationale for studying social housing ECs and, in particular, linear multi-story buildings that comprise a significant proportion.

Energy communities represent an innovative solution for managing locally produced renewable energy. In this context, the present study focuses on the simulation of three energy community scenarios that involve integrating photovoltaics and using innovative technologies such as heat pumps and hydrogen production. The purpose research simulates three energy community scenarios using photovoltaics, heat pumps, and hydrogen production. The aim is to assess the impact of these technologies on renewable energy production and CO2 reduction. The simulations utilize semi-dynamic models (Simulink) considering variables such as individual energy demand, solar energy production, and grid feed-in. Four scenarios are simulated: two with photovoltaic system integration (sized at 100% and 50% of needs) and two with the additional integration of heat pumps (sized at 50% and 100%).

1.1. Framing the case study

The Tor Bella Monaca (TBM) district in Rome exemplifies the key characteristics of Italian mass housing constructed between the 1960s and 1980s under the PEEP (low-cost social housing schemes) and Law 167/62. The TBM megastructure covers nearly 2,500,000 cubic meters and was initially designed to accommodate around 27,000 residents. The neighborhood reflects the common features of many mass housing districts in Italy and conforms to the planning principles adopted in Europe during the same period [13]. This study focuses on the monumental in-line-multistorey building R5 (Fig. 1).



R5 DISTRICT
n. of apartments: 1.266
tot. sq. m: 93.331
Constructive details: The structure was executed using beams and precast slabs. The infill walls were made with sandwich panels, while the partition walls were made using perforated gypsum panels.

Figure 1. R5 District

2. Methodology

This section presents the workflow (Fig. 2) employed for characterizing the considered scenarios. Initially, spatial data encompassing floor plans of buildings, roads, parks, and the surrounding urban development were collected. These data underwent processing through a Geographic Information System (GIS) [16]. Subsequently, Grasshopper scripts [17] were used to process the shapefile data by associating a reference layer with each category. This involved transforming the point representations of building shapes into polygons, which were further manipulated in Rhinoceros to create 3D building models through extrusion and height adjustments. Additionally, the Rhinoceros environment utilized [18], where each building was linked to a building template developed by Vallati et al. [19]. This template introduced a new building archetype paradigm that incorporated not only technical and architectural characteristics but also energy aspects. By analyzing real data, such as heating operating hours, a comprehensive range of public residential buildings in Italy and Europe were represented by a model building. UMI simulated the energy loads of the examined buildings and exported hourly consumption data for each load type (e.g., electricity, heating) at both the individual building and urban area levels. These load data were then imported into Simulink to perform semi-dynamic energy simulations for four distinct scenarios.

The first step involved two settings for renewable energy utilization: one entailed sizing renewable energy systems to cover 100% of the total energy consumption, while the other considered sizing them to cover 50%. For each of these settings, two scenarios were simulated:

- Scenario 1 (s1): This scenario examined the impact of installing roof-mounted photovoltaic systems (sized at 100%) on self-consumption, which refers to the direct consumption of solar energy generated within the building.

- Scenario 2 (s2): This scenario assessed the changes in self-consumption resulting from the integration of photovoltaic systems (sized at 100%) with a heat pump system for heating and hot water. It aimed to analyze the combined effect of solar electricity generation and heat pump technology on self-consumption.

- Scenario 3 (s3): Similar to Scenario 1, this scenario explored the trend in self-consumption but focused on roof-mounted photovoltaic systems sized at 50% only.

- Scenario 4 (s4): This scenario investigated the impact of integrating photovoltaic systems sized at 50% with a heat pump system on self-consumption, similar to Scenario 2.

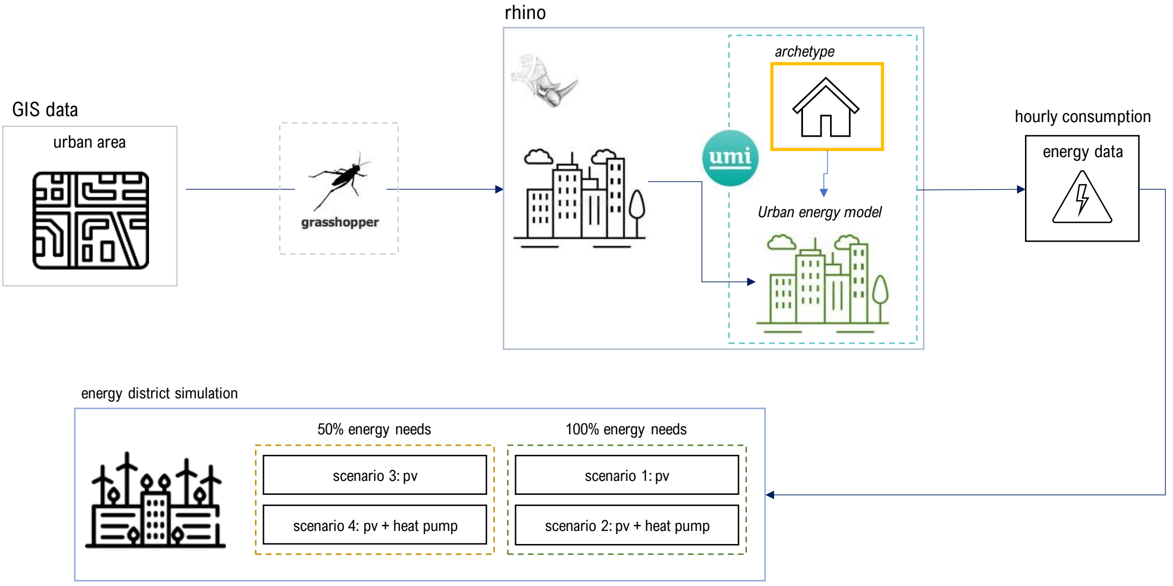


Figure 2. Digital methodology workflow

The objective of these scenarios was to analyze the potential benefits and trends in self-consumption when utilizing renewable energy systems. By assessing different settings and scenarios, the study aimed to provide insights into the feasibility and effectiveness of incorporating renewable energy technologies to meet energy demand, with and without the integration of heat pump systems.

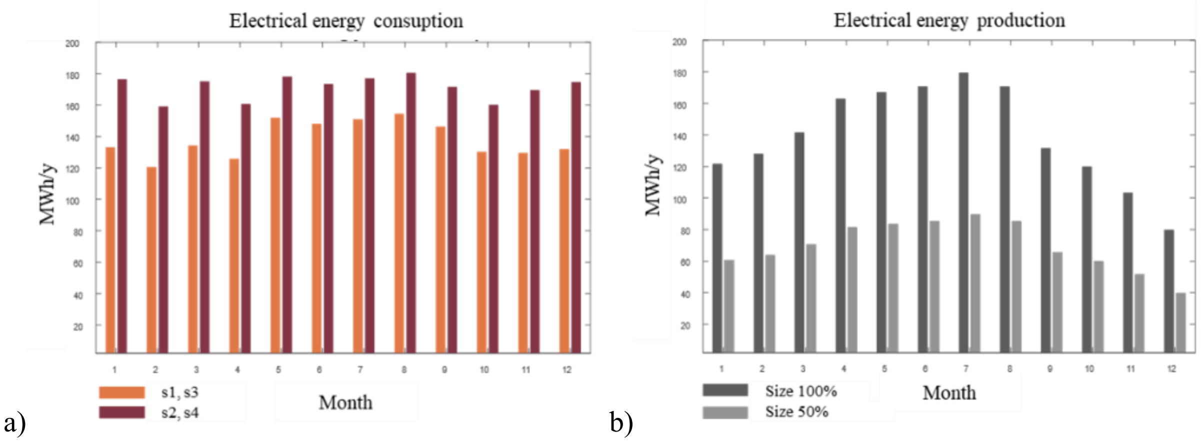
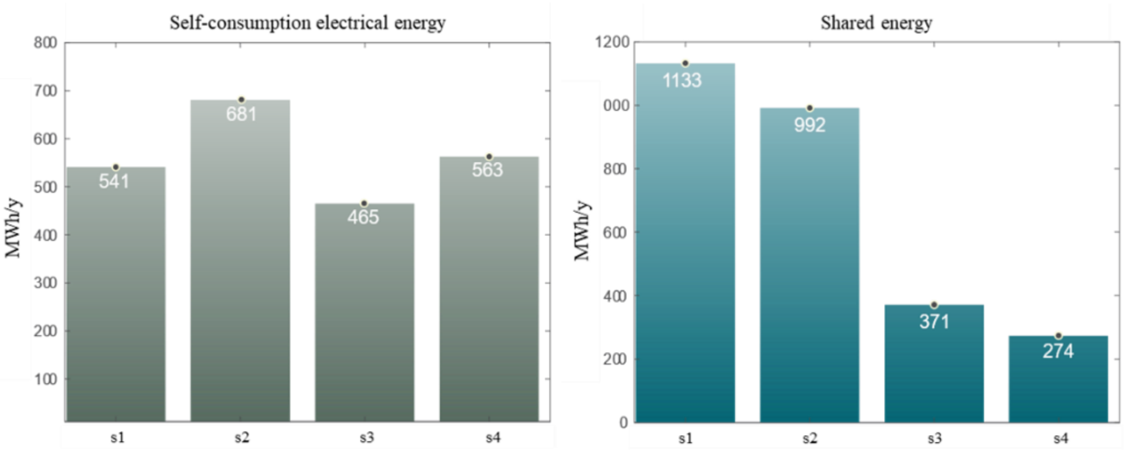


Figure 3. a) Electricital energy consumption. b) Electrial energy production.

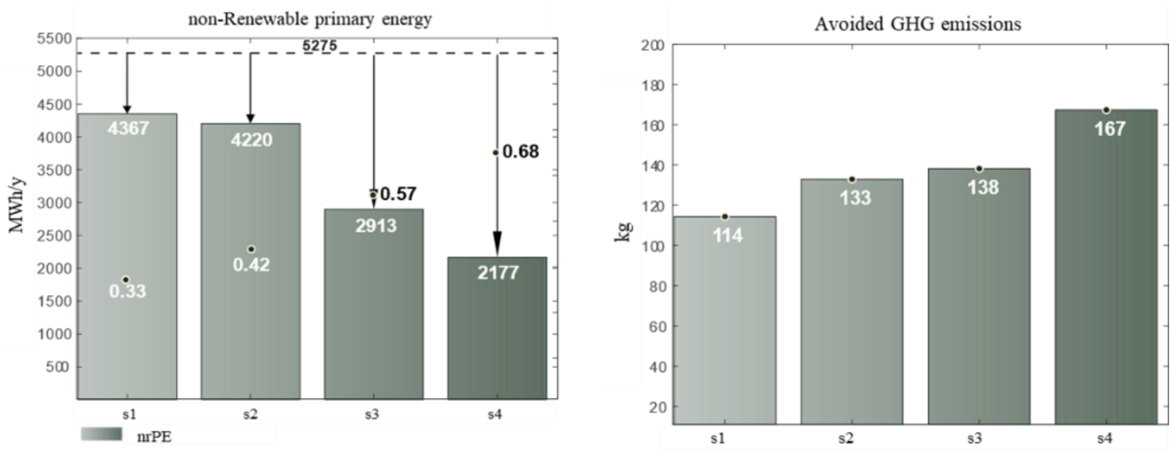
Furthermore, a comparative analysis was conducted among the simulations of the different scenarios to determine the setting that yielded the highest percentage of self-consumption relative to energy efficiency. Therefore, s2, s4 scenarios therefore use electricity as the energy carrier to power heating and domestic hot water; in contrast, the s1, s3 scenarios use natural gas to meet these loads. In fact, scenarios 2/4 have a higher energy demand (Figure 3a) due to the use of the heat pump. On the other hand, electricity production from solar energy is twice as high in the configuration where the photovoltaic system is sized at 100% of the building complex's energy needs (s1,s3) for a total of 1.7 GWh/y compared to the second configuration with 50% sizing, which has 0.85 GWh/y.

3. Results

By interpolating the production and hourly consumption data throughout the year, the percentage of electricity consumed on-site was determined for the four scenarios: s1 (33%), s2 (42%), s3 (57%), and s4 (68%) (Figure 4.a). The variation in self-consumption share is influenced by the sizing of photovoltaic (PV) systems and changes in energy demand. The increase in electrical load is directly proportional to the increase in self-consumed energy. Specifically, there is a positive change in self-consumption of 9% between s1 and s2, and 11% between s2 and s4. In contrast, the sizing of the PV system has a significant impact, resulting in a 24% difference in the s1/s3 comparison and a 26% difference in the s2/s4 comparison. Simulating a PV system sized at 50% of the total energy demand (s3 and s4) leads to high levels of self-consumed energy but a decrease in energy fed into the grid. Comparing s1 and s3, the share of self-consumed energy decreases by 14%, and shared energy in the grid decreases by 67%. Similarly, comparing s2 and s3, self-consumption decreases by 17%, with a 72% decrease in energy shared in the grid. Although the electric production is halved in s4, self-consumed electric energy is 4% higher than in s1. The design variation in electrifying consumption within an energy community environment leads to increased self-consumption and reduced grid dependence, compared to increasing electric power. Furthermore, the impact of non-renewable primary energy in the four scenarios was evaluated compared to the initial scenario (s0). Comparing s0 and s3, there is a 17% decrease in non-renewable primary energy; s0 and s1 show a 20% decrease; s0 and s4 demonstrate a 45% decrease, and s0 and s2 exhibit a 59% decrease (Figure 4.c). Analyzing the difference between s0 and s1, s3 reveals that using non-renewable sources for heating and hot water, doubling the size of the PV system leads to only a 3% decrease in non-renewable primary energy (s1/s3), with a maximum overall primary energy savings of 20% (s0/s1). In contrast, electrifying the heating and hot water loads using different technologies results in a 24% decrease in primary energy consumption in scenario s4 compared to scenario s2. Evaluating the difference between the initial scenario and the other scenarios, there is a decrease in non-renewable primary energy of 59% (s0/s2), 33% (s4/s3), 50% (s2/s3), and 45% (s0/s4).



a) b)



c) d)

Figure 4. a) Self-consumption electrical energy. b) Shared energy in the grid. c) non-renewable primary energy (nrPE). d) Avoided kg GHG emissions

Finally, the amount of CO2 emissions avoided was calculated by considering the energy generated on-site by the PV system (Figure 4.d), which corresponds to the same amount of energy that would have been sourced from the grid. The introduction of a heat pump system leads to an increase in CO2 emissions avoided. Particularly noteworthy is the reduction in greenhouse gas emissions in scenario s3, where a 50% sized PV system powers the heat pump.

4. Conclusion

The implementation of energy community scenarios has a significant impact on the transition to renewable energy sources. Integrating technologies such as photovoltaic modules, heat pumps, and hydrogen production can effectively increase the self-consumption of renewable energy and reduce CO2 emissions. Analyzing different sizing combinations of photovoltaic systems revealed that simulating a system sized at 50% of the total energy demand results in high self-consumption but a decrease in energy supplied to the grid. This highlights the potential of greater electrification of consumption within energy communities to enhance self-consumption and reduce strain on the grid, compared to simply increasing electrical power capacity. The integration of heat pumps alongside photovoltaic modules further amplifies energy self-consumption. In summary, the establishment of energy communities and the adoption of innovative technologies contribute to the effective management of local renewable energy resources. These findings provide valuable insights for the transition to sustainable energy models in urban areas. However, careful evaluation of photovoltaic system sizes and the integration of other technologies is necessary for future developments to maximize energy self-consumption and minimize CO2 emissions. Exploring the inclusion of thermal and electrical storage as a means to optimize self-consumption is a promising avenue for investigation. This entails assessing their utilization, sizing, and economic viability, considering factors such as payback periods, cash flow, and potential European funding opportunities, with the ultimate goal of achieving near-Zero-Energy-District (nZED) targets.

5. Acknowledgement

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