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Distributed Energy Systems: Constraints and Opportunities in Urban Environments

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Abstract: Cities need to make themselves energy self-sufficient by exploiting renewable sources and, above all, to evaluate the potential and constraints that each city can express by virtue of its own characteristics. This study focused on how the realisation of a renewable energy community could be approached in urbanised contexts. The methodology involved the selection of three case studies in Rome analysing the feasibility, programming and design scale, and the implications of planning RECs. Through simulation at three levels of detail, this study identifies elements to assess the feasibility of RECs and to elaborate scenarios to support their planning and dimensioning. The practical importance is to identify a possible methodological path and relevant factors which public or private stakeholders can consider at different levels in setting up RECs in an urban context. The research conclusions of these simulations point out that the specificities of a context affect many factors, among which an important role is played by the facilities and spaces for public use, as they are synergetic to a shared use of energy between residential and non-residential functions, but above all, because they are also available to accommodate services for the energy community.

Keywords: distributed energy systems; renewable energy community; renewable energy; urban fabric; energy production simulation; energy balance; open proximity spaces; decarbonisation scenarios

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1. Introduction

Cities are facing a triple crisis: the health impacts of COVID-19, the climate and ecological emergency, and social and economic inequality. To support cities in facing the challenges of polycrisis [1], moving from a model that has proven to be 'fragile' to a 'safer' one, the EU has outlined a short- and long-term policy framework. Europe's main roadmap to facing climate change [2] is based on accelerating the path to Net Zero Emissions by 2050, on supporting the transition to a sustainable, safe, and just social substrate, and on incentivising homogeneous economic growth to overcome social and economic inequality [3]. Many initiatives have been taken in this direction so far: the European Green Deal Strategy (EGD) [4]; the NextGenerationEU [5]; the National Recovery and Resilience Plan (NRP) [6], and the New European Bauhaus (NEB) [7].

In this strategic framework, cities represent an important driving force for the green recovery and equitable growth of European countries, precisely because of their potential for cross-sectoral integration, which can bring about economies of scale for the experimentation and empowerment of new ideas. Indeed, cities are centres of innovation and social engagement where strategies for transition through the decarbonisation of energy, transport, buildings, industry, and agriculture can coexist and be triggered [8].

Among the strategies envisaged by energy policies to reduce emissions, there is the acceleration of mitigation measures and, in particular, an increase in the share of energy from RES and increased energy efficiency: the 'Energy Efficiency First' principle [9], promotes more cost-effective solutions in the management of energy supply and demand, from production to grid transport and energy savings in end use [10].

Moreover, in order to implement the green transition by 2030, the EU 'REPowerEU' plan [11] envisaged an increase in electricity production from renewable sources and the mandatory installation of photovoltaic systems in public buildings, with a possible extension to private residential buildings.

The awareness that it is not enough to incentivise energy efficiency and conservation has thus matured. It is necessary to make cities energy self-sufficient by also initiating the decarbonisation of the energy system in them [12] through the development of decentralised energy systems, currently supported by advanced smart grid and energy storage technologies, increased convenience of RES, market liberalisation, and improved security [13,14].

These aforementioned premises outline the potential scenarios for the evolution of energy transition towards a polycentric system spread over the territory in which the grid not only distributes, but also collects the energy produced locally, using it to heat and cool buildings, to promote non-polluting mobility, and to manage waste, water, communication, mobility, and other community support services, thus transforming the territory into a widespread energy infrastructure [15].

While decentralised energy systems already have their own history in small inhabited contexts or in non-urbanised areas [16], there are still few examples of decentralised energy production in cities in Italy [17] that can be considered as a new model of social organisation and collaborative economy to promote energy production from renewable sources [18].

This new model is not only about how energy is produced, but also identifies RECs as units of social innovation in which the active participation of members as prosumers can support them economically and, at the same time, support the creation of complementary services for community use [19–21].

An example, recently realised in Naples, Italy, is the first Solidarity Energy Community, which involved 40 families in the creation of an REC with the installation of a 53 kWp solar system. The social purpose of this project lies in economically supporting the members' energy bills, preventing energy poverty, and in environmental education by monitoring electricity consumption to teach proper energy management of their houses [22]. In fact, the literature on energy citizenship emphasises that for citizens to be protagonists in the energy transition, it is necessary that they participate not only with their investment and energy consumption decisions, but also as social actors, particularly when they are in energy poverty [23].

After all, even the contribution of European countries to the transformation of the energy system through the active involvement of citizens identifies a trend toward collective prosumerism as a social movement that engages in the transformation of the energy system [24–26].

In this direction, many municipal administrations in Europe [27–29] have launched various experiences. In Italy, the municipality of Rome has just launched 15 REC projects, one for each municipality, to be implemented on the roofs of public buildings to produce energy for schools or other services, and to share the energy with the members of the energy community, involving families in difficulty.

However, decentralising energy production in cities raises certain issues:

- The transition from a unidirectional flow of energy to one that is distributed, interconnected, and interdependent;
- The compatibility between infrastructure and territory, characterised by potentialities, peculiarities, and constraints;
- The geographies of connection, dependence, and control with even more significant implications in the transition from the urban scale to that of individual contexts.

The programming of energy mixes from different renewable sources, each characterised by its own cycle [30,31]. In other words, the transition towards decentralised energy production systems requires thinking about new geography of territories and their environmental, economic, and social resources [32,33]. For example, thinking of biomass, photovoltaic, solar-thermal, wind, or geothermal, it is easy to imagine how each of these technologies, when developed at different scales, relates differently to the context in terms of energy production, utilisation according to energy needs, space required, connections, physical infrastructures, and potential environmental impact. Moreover, precisely in the interrelation with the territory, the need arises to evaluate the amount of land or surface area required for each different production technology, the convenience in terms of the energy yield of one over the other in relation to the characteristics of the location, as well as the competition between different energy sources to occupy the same space [34–36].

The literature produced shows how the number of publications on energy communities has been growing fast recently, focusing on technological challenges, and an institutional point of view about cover policies, price reforms, and values. In a review article, it is highlighted that evaluative criteria for such communities are limited to greenhouse gas emissions and economic aspects, while indicators about soil pollution or spatial planning, which can play a very important role, are ignored [37].

Furthermore, RECs are widely recognised for their potential to generate renewable energy but, by contrast, the ability of RECs to reduce energy demand and promote flexibility has attracted little attention until now, despite their theoretical potential to do so [27].

In addition to the aforementioned, many cutting-edge energy communities have recently been involved in smart grid experiments in which they explore innovative ways of managing, storing, and distributing renewable energy [38,39]. These communities use virtual power plants to manage energy supply and demand, allowing citizens to take a more active role in the energy system [40], and providing the demand-side flexibility needed to balance the supply–demand system within the electricity grid of an increasingly renewable-based energy system [41,42].

Within this context, the study presented stems from some questions: What elements can condition the feasibility of autonomous energy systems in an urban context, constituting benchmarks for making effective choices? What potential does an urban fabric express in terms of energy production and in relation to the energy needs expressed by its inhabitants? How do the buildings and open spaces of the urban fabric condition the feasibility of RECs, also with respect to their role as providers of collective services and social purposes, support them?

On the basis of the results of a previous study [43], the experimentation proposed in this paper develops an articulated analysis at different scales on selected case studies within the city of Rome. The main innovative results of this research concern the identification of those factors useful for:

- Planning and design of Renewable Energy Communities (RECs) in urban settings;
- Forecasting and planning the balance between production and consumption for better energy management and optimised flexibility, thanks to the active cooperation of users.

This paper is organised as follows: in Section 2, the research outlines a methodology based on three levels of in-depth analysis of the case studies; in Section 3, the results of the three levels of analysis are presented. Finally, the methodology and its possible developments are discussed together with its possible future developments.

2. Materials and Methods

The research methodology was set up according to three steps of analysis to assess the potential of a certain urban area to be transformed into a distributed energy system following three levels of in-depth design of an REC: preliminary feasibility, planning, and actual sizing for implementation [33]. Appropriate criteria and tools were identified to support these three steps: an evaluation model based on parametric indicators; the elaboration of scenarios based on georeferenced systems, and a calculation model for sizing.

The preliminary feasibility analysis answers the question: What is the potential in the current state of an urban area or its individual buildings for assessing the feasibility of an

REC? This could be posed by a private party represented, for example, by the owners of apartments buildings wishing to understand their technical, economic, and even financial potential and constraints [44].

The planning analysis answers the question: What elements can be significant in order to elaborate useful scenarios for the planning of distributed energy systems within an urban area? This could concern a public subject, such as a municipal administrator, who can be supported in identifying the most effective scenario also in combination with other interventions aimed at improving the energy efficiency of the buildings that will constitute the RECs.

Finally, the third analysis answers the question: How do you organise an energy system and optimise the sizing of the components, and what actual size do they take? This represents the point of view of a planner, who is called upon to give precise indications in terms of, for example, achievable power in relation to energy needs, sizing of the necessary surfaces, space to be occupied by storage systems, and so on.

The methodological approach was tested on three case studies in the city of Rome, characterised by urban fabrics that differ in terms of the construction period and housing density and, therefore, representative of different types of building fabric and different relationships between built-up areas and open spaces. Testaccio, Balduina, and Prima Porta are three neighbourhoods that well represent the historical city, the contemporary city, and the city born without planning in many Italian cities (Figure 1).

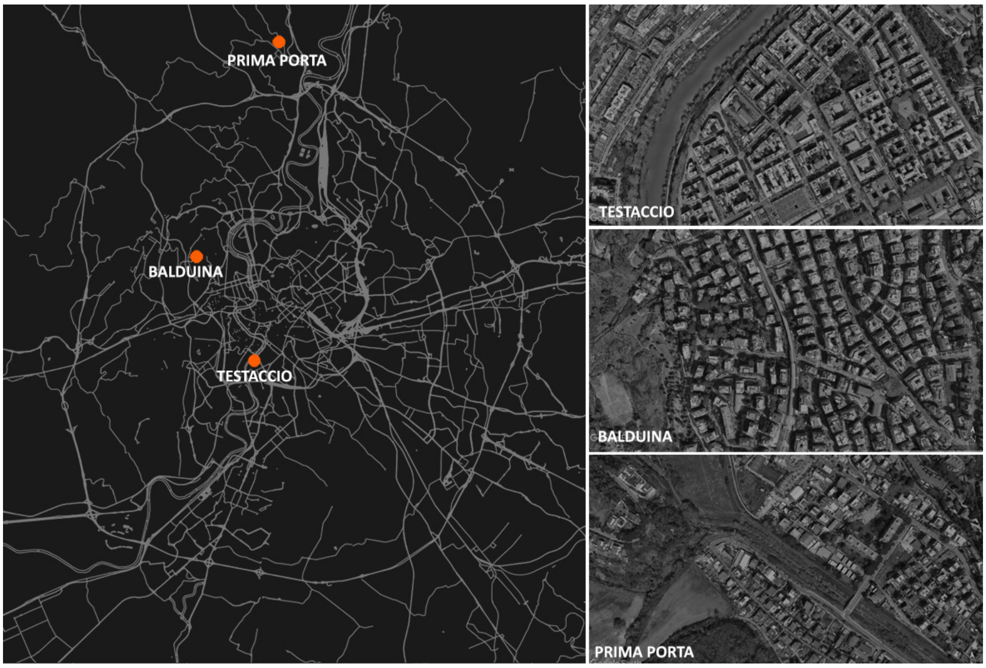


Figure 1. The map of Rome with the districts chosen as pilot cases: Testaccio, Balduina, and Prima Porta, characterised by a different relationship between built-up areas and open spaces.

The Testaccio district was built between 1883 and 1912. It is characterised by high territorial and building density; a high coverage ratio; a good endowment of public services; street spaces with parking functions and a scarcity of greenery, and condominium courtyards with a high degree of functional flexibility.

The Balduina district was built between 1955 and the end of the 1980s. It is characterised by high territorial and building density; a very high coverage ratio; sufficient public services; street spaces with parking functions, and a scarcity of greenery, minimal areas pertaining to the buildings, with greenery for decoration only.

The Prima Porta district was built between 1959 and 2003. It is characterised by moderate territorial and building density; moderate coverage ratio; sufficient endowment of public services; restricted road space with parking functions; scarcity of equipped green spaces, and private appurtenant spaces.

For each methodological step, due to the different level of in-depth analysis required by the design evaluation, all three case studies were considered in step 1, two cases in step 2, and only one case in step 3.

2.1. Preliminary Feasibility Analysis of RECs

This analysis is based on results of a previous simulation [43] developed with the RECON (Renewable Energy Community ecONomic simulator) tool of the ENEA—National Agency for New Technologies, Energy and Sustainable Economic Development. Tools of this type make it possible to collect data and process simulations on a parametric basis, also targeting the economic evaluation and return on the investment required. The tool allowed the clustering of the building's residential units, based on the number of inhabitants, and the number of inhabitants staying in the house during the day. In addition, the simulation included a low-quality envelope, Italian Energetic Classification E/F, the presence of a heating and DHW system with a methane gas boiler (with a fraction of 20% covered by electricity for the use of heating splits), and the presence of a cooling system for 50% of the surface area of each flat.

In addition, the tool allowed the inclusion of economic parameters such as the cost of ordinary maintenance and operation of the production system and operation of the energy community, the average purchase price of electricity of the utility directly connected to the renewable energy system. Included in the calculation was the average selling price of energy produced and fed into the grid, an interest rate used in the financial analysis to discount cash flows, an average inflation rate, a periodicity of years for maintenance, a bank loan with specification of the interest rate, and duration of the loan with a definition of the number of annual payments.

The first simulation resulted in a preliminary assessment of the feasibility of the three neighbourhoods to receive RECs, assuming:

- Estimation of energy needs to be calculated according to the respective user types and building characteristics;
- Use of photovoltaic solar technology positioned on the roof of buildings, for 60% of their available surface area in the case of flat roofs with freestanding installation, and for the total surface area of pitched roofs, if favourably exposed;
- Same production limit of 200 kWp (prior to the transposition of RED II [45], this was the maximum production limit allowed for RECs).

2.2. Analyses and Scenarios for REC Programming

The first assessment, although based on parametric reference values, is certainly a useful tool for an indicative evaluation that can help individual owners of public or private buildings, or condominiums, to assess the feasibility and convenience of implementing an REC. However, the administrations of a city or parts of a city may be confronted with the need to implement intervention strategies based on an assessment of greater effectiveness, both in technical and economic or social terms, by choosing where and how to implement an REC. This is what could result from the RED II Directive by which RECs can be built with a peak power output of up to 1 MW of photovoltaic energy production and be connected to the primary or high-voltage cabin. This possibility expands the size of RECs and the territory to be considered. Therefore, assessing the energy production potential in relation to the needs expressed by a larger territory is necessary.

It is easy to imagine that to undertake a study aimed at planning RECs, a lot of data must be collected and processed using a GIS-based QGIS system in which the information related to the users, the available surfaces with their exposure characteristics, and the current state of energy consumption are collected.

The objective of the experimentation of this second phase was, therefore, to 'measure' the actual energy production potential of the Testaccio and Balduina neighbourhoods in terms of their relative energy needs, and to assess the relationship between the two quantities. Starting from this comparison, it was decided to simulate three scenarios representing three possible progressive intervention strategies to reduce the gap between needs and production.

To map current electricity and heat consumption expressed in kWh/a, some parametric values taken from the Italian National Integrated Energy and Climate Plan (NIPECs 2019) were considered:

- Multi-family residential
  - Electricity consumption 21 kWh/m^2 per year
  - Thermal consumption 123 kWh/m^2 per year
- Schools
  - Electricity consumption 17 kWh/m^2 per year
  - Thermal consumption 89 kWh/m^2 per year
- Offices
  - Electricity consumption 111 kWh/m^2 per year
  - Thermal consumption 45 kWh/m^2 per year
- Commercial buildings
  - Total consumption 448 kWh/m^2 per year

Flat and pitched roofs were considered for production assuming the full area of the pitched roof areas on all favourable exposures; the 60% of flat roof surface of residential buildings (to leave a part for condominium use), and 80% of public buildings. Similarly, parameters were also calculated to exemplify production, multiplying the kWp, by the annual average value of solar radiation on the horizontal plane at the latitude of Rome, by the correction coefficients for central Italy based on azimuth and tilt.

On the basis of the data, three scenarios were elaborated for Testaccio and Balduina: 01—Estimated consumption (current electricity only) and production (using only the roofs of public buildings); 02—Estimated consumption (electricity and heat, with electrification of thermal consumption) and production (using all available roofs); 03a—Estimated consumption (reduction of 20%) and production (using only the roofs of public buildings); 03b—Estimated consumption (reduction of 50%) and production (using only the roofs of public buildings).

2.3. Designing an REC

This third phase is a further scale of in-depth study aimed at the design of the system which, therefore, responds to the need to precisely quantify the impact of the REC on the urban environment considered.

In order to address the design of the energy system, the following conditions were assumed and explored:

- The areas available, considering possible installations of photovoltaic panels on façades, roofs, flat roofs or canopies on them, pitched roofs;
- The power that can be installed, considering the type and peak power (in our study we considered monocrystalline silicon photovoltaic panels, installed to the south, with a peak power of 1 kWp per 12 m^2 for free-standing systems and 1 kWp per 6 m^2 for pitched systems);
- The angle of azimuth, between the surface considered and the geographic south assuming 0° if it is exposed to the south, −90° if it is exposed to the east, +90° if it is exposed to the west;
- The tilt angle, considering an optimised tilt of 35° for free-standing installations on flat roofs at the latitude of Rome, and a tilt of 20° for roof pitches;
- The type of plant, assuming higher efficiency for free-standing plants, which are subject to greater cooling due to the structural characteristics;

- Losses, resulting from cables, inverters, poor module cleaning, and the loss of module power over the years, which, for monocrystalline silicon modules, is about 14% [46].

To forecast the annual energy production from off-grid photovoltaics on totally flat roofs, and the sizing of the accumulators, the calculation was developed using the PVGIS-SARAH2 database with satellite data from 2005 to 2020, while the data analysis was carried out in the MATLAB environment [47].

The estimated annual energy produced by the system was calculated from the incident solar radiation and, when the power output resulted greater than consumption, the excess quantity was assumed to be stored in the battery and vice versa, the missing quantity taken from the battery. When the battery resulted fully charged, all the power delivered, in excess of consumption, until partially discharged, was not being used either in the load or in the battery, and was considered wasted. A missing energy case was assumed upon the occurrence of the following conditions: attainment of the cut-off limit, and power and battery supply not sufficient.

In this third phase, the experimentation was applied to the simulation of an REC design considering 49 buildings in Testaccio (Rome).

3. Results

In this section, starting from the analysis carried out on the three case studies, the results of the three levels are outlined concerning the first step of the 'preliminary feasibility assessment', necessary to identify the potential of the urban fabric; the second step of the 'planning', necessary to direct the choices of intervention areas, and the third step of the 'design', necessary to simulate the dimensions and components of the REC system.

3.1. Preliminary Feasibility Assessment of RECs

The first analysis showed that given the characteristics of the three urban areas and their respective fabrics, even if an extensive installation of photovoltaic panels were to be hypothesised, with the conditions listed above, it would be possible to cover about 30/35% of current electricity consumption in Testaccio and Balduina, and about 60% in Prima Porta (Figure 2).

Moreover, the simulation showed how, due to the different morphology of the three urban fabrics, to realise an REC in Testaccio, only one block would be needed (configuring it rather as a 'collective self-consumption'); in Balduina, five small buildings, and in Prima Porta, 17 small buildings. These results could, of course, be improved by intervening in the energy efficiency of the buildings and their envelope.

In Testaccio, with its high coverage ratio and high territorial and building density, although the roofs of the buildings can accommodate a considerable number of panels, the high presence of public spaces and relict areas also suggests the use of them for both energy production and storage. In this type of fabric, possible RECs with a limit of 1 MWp could also involve four or five buildings in the neighbourhood with the possibility of using both the large condominium spaces and the neighbourhood public spaces.

On the contrary, in Balduina, characterised by a denser urban fabric, a high percentage of condominium and private surfaces and a low percentage of public spaces, against a low percentage of consumption coverage, highlights a low possibility of housing additional technological elements for energy production and storage, outside the roofs of buildings, or making private spaces available for public use. In this type of fabric, against the trend of consumption and production possibilities, possible RECs with a limit of 1 MWp could reach about 25 apartment blocks which would certainly require mediation and synergy between a high number of administrations involved. For this reason, in urban fabrics such as this, smaller RECs or collective self-consumption in individual apartment blocks seem more appropriate, not only because of the administrative difficulties but also because of the housing difficulties of the technological elements.

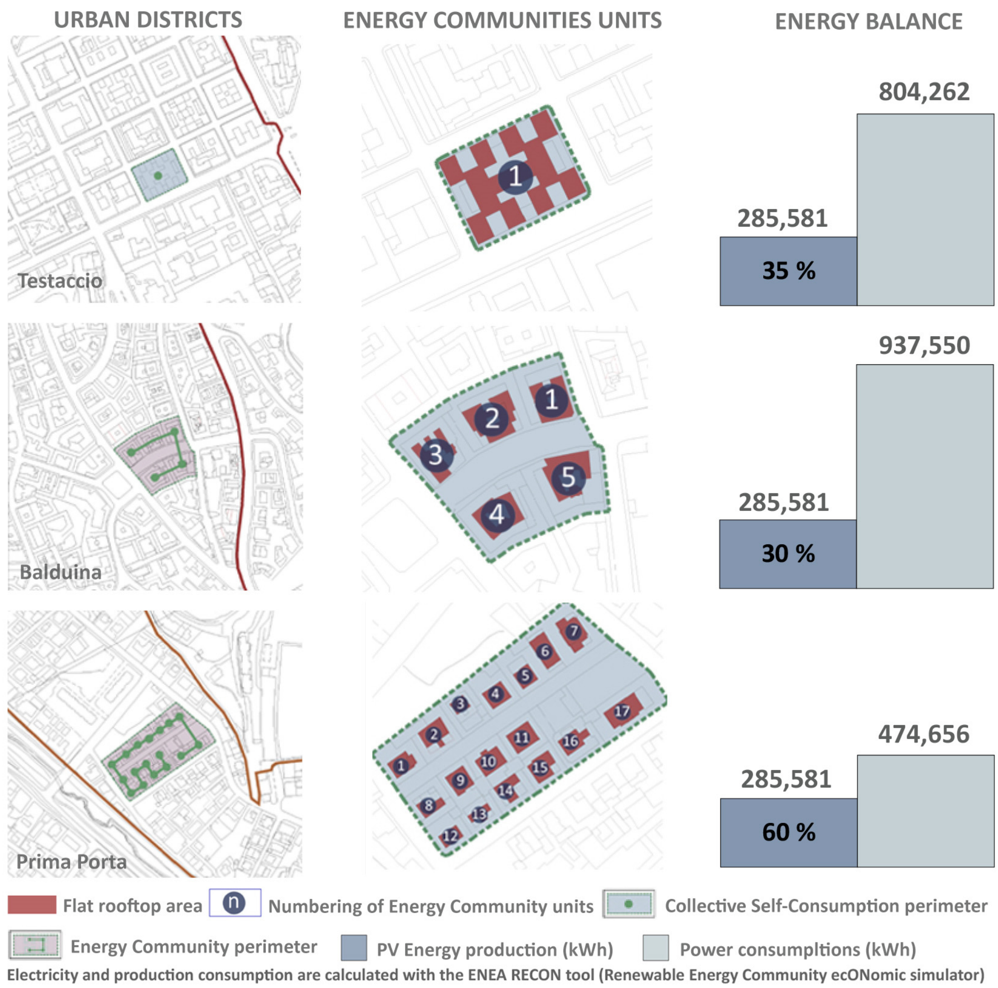


Figure 2. The picture shows the different sizes of Energy Communities and Collective Self-consumption in the Testaccio, Balduina, and Prima Porta neighbourhoods using the same 200 kWp photovoltaic production. The percentage ratio between energy produced by photovoltaics and energy consumed is specified. The source of this image is the article number [43] in the bibliography.

Similarly, in the Prima Porta district, characterised by urban sprawl, with a lower coverage ratio and a lower territorial and building density, although the percentage of consumption coverage is about double that of the other two districts, the prevalent presence of private spaces, and the reduced presence of public spaces, does not easily predispose one to foresee the use of these spaces both for services for common use and for the technological equipment of decentralised energy systems. In this type of fabric, considering the trend of consumption and production possibilities, possible RECs with a limit of 1 MWp could involve around 85 buildings, also represented by as many condominiums, and therefore difficult to manage in both the creation and management phases of RECs. For this reason, in urban fabrics such as this one, smaller energy communities in which synergy between private subjects and the provision of private spaces for the benefit of the community would seem more appropriate; moreover, for all three neighbourhoods, with a prevalence of brick and reinforced concrete buildings.

An essential role is also played by the services that the REC can activate. This is demonstrated by the Testaccio case study, for which the economic financial analysis showed that, by increasing services in the REC, it is possible to improve the return on investment because, by increasing the share of physical self-consumption and instantaneously consuming the energy produced, it is possible to avoid the variable part of grid and system charges. Increasing services means envisaging, for example, using self-generated energy to power car charging stations, compost bins, lighting public spaces, watering green spaces, and so on. All these possibilities will depend on the unbuilt common spaces available in each urban area (Figure 3).

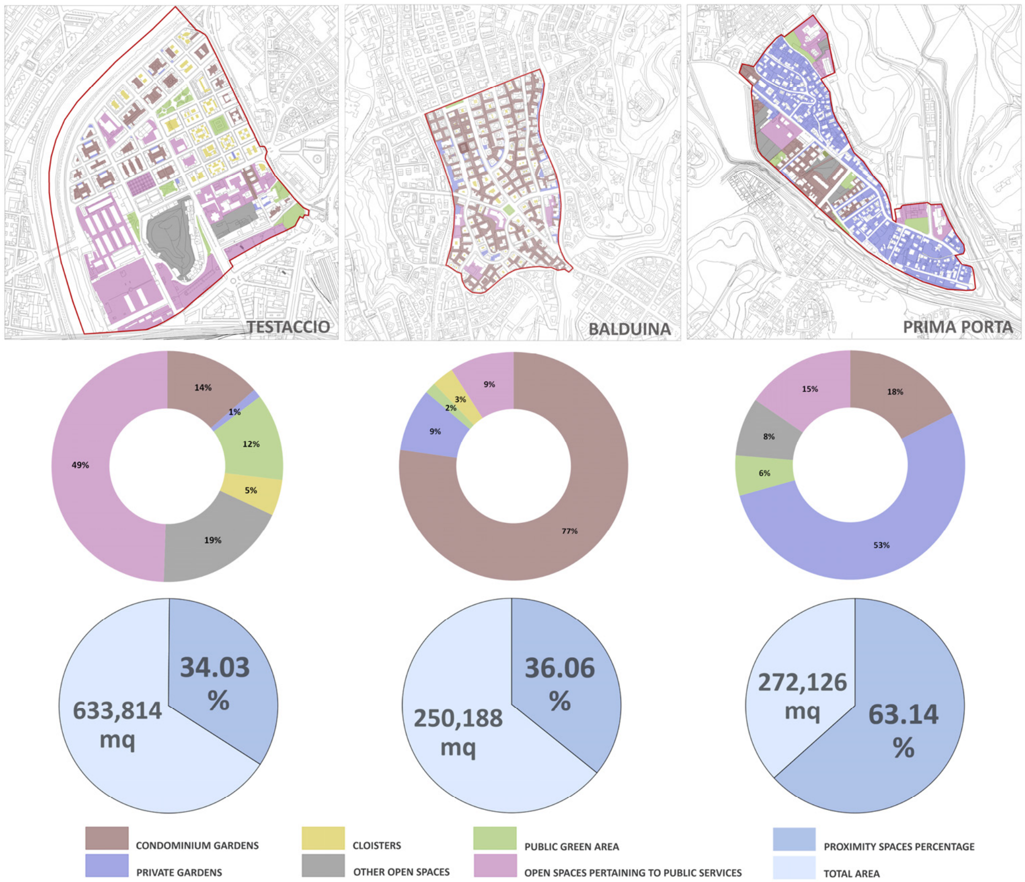


Figure 3. The figure shows maps with the identification and counting of the proximity of open spaces in the districts, also indicating the percentages of the different types of space in each.

The analysis of the three case studies shows, in fact, that precisely because of the presence of numerous courtyards, the Testaccio fabric, characterised by an even public building property, certainly lends itself to accommodating in proximity open spaces, and potential social services in support of the RECs, as, for instance, neighbourhood concierge, medical surgeries, territorial school poles, urban centres, and so on.

The opposite would be the case in the Balduina district, made up of predominantly private buildings, in which spaces for common use, as well as public buildings, are absent. Similarly, the thinned-out urban fabric of Prima Porta with its single-family houses would instead require the identification of more appropriate types of services for a peripheral and now predominantly private context.

Therefore, the preliminary feasibility assessment is an essay on the potential of energy production from REC that depends not only on the technological system, but also and above all on the type of urban fabric, its building and housing density, exposure conditions, and the economic and financial aspects involved (Figure 4).

PHASE	GOAL	DATA FOR EVALUATION	OUTPUT DATA
A. **PRELIMINARY FEASIBILITY ASSESSMENT**   	Preliminarily assessing the potential in terms of energy production from renewable sources (RES) of an urban area from its buildings	**technical feasibility assessment** - climatic characteristics - grid connection (low voltage or medium voltage) - households - energy consumption - electricity-powered end uses: o cooling and/or heating systems o domestic hot water production - thermotechnical characteristics of the dwelling o cooled surface o heated surface o thermal quality of the envelope - characteristics of installations o types of air conditioners o type of fuel in the heating system, o type of generator for domestic hot water production if electric - photovoltaic system type o installed peak power under standard conditions o photovoltaic cell technology (crystalline silicon, CIS thin film, CdTe thin film) - type of module installation o free-standing o on building - inclination with respect to the horizontal plane - orientation with respect to the south direction - average annual percentage of module efficiency loss due to ageing **economic feasibility assessment** - initial cost of the production plant - annual maintenance costs - photovoltaic system management costs - managing the operation of the energy community - average electricity purchase price of the utility directly connected to the RES plant - average selling price of electricity produced by the plant and fed into the grid **financial feasibility assessment** - interest rate - average inflation rate - periodicity of extraordinary plant maintenance (years) - possible financing o duration o number of annual instalments o annual interest rate	- annual electricity consumption and production o total electricity consumption o daytime electricity consumption o plant production o physical self-consumption o energy fed into the grid o shared energy o surplus energy - energy-environmental performance o physical self-consumption index o virtual self-consumption index o total self-consumption index o energy self-sufficiency index o Annual CO2 avoided - investment costs o plant surface o initial plant cost o financing o self-financed initial investment o possible tax deductions - annual running costs o savings from physical self-consumption o savings from energy fed into the grid o total savings and revenue o operation and maintenance costs - return of annual tariff components o shared energy incentives o return of tariff components o network losses avoided - financial indicators o payback time o NPV at 20 years o internal rate of return - IRR o total interest on financing

Figure 4. The figure shows the structure of the parameters useful for the preliminary feasibility assessment.

This first phase pointed out that:

- Morphology and density of the building fabric significantly affect size and configuration of RECs, calling for smaller CERs, or collective self-consumption;
- Little availability of public open spaces and prevalence of spaces of a private nature make it difficult to insert energy production and storage systems outside the roofs of buildings if not through the provision of private outdoor spaces for public use to support RECs;
- The presence of public open spaces is an important feature to implement the social functions of RECs;
- Improving the energy performance of buildings is a prerequisite for being able to balance consumption and production.

3.2. Planning an REC

To draw up maps of the electrical and thermal consumption of individual buildings in a district, a GIS database was constructed representing the energy production capacity based on the areas actually available for photovoltaic systems. Three scenarios were elaborated for both studied neighbourhoods.

Scenario 01 considers current electricity consumption, excluding thermal consumption, calculated on average values from NIPECs 2019, and considering production on public buildings only. This scenario, therefore, takes a snapshot of the current situation and realistically considers the possibility of RECs relying on the surfaces of public buildings only (Figures 5 and 6).

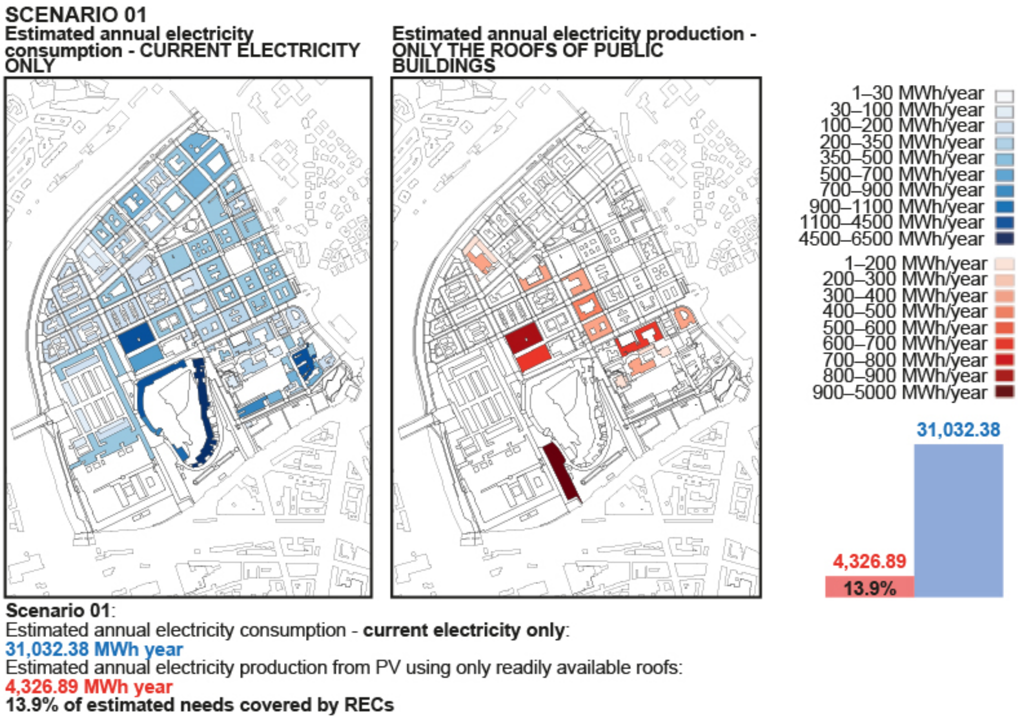


Figure 5. Testaccio_Scenario 01—Estimated consumption (current electricity only) and production (using only the roofs of public buildings).

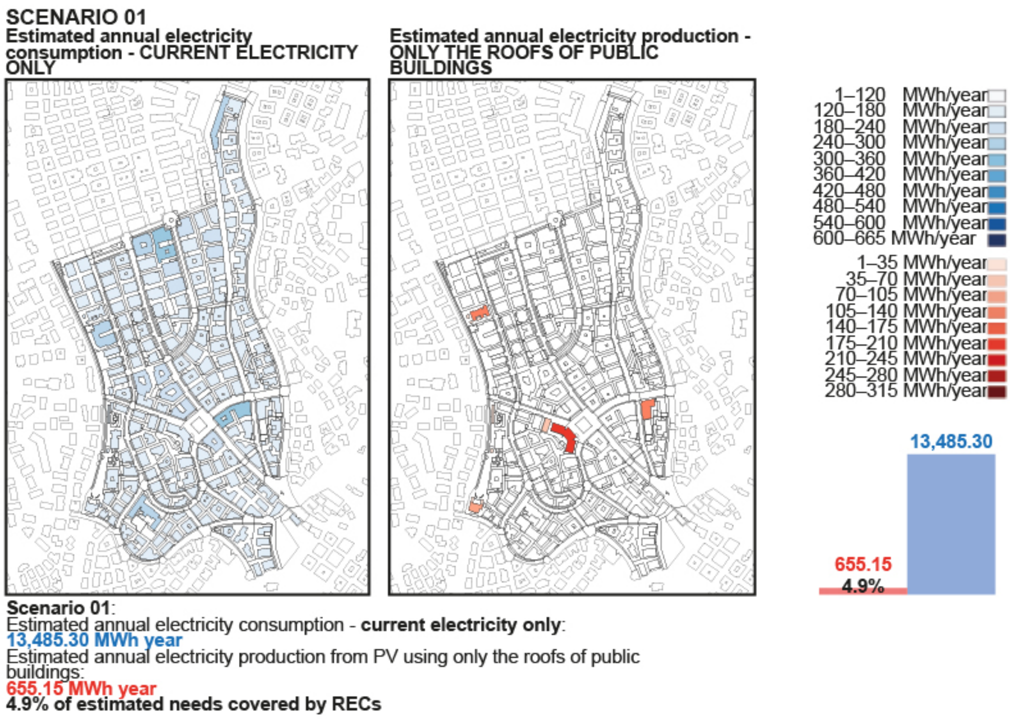


Figure 6. Balduina_Scenario 01—Estimated consumption (current electricity only) and production (using only the roofs of public buildings).

Scenario 02, which is more futuristic, envisages the extension of energy production to all buildings in the district, the electrification of thermal consumption, combined with the installation of heat pumps with a COP 4 performance coefficient. Following the procedure described above, the total electricity demand was calculated and compared with the district's consumption (Figures 7 and 8).

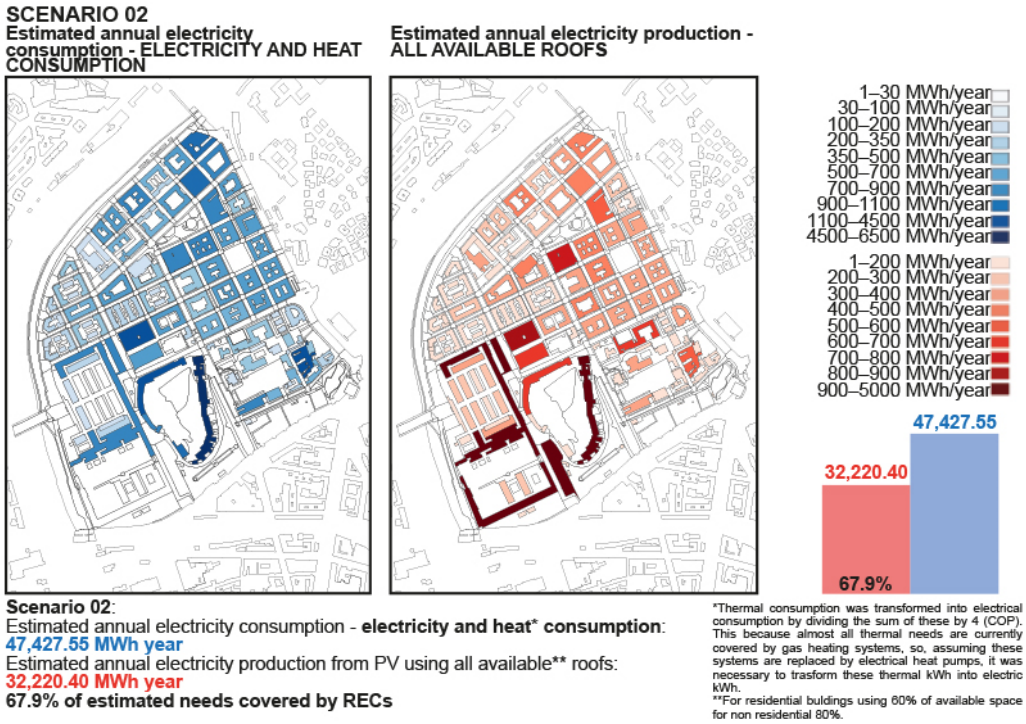


Figure 7. Testaccio_Scenario 02—Estimated consumption (electricity and heat, with electrification of thermal consumption) and production (using all available roofs).

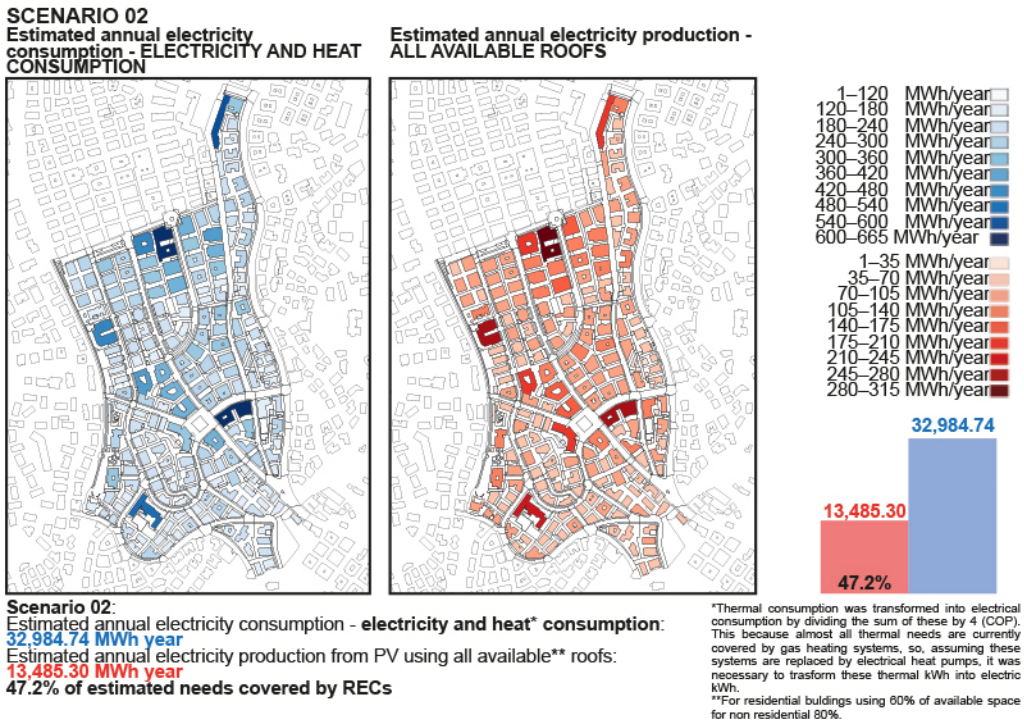


Figure 8. Balduina_Scenario 02—Estimated consumption (electricity and heat, with electrification of thermal consumption) and production (using all available roofs).

Scenario 03 envisaged, in addition to using only the roofs of public buildings and the electrification of thermal consumption, the reduction of dispersion by intervening on the efficiency of the envelope with consumption reduction assumptions of the first 20% (scenario 03a) and then 50% (scenario 03b) (Figures 9–12).

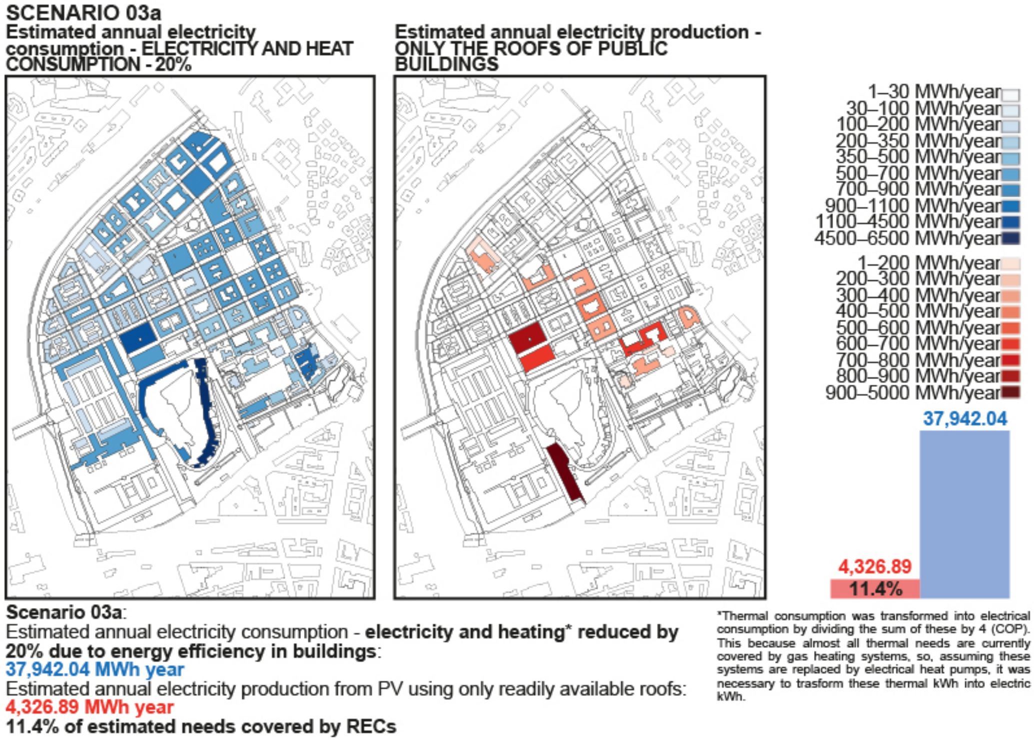


Figure 9. Testaccio_Scenario 03a—Estimated consumption (reduction of 20%) and production (using only the roofs of public buildings).

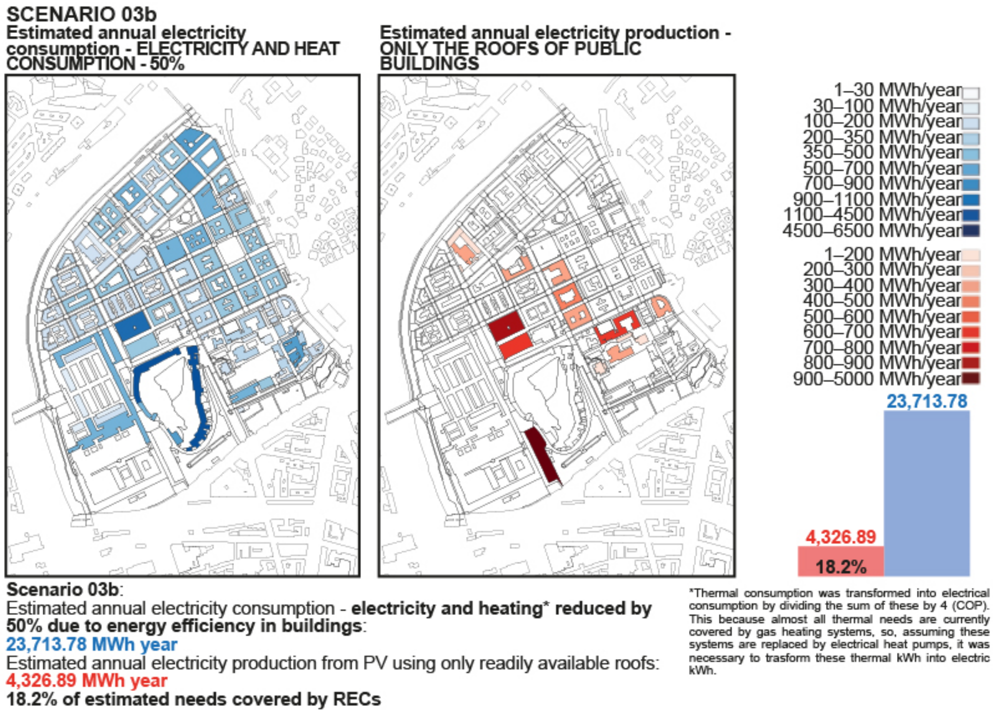


Figure 10. Testaccio_Scenario 03b—Estimated consumption (reduction of 50%) and production (using only the roofs of public buildings).

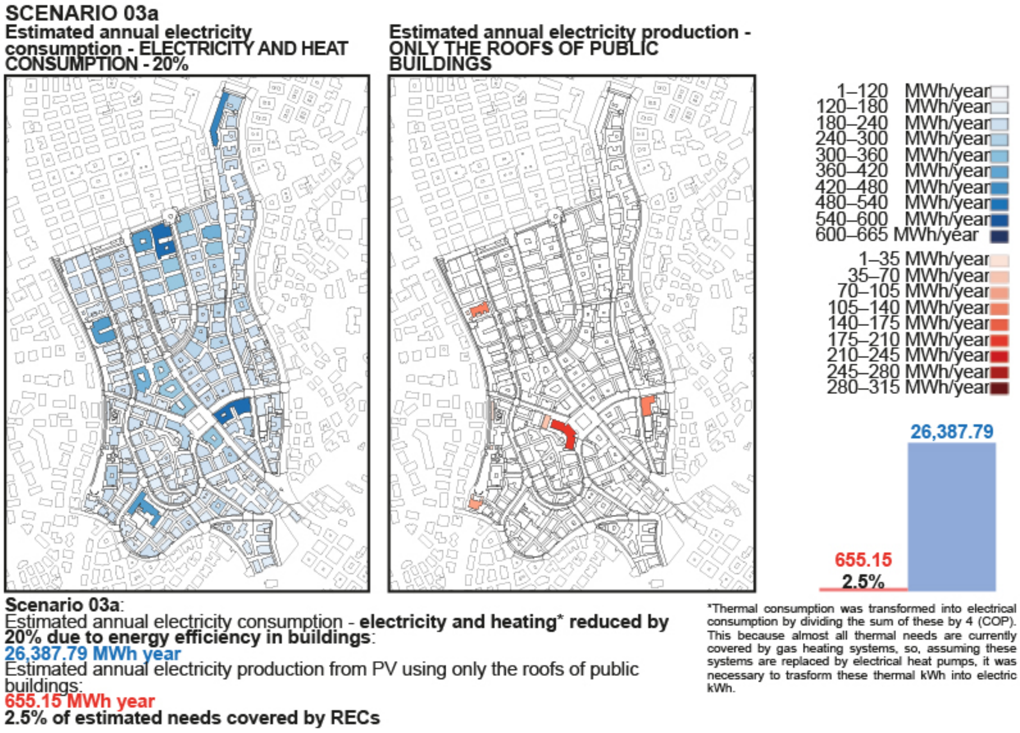


Figure 11. Balduina_Scenario 03a—Estimated consumption (reduction of 20%) and production (using only the roofs of public buildings).

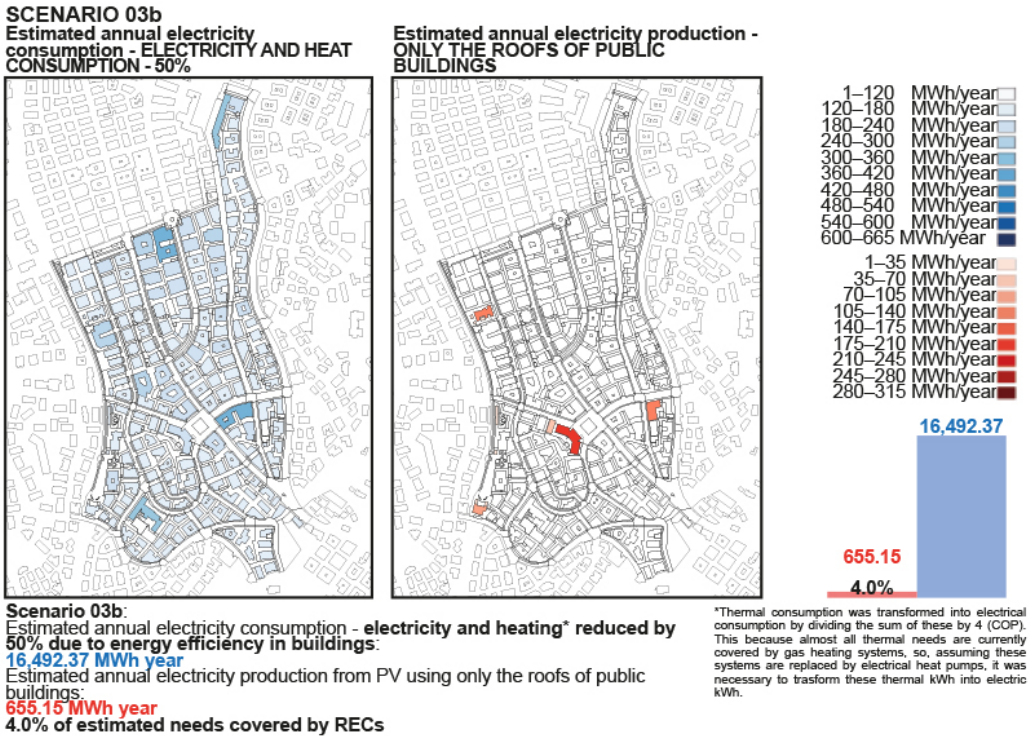


Figure 12. Balduina_Scenario 03b—Estimated consumption (reduction of 50%) and production (using only the roofs of public buildings).

Clearly, the results (Tables 1 and 2) are not comparable between the two neighbourhoods in absolute terms, because they are characterised by different population densities and urban morphology. However, it can be highlighted how, with a population density of about twice as much in Balduina (21.969 inhab/km^2) as in Testaccio (11.720 ab/km^2), and a building density slightly less than twice as high in Balduina (5.74 m^3/m^2) than in Testaccio (2.96 m^3/m^2), the percentage of production in scenario 01 (energy production only on public buildings) in both districts shows an inverse result, with 13.9% of total consumption covered by RES in Testaccio, and only 4.9% of total consumption in Balduina.

Table 1. Results of Testaccio simulations in tabular form.

Scenario	Estimated Consumption	Estimated Production	% Needs Covered by RECs
Scenario 01	31,032.38 MWh year	4326.89 MWh year	13.9% REC covered
Scenario 02	47,427.55 MWh year	32,220.40 MWh year	67.9% REC covered
Scenario 03a	37,942.04 MWh year	4326.89 MWh year	11.4% REC covered
Scenario 03b	23,713.78 MWh year	4326.89 MWh year	18.2% REC covered

Table 2. Results of Balduina simulations in tabular form.

Scenario	Estimated Consumption	Estimated Production	% Needs Covered by RECs
Scenario 01	13,485.30 MWh year	655.15 MWh year	4.9% REC covered
Scenario 02	32,984.74 MWh year	13,485.30 MWh year	47.2% REC covered
Scenario 03a	26,387.79 MWh year	655.15 MWh year	2.5% REC covered
Scenario 03b	16,492.37 MWh year	655.15 MWh year	4.0% REC covered

This inversion highlights how a predisposing factor of the areas also lies in the presence or absence of public buildings as possible energy drivers. In fact, comparing the surface area of the footprint of residential buildings and public buildings with respect to the total surface area of the urban area considered, it can be seen that while in Balduina, against a percentage of residential buildings of 35.81%, the percentage of public buildings is only 1.31%; in Testaccio, against a much lower percentage of residential buildings of 15.35%, the percentage of public buildings is much higher, reaching 6.36%. This is supported by the fact that the surfaces available on public buildings for production are about five times more in Testaccio than in Balduina, covering about 16,377 m^2 in Testaccio, and only about 3586 m^2 in Balduina, corresponding to 60% of the flat roofs of residential buildings, 80% of the flat roofs of public buildings, and 100% of pitched roofs.

Conversely, when considering the more futuristic scenario 02 that considers using all building roofs, the difference between the two neighbourhoods is not so evident as shown by the two percentages of coverage of energy production from RES compared to needs (67.9% in Testaccio; 47.2% in Balduina).

Another comparison consideration between the two urban fabrics lies in the availability of outdoor areas, which determines their greater or lesser predisposition to support decentralised energy systems. In particular, it can be seen that in the area considered in Testaccio, compared to that in Balduina, in addition to the areas available for production on buildings, there is a predominant presence of other surfaces available in open spaces with a percentage in Testaccio of 6.33% of production on the surfaces available in open spaces and 93.67% of production on buildings, and in Balduina with the total of production on buildings and a complete absence of surfaces in other open spaces available for production (Figures 13 and 14).

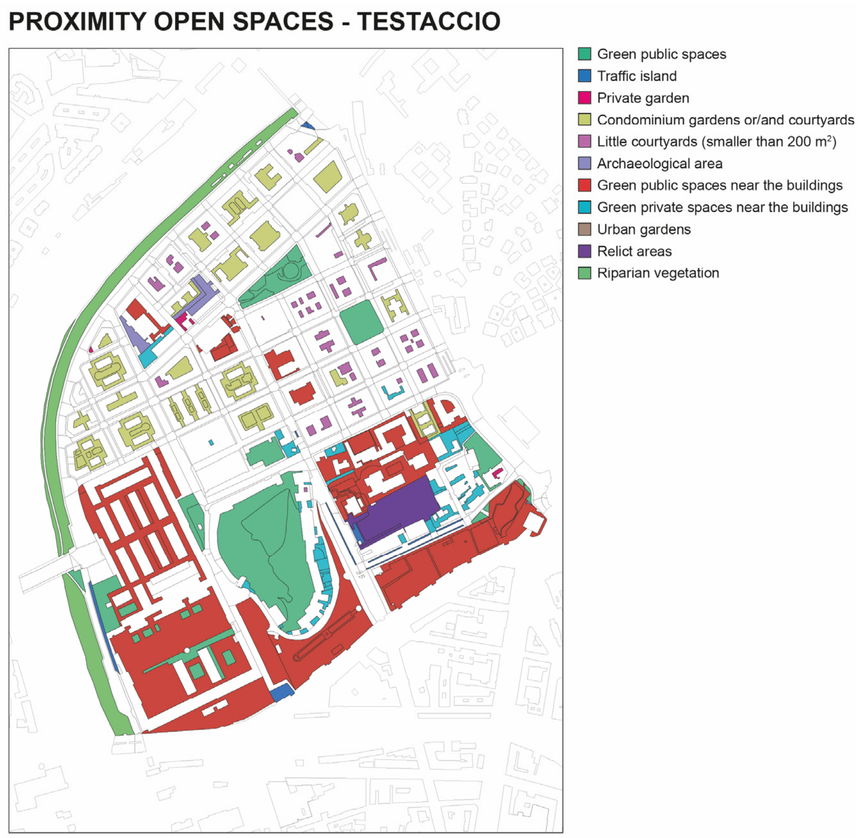


Figure 13. Testaccio_Map of proximity open spaces.

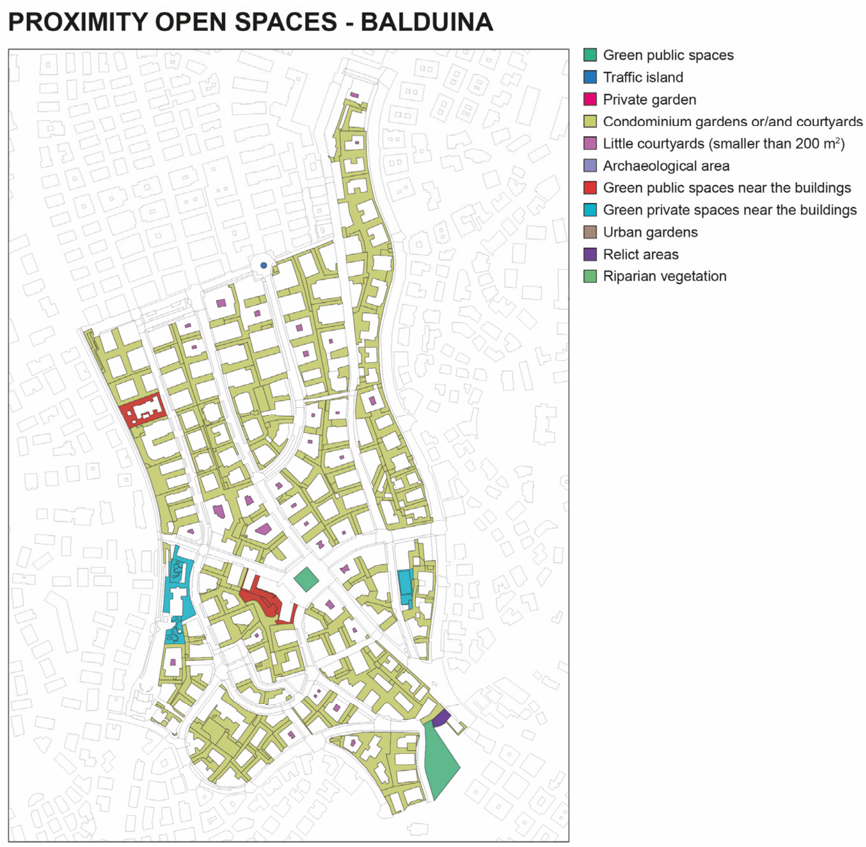


Figure 14. Balduina_Map of proximity open spaces.

Therefore, in neighbourhoods with scarce availability of other areas for production, one can think of allocating part of the other public areas for this purpose or, as a last resort, decentralising production to other contexts further away from the neighbourhood (Figure 15).

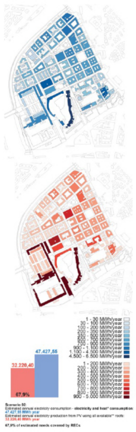
PHASE	GOAL	DATA FOR EVALUATION	OUTPUT DATA
B. **PROGRAMMING** 	Outline intervention scenarios to guide strategies aimed at planning Renewable Energy Communities in an urban area	**population** - inhabitants **energy consumption** - electricity consumption - thermal consumption **characteristics of the urban fabric** - total neighbourhood area - volume of existing buildings - floor area (footprint) residential buildings - ground area (footprint) public buildings - total surface area open spaces o surface area of public green areas o private gardens o communal gardens and/or courtyards o cloisters (smaller than 200 m^2) o archaeological areas o open spaces pertaining to public services o open spaces pertaining to private services and productive activities o urban gardens o other areas (roads and relict areas) **surfaces available for RES installation on the roof of buildings** - available surface area covering residential buildings o flat roofing surfaces o inclined roofing surfaces for orientation - available surface area covering public buildings o flat roofing surfaces o inclined roofing surfaces for orientation o surfaces available for installation in open spaces - area available in proximity open spaces **production** - production on building roofs - production on open areas - total production	- electricity consumption map - heat consumption map (electrified) - energy production map on building coverage (residential and non-residential) - map energy production in available open spaces

Figure 15. The figure shows the structure of the parameters useful for the programming phase.

This second phase pointed out that:

- The correlation between population density, building density, and the percentage of consumption and production are decisive elements in the predisposition of a building fabric to the creation of RECs;
- The presence of public buildings determines a greater susceptibility to immediate energy decentralisation and REC creation, both because of the greater ease of management of mediation synergies that it requires, and because of the greater energy flexibility due to the different energy use profile between residential and public destinations;
- The availability of areas outside the buildings determines the greater or lesser predisposition to support decentralised energy systems, determining, in particular, in the fabrics with a higher percentage of spaces, a greater predisposition to the insertion of energy production and storage systems; in the fabrics with a low percentage of outdoor spaces, on the contrary, a lower predisposition to accommodate production and storage systems, and a tendency to decentralise remote production to more peripheral contexts are evidenced.

3.3. Designing an REC

To search for the best balance between available energy from the sun and consumption by the users, even in conditions of insufficient irradiation through storage systems, PVGIS software was used in off-grid mode for the simulation of isolated systems, and the following input parameters were entered: installable power data, azimuth angle, tilt angle, system type, losses, battery capacity, battery discharge cut-off limit, and daily energy consumption.

As an example, the simulation and subsequent complete analysis of a flat-roofed building for residential use and a mixed-roofed building for public use is shown here.

In the flat-roofed building for residential use, the simulation was carried out in off-grid mode, and the building, the details of which are shown here (Figure 16), the roof is utilised for 60 per cent of the area assuming the installation of 1 kWp per 12 m^2 with monocrystalline silicon technology and free-standing configuration.

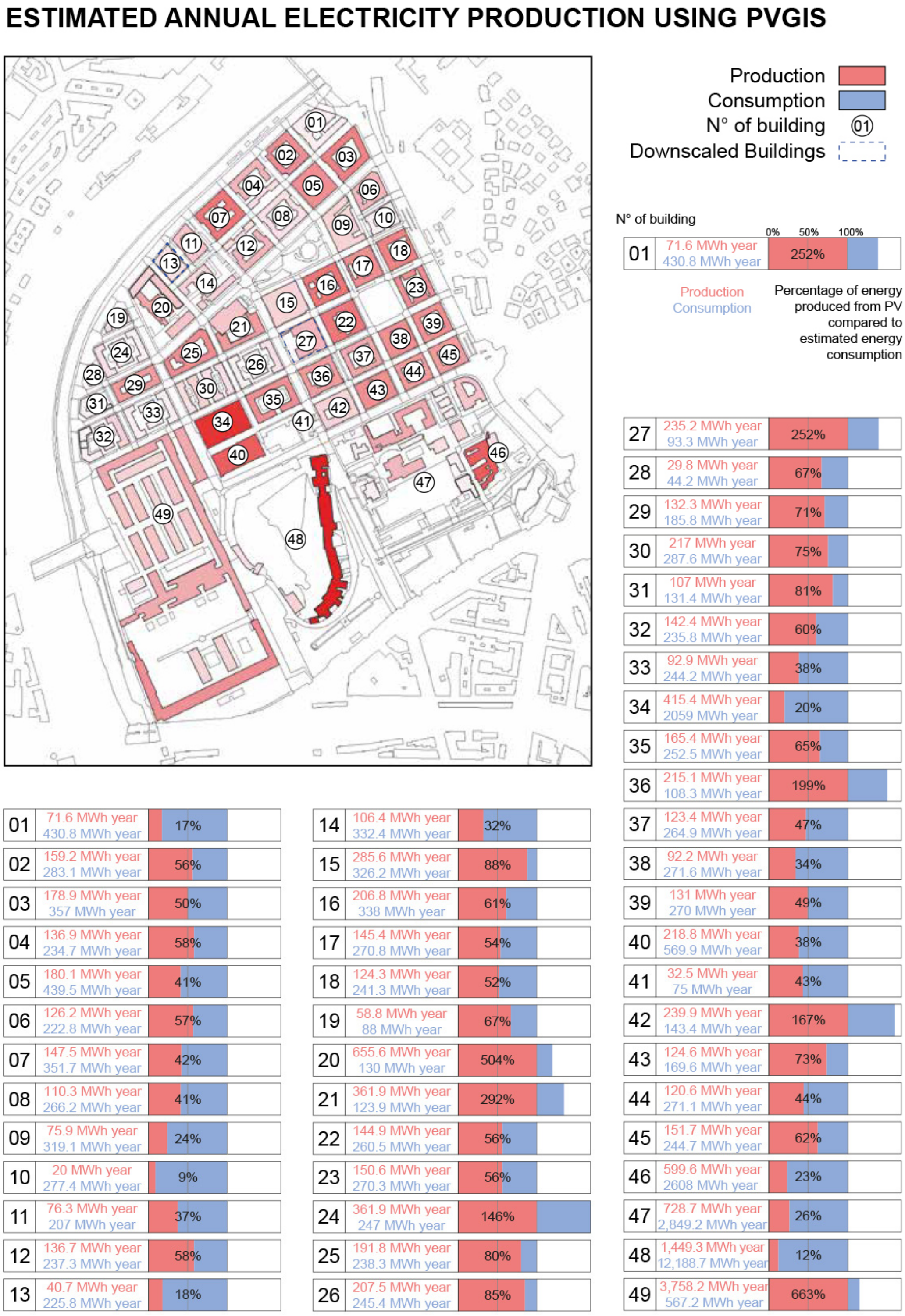


Figure 16. Testaccio_Electricity production map of actual scenario estimated through PVGIS for each building.

The power that can be installed in the building is 31.1 kWp, and from the annual electricity consumption of 225,765 kWh, estimated in GIS for the current scenario, the building's daily consumption is approximately 618,534 kWh.

To estimate the size of the accumulator, two simulations were performed with different sizes considering, for the first, to use a 62.2 kWh battery and to accumulate twice the peak power supplied by the system in one hour and, for the second estimate, to use a halved battery of 31.1 kWh and to accumulate exactly the peak power of the system in one hour.

To verify the effectiveness of the building's 31 kWp system, simulations were carried out using the PVGIS tool. The software outputs an array of 12 values, one for each month of the year, relating to the monthly average of the daily energy produced and used. By multiplying each of these values by the number of days in the corresponding month, after summing these monthly values, it was possible to calculate the energy that the plant can produce and that can actually be used by the load. Similarly, PVGIS provides an array of 12 values for the monthly average of energy lost; following the same procedure, it is possible to calculate the annual energy that is produced but not used, and all these values of the monthly average of daily energy produced and used or produced and wasted are collected in Table 3.

Table 3. Monthly average values of daily energy produced and used and produced and wasted using a 31.1 kWh battery and a 62.2 kWh battery, respectively. From these values, it is possible to obtain the total energy used and wasted in each month and, after, in the year.

Output Parameters of Simulation	Smaller Battery	Larger Battery
Monthly averages of energy used (Wh)	72,219.6	72,517.1
	88,932.36	91,111.03
	106,319.13	111,372.79
	118,720.1	125,393.15
	128,689.31	135,197.25
	140,519.63	147,087.51
	145,540.53	153,163.72
	136,546.54	143,575.14
	114,399.77	118,920.28
	92,840.42	94,684.71
	73,704.04	73,858.28
	70,257.08	70,257.08
Monthly averages of energy wasted (Wh)	297.5	0.0
	2178.67	0.0
	5066.46	12.79
	6676.11	3.07
	6508.4	0.47
	6567.88	0.0
	7623.19	0.0
	7028.6	0.0
	4520.51	0.0
	1844.29	0.0
	154.25	0.0
	0.0	0.0

The total energy produced by the solar system is the sum of the energy produced and used and the energy produced and lost and is 40,713.19 kWh per year. The estimate of the total energy remains the same by varying the size of the battery; however, the share of energy used and, consequently, of energy lost, changes. In the simulation with the smaller battery size, the energy produced and utilised was 39,235.2 kWh per year, while the energy lost was 1477.98 kWh per year. In the simulation with the larger size accumulator, the energy used was 40,712.68 kWh per year and the energy lost was 0.50 kWh per year.

Following the estimation of the energy produced, it was possible to calculate the actual energy balance, i.e., the difference between the energy produced and used and the consumption (the actual balance is subject to change by varying the size of the accumulator), and the total balance, i.e., the difference between the total energy produced and consumed.

The actual balance obtained for the building is −186,530.02 kWh per year with the smaller accumulator and −185,052.54 with the larger accumulator. The total balance in both simulations remains at −185,052.03 kWh per year.

To choose the most suitable accumulator, it was assumed that lithium technology would be used. To get an idea of the possible space occupancy and costs associated with current storage technologies on the market, a battery from the RESU range produced by LG Chem was identified, with a volumetric energy density of 0.152 Wh/cm^3 and cost per unit of energy of EUR 0.727/Wh [46]. It should be emphasised that the costs of modern batteries are constantly falling; in fact, lithium-ion technologies are already commercially available with lower costs (by around 20%) than the data provided in the documentation used in this work. In order to analyse the batteries, an assessment was made with respect to cost, the percentage of days when the battery becomes full, and the space occupied as specified below:

- Smaller battery size—the percentage of days with a full battery is 48.17%, with a space occupancy of 204,605.25 cm^3 and an expected expenditure certainly lower than the EUR 22,000 estimated with the technology data considered in this work;
- Larger battery size—the percentage of days with a full battery is 0.19%, with a space occupancy of 409,210 cm^3 and a cost of less than EUR 45,000.

It should be noted that the scenario simulated in this case is the existing one, and therefore, the portion of annual electricity consumption and daily building consumption, on the basis of which the energy and storage portions were calculated, does not include consumption attributable to heating and cooling systems, nor any intervention on the building envelope to reduce consumption. Therefore, the percentage coverage of electricity consumption by energy from RES is also relative to the existing scenario.

Against this aforementioned consideration, it can be seen from the results that, with the smaller accumulator, the energy used is lesser than in the case with the double battery, and the actual energy balance is more disadvantageous as the balance is negative, albeit with half the space occupied and half the cost. Finally, for the case with the smaller accumulator, the value of 48% when the battery is full is acceptable and, at the same time, in the case with the larger accumulator, the actual balance is more advantageous despite the fact that the space occupied and the cost doubled, and the percentage of 0.19% of the days with a full battery is too low to be acceptable. The parameters of interest from this analysis are collected in Table 4.

The building with a mixed roof for public use, on the other hand, is characterised by the coexistence of pitched roofs, with a pitch of approximately 20 degrees, and flat roofs.

In the simulation, it was therefore necessary to separate the contributions, distinguishing the pitches according to their orientation with respect to the south, and it was not possible to make considerations similar to the case with exclusively flat roofs.

For the building considered, with public use, the flat area is 1215 m^2, 80% exploitable, i.e., 972 m^2. The pitches were grouped according to orientation into two groups, the first with an area of 264 m^2 and an inclination of 26° to the south, and the second with an area of 243 m^2 and an inclination of 64° to the south.

For the flat roof, an installable capacity of 1 kWp for every 12 m^2 was considered, giving a total of 81 kWp; for the pitches, 1 kWp for every 6 m^2, giving a total of 44 kWp for the first group of pitches and 40.5 kWp for the second group of pitches, giving a total estimate of 165.5 kWp.

In order to size the accumulator, double and triple the kWp size is again assumed, assuming to store double or triple the peak power in one hour.

Table 4. Summary of the relevant parameters deriving from the study, the simulations, and the analysis of the simulation results, characterising a residential building located in the Testaccio district (RM), assuming the installation of a 31.1 kWp photovoltaic system.

Simulation of a Plant Power of 31.1 kWp in a Residential Building with 225,765 kWh of Annual Consumption	Smaller Battery	Larger Battery
Battery size (kWh)	31.1	62.2
Annual energy produced and used (kWh/y)	39,235.2	40,712.68
Annual energy produced and wasted (kWh/y)	1477.98	0.5
Total annual energy (kWh/y)	40,713.19	40.713,19
Effective energy balance (kWh/y) Total energy balance (kWh/y)	−186,530.02 −185,052.03	−185,052.54 −185,052.03
Percentage of days with full battery (%)	48.17	0.19
Battery occupation (cm^3)	204,605.25	409,210.50
Battery cost	>EUR 22,000	>EUR 45,000
Battery size (kWh)	31.1	62.2
Annual energy produced and used (kWh/y)	39,235.2	40,712.68
Annual energy produced and wasted (kWh/y)	1477.98	0.5

Two accumulators were assumed, one with 331 kWh, the second with 496.5 kWh, whose estimated costs and space occupancy are respectively less than EUR 240,000 in 2,177,631 cm^3 and less than EUR 360,000 in 3,266,447 cm^3. As far as the cost estimate is concerned, the previous considerations regarding the continuously decreasing price trend associated with modern storage technologies remain valid.

The expected production summing the contributions of the three available surfaces (flat roof, pitched roof with 26° inclination, pitched roof with 64° inclination) is 235,170.8 kWh, with a total energy balance (calculated by the difference between production and annual consumption), positive, and +141,869.08 kWh, capable of satisfying the needs of the entire building, with an energy surplus that could potentially be exploited by other ERC buildings, or with a view to increasing future electrification, which could partially or totally cover current thermal consumption, as the case may be. All the relevant results are collected in Table 5.

Table 5. Parameters of interest in the analysis of energy production from a photovoltaic system on a public building in Testaccio (RM) characterised by flat roofs and pitched roofs, assuming the installation of a 165.5 kWp photovoltaic system.

Simulation of a Plant Power of 165.5 kWp in a Public Building with 93,301.74 kWh of Annual Consumption	
Annual energy produced (kWh/y)	235,170.82
Energy balance (kWh/y)	+141,869.080
Battery 1 (kWh) Battery 2 (kWh)	331 496.5
Cost battery 1 Cost battery 2	>EUR 240,000 >EUR 360,000
Battery 1 occupation (cm^3) Battery 2 occupation (cm^3)	2,177,631 3,266,447

The positive balance condition, although atypical in a city like Rome, can be attributed to the use of public buildings which, as is well known, often have lower consumption profiles than residential buildings, opening up interesting scenarios of energy sharing and assuming the role of energy flywheels supporting the neighbourhood (Figure 17).

PHASE	GOAL	DATA FOR EVALUATION	OUTPUT DATA
C. DESIGN 	Define the technical and dimensional characteristics of the technological components of an autonomous energy system	**surfaces available for RES installation on the roof of buildings** - available surface area covering residential buildings ○ flat roofing surfaces ○ inclined roofing surfaces for orientation - available surface area covering public buildings ○ flat roofing surfaces ○ inclined roofing surfaces for orientation ○ surfaces available for installation in open spaces - area available in proximity open spaces **technological features** - installable power ○ typology ○ peak power - azimuth angle - tilt angle - type of PV module installation ○ free-standing ○ on building - leaks - battery capacity - battery discharge cut-off limit **daily energy consumption** - electricity consumption - thermal consumption	- surface area required by the production system - space occupied by the storage system - monthly average of the daily energy produced and used by the load or stored; - monthly average of daily energy produced but not used or stored (full battery) - monthly average of battery full charge frequency or cut-off value - annual average of missing energy and lost energy

Figure 17. The figure shows the structure of the parameters useful for the designing phase.

From these values obtained as output from the simulations in PVGIS, it is possible to make further analyses to assess the real efficiency of the REC production system, calculating the portion of energy produced and used and produced and lost, and the portion of missing energy and the total energy produced; finally, estimates can be made of the real energy balance and the ideal hypothetical balance if all the energy produced were used.

In addition, it is possible to make assessments on the size of the storage system, since undersizing a storage tank results in a greater loss of energy, while also nullifying the action of a large production system, and oversizing it results in higher costs and wasted space and materials, so attention must also be paid to the correct sizing of it.

Therefore, from the outcome of the simulations, the storage system is also sized, starting with the percentage of days when the battery is full because, if it does not exceed 50%, its size will probably already be large enough; if it falls below 25%, it will probably be too large; if it exceeds 50%, its size will probably be too small with the risk of having more than 50% of days when the energy cannot be stored and, if not used by consumers, will be wasted. The desirable condition is between 50% and 75%, and the optimum estimated in this work is between 45% and 55%.

For composite buildings, consisting of several distinct blocks with morphologically different roofs, PVGIS simulations cannot be conducted in off-grid mode, because it would be impossible to connect the production contributions of the different strata by reliably distributing the consumption of the entire building between the different areas.

The proposed approach is to simulate the output of the different areas separately, each with its own physical and geometric characteristics, and finally, add up all contributions to estimate the overall output of each building.

Following the evaluation of the input parameters to carry out the simulations, the results obtained and through subsequent analysis of the output data, certain information can be obtained, such as:

- Surface area of photovoltaic panels that can be installed;
- Energy produced;
- Energy consumed;
- Energy lost;
- Missing energy;
- Sizing of storage;

- Storage battery footprint;
- Frequency of battery charging.

This third step highlights how:

- At the REC design level, the specificity of each building requires a careful choice of system and a specific evaluation. In fact, the balances of the two buildings analysed show that in one case, the balance is positive and in the other not;
- The dimensioning of RECs by comparing consumption and production capacity must be accompanied by the analysis of lost energy and missing energy in order to correctly size the storage system as well;
- The correct sizing of the storage system allows costs to be saved and space to be optimised, which, especially in urban contexts with limited availability, becomes essential;
- To aspire to the horizon of decarbonisation without correctly quantifying the right balance between energy produced, energy consumed, energy lost, energy missing, sizing, costs, and storage spaces, does not allow one to effectively quantify the capacity of an urban context to affect the transition.

4. Conclusions

Recent European directives and initiatives are pushing member states to implement measures aimed at decarbonising their activities. Among these, decentralised energy systems, although already tried and tested in various contexts and with various configurations, are now an unavoidable possibility, also in light of the various crises underway.

Cities have thus begun to confront the need to make themselves energy self-sufficient by exploiting renewable sources and, above all, to evaluate the potential and constraints that each can express by virtue of their own characteristics.

Decentralising energy production requires an expert assessment of the actual resources available in the area, such as the environmental conditions that characterise it and direct it towards the most appropriate energy sources; the space actually available with respect to prevailing consumption and any constraints imposed by regulations at various levels, and the people living there and their ways of using it.

All these characteristics become founding elements of a new geography of network infrastructures which, consequently, also requires substantial intervention in the existing urban fabric, assessing its constraints or compatibility. It is also for these reasons, in addition to the implementation complexities related to the rules governing RECs, that the various experiments undertaken so far have been limited to small towns where the management of procedural, technical, social, and economic complexities is certainly less complex than in densely built-up urban contexts.

In fact, it is interesting to highlight how the realisation of decentralised energy systems in urban contexts, consolidated and characterised by different types of building fabric, is not an intervention that can be implemented exclusively by resolving the technical issues inherent in the design of an energy production system from renewable sources. On the contrary, it needs to first identify and build a community regulated by a statute, to recognise the collective services that can support its social role, and to identify spaces that are available to house the components of the technological system necessary for the production, storage, and distribution of energy [48].

Certain factors are decisive for the feasibility of an REC:

- The energy production needs to be actually achievable, quantifying the m^2 of building and open space areas for the location and sizing of the production and storage system;
- Energy needs, assuming in kWh per year, household consumption, and collective consumption of buildings in relation to their intended use and settled inhabitants;
- Savings, assuming in kWh per year the reduction in energy consumption achievable through energy efficiency and mitigation measures;
- The possibility of integrating the components of the energy system into the context, assuming the characterising elements of the urban landscape and the possible con-

straints related to urban morphology, site identity, historical value, and the visibility of the installations from the context;
- The social value recognised by the REC and the desire for participation, assuming the active role of the inhabitants in enhancing local resources through the promotion of community-based production aspects to govern energy needs and encourage its collective and shared use.

The study proposed here sought to understand how the realisation of an REC could be approached in urbanised contexts by choosing three case studies in the city of Rome, representative of different types of building fabric, housing density, building characteristics, construction periods, the relationship between built and open spaces, and energy consumption. Through simulation at three levels of detail, the study identified some elements necessary to assess the feasibility of an REC, to elaborate scenarios to support their planning also in synergy with other climate mitigation interventions, to size them considering the interaction between available surfaces, installable power, energy needs, and storage systems.

Three possible methodological paths emerged from the simulations with the relevant factors that public or private stakeholders can implement at different levels if they are interested in setting up RECs in an urban context: a first level is that of a preliminary expeditious assessment to establish the technical feasibility and economic financial viability; the second level concerns the planning of intervention strategies according to scenarios, and the third level deals with questions concerning the design of the REC by defining its size.

From these simulations, the specificities of a context affect many factors, among which the dimensional, exposure, and location characteristics of the spaces and surfaces available to accommodate the components of the energy system, here considered in the sense of photovoltaic panels, are certainly of priority.

However, a very important role is played by the facilities and spaces for public use in each area of the city, as they are synergetic to a shared use of energy between residential and non-residential functions, but above all, because they are also available to accommodate services for the energy community. To this consideration must also be added the need, given the imbalance between the not always sufficient production and the relative demand for energy, to accompany the realisation of RECs with energy efficiency measures in order to guarantee the decarbonisation objectives shared at the European level. This would also allow public administrators to be realistic in their policies, demonstrating through scenarios the gradual and necessary steps to achieve them.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

EU	European Union
EGD	European Green Deal
NRP	National Recovery and Resilience Plan
NEB	New European Bauhaus
RES	Renewable energy sources
CO_2	Carbon dioxide
REC	Renewable energy community
RECs	Renewable energy communities
ENEA	Agenzia Nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile (National Agency for New Technologies, Energy and Sustainable Economic Development)
RECON	Renewable Energy Community ecONomic simulator
kWp	Kilowatt peak
NIPECs	Integrated National Energy and Climate Plans
COP	Coefficient of performance
RED	II Renewable Energy Directive II (EU n. 199/2021)
MWp	Megawatt peak
kWh/m^2	Kilowatt-hour/square metre
inhab/km^2	Inhabitants/square kilometre
m^3/m^2	Cubic metre/square metre
PVGIS	Photovoltaic Geographical Information System
SARAH-2	Surface Solar Radiation Data Set—Heliosat—Second Edition
MATLAB	Matrix Laboratory—numeric computing platform
m^2	Square metre
kWh	Kilowatt-hour
GIS	Geographic Information System
Wh	Watt-hour
RESU LG	Name of battery
Wh/cm^3	Watt-hour/cubic metre
€/Wh	Euro/watt-hour
cm^3	Cubic metre
RM	Rome
PV	Photovoltaic
PRIN	Projects of relevant national interest

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