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Towards the energy optimization and decarbonization of urban settings: proposal of a strategy at Neighbourhood Level to Foster Nearly Zero and Positive Energy Districts

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***Abstract*—Optimizing energy management in urban contexts has been one of the biggest challenges of the last decades for both the scientific community and international governments to pursue carbon neutrality, enhance energy security and promote energy equity and accessibility. In this regard, particular emphasis has been given by the EU and its member States on improving the energy performance of built environments by reducing building energy consumption (implementing adequate retrofit interventions) and fostering the integration of renewable energy sources (RES) to achieve the conditions of Nearly Zero and Positive Energy Districts. To this aim, the most recent energy-environmental initiatives promote as an effective solution the joining of energy users into groups/units (e.g., Energy Communities, consortia, etc.) which usually include buildings located in portions of territory, i.e. districts that share and collaborate in the management of energy supply and consumption. The case study presented in this paper intends to provide a contribution to this matter by using a modeling/simulation-based approach involving the evaluation of different scenarios of energy efficiency measures, i.e. building envelope retrofit interventions, RES integration and their combination, in a historic existing neighborhood. The analysis aims at identifying which are the most effective strategies to implement at district level in a typical Southern Italy building context.**

***Keywords*—Urban Energy Efficiency, Positive Energy District, Nearly Zero Energy District, Building Simulation, Energy Efficiency, Building Envelope Retrofit, RES Integration.**

I. Introduction

Buildings represent one of the largest energy consumers worldwide, in Europe and in Italy, being responsible for about 40% of the total energy consumption and greenhouse gases emissions in urban areas. In particular, heating and cooling are the uses for which nearly 50% of the total energy consumption is spent [1-4]. In light of this, the optimization of the energy management in urban contexts has been one of the biggest challenges of the last decades for both the scientific community and governments bodies to pursue carbon neutrality, enhance energy security and promote energy equity and accessibility [5], which has been even more highlighted by the intensification of the energy-economic crisis due to the recent Ukraine-Russia conflict related events.

Among the most relevant policies/initiatives concerning the issues of urban energy efficiency and carbon neutrality are the UN Sustainable Development Goals – SDGs (particularly, "Goal 11 – Make cities and human settlements inclusive, safe, resilient and sustainable", "Goal 12 – Responsible consumption and production" and "Goal 13 – Climate action") [6] the EU climate-energy frameworks long-term strategies [5, 7], Green Deal [8] and recovery plan Next Generation EU [9]. These two latter strategies, in particular, are focused on the dual green and digital transition that aim to make Europe the first climate-neutral continent by 2050. Consistent with what these European initiatives foresee, Italy has recently enacted the National Recovery and Resilience Plan – PNRR [10], which is the most recent and decisive drive to initiate a major green transition process. As part of the main objectives of the PNRR is, in fact, also the increase in urban energy savings by enhancing the level of efficiency of buildings; this is a strategic objective for a country like Italy, where 60% of the building stock has an average age of more than 45 years [11, 12]. Moreover, improve the energy performance of the building stock would also contribute to the reduction of foreign energy dependency, hence help in enhancing energy security as encouraged by the EU [5].

In this regard, the well-known concept of nearly zero-energy building – NZEB (introduced by the EPBD Directive [13, 14]), according to which buildings need to be (and/or aspire to be) self-energy-sufficient, has recently expanded to that of Positive Energy Building (PEB) [15]. According to it, buildings can use renewable energy sources (RES) to produce more energy than they need and, therefore, exchange the surplus among them and/or other types of consumers, hence reasoning in terms of Nearly Zero District (NZED) and Positive Energy District (PED) [16, 17]. This is in analogy with what was proposed by a recent Directive introducing the concept of renewable Energy Communities (EC) [7] and their

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interaction/integration with the local/national electricity systems. In PEDs, in fact, the demand and supply of renewable energy can be unevenly distributed within the district, which push towards a more strategic implementation of renewable energy generation and storage systems [18].

To meet these pressing needs, the scientific community together with administrative and economic actors have been committed in finding measures intended at improving the energy and environmental performances of existing buildings [19, 20, 21]. Such strategies have sought to be increasingly stringent, promoting not only the integration of renewable energy sources [22], but also the implementation of sustainable retrofit actions mostly aimed at enhancing the performance of envelope components to allow for reduced energy consumption while maintaining comfort and safety [23-26]. Furthermore, it has also been observed how retrofitting existing buildings by means of sustainable solutions also allows for a series of other short-term and long-term urban benefits, especially in densely populated areas [27, 28, 29]. Additionally, the financing (e.g., investment incentives, public funding, tax deductions, etc.) of green strategies for the improvement of urban energy and environmental performance represents an important economy driver able to affect local and national economy [30, 31, 32].

Within this context, it is evident the importance of finding accurate strategies to foster NZEBs and PEDs by identifying appropriate mixtures of retrofit interventions and RES integration. In fact, such strategies are also a key element in relation to economic investments when prioritizing interventions within the allocation of available economic resources [33-36].

Based on the above reported considerations and with the aim of contributing to this matter, in this paper it was decided to approach the energy analysis of a real district, aimed at assessing its potential in terms of PED achievement. To this end, the present work concerns the case study of a neighborhood in the city of Palermo, in southern Italy, considered as representative in terms of both old/historical-building variety and intended use. Specifically, a comparison between the energy performance of the neighborhood in its actual conditions and those consequent to the implementation of some selected retrofit and RES intervention was carried out, estimated through building dynamic simulation, and also taking into account the economic aspects.

II. Materials and Methods

The objective of the case study is to show how the use of the PED approach on a given existing urban context (and not new construction areas), can contribute to implement sustainability policies aimed at energy improvement and decarbonization, in accordance with the latest initiatives on mitigation and resilience to the negative effects of climate change. To this aim, the work was developed according to the following methodological steps:

- historical-urbanistic framing of the urban area aimed at identifying within it a district representative of the variety of the building stock;
- analysis of the buildings in the district by means of a data collection campaign (period of construction, building type, intended use, size, geometry and orientation) and creation of a related database on a GIS platform;
- definition of building types representative of the variety of constructions in the district;
- dynamic simulation of the behavior of identified building types in their current state of preservation using EnergyPlus code for the calculation of energy needs;
- extension of the obtained results to the district level to estimate the overall energy demand;
- identification of energy efficiency measures, e.g., envelope retrofits and RES integration, most suitable for the analyzed context;
- dynamic simulation of the behavior of type buildings following the implementation of the identified improvement measures, analyzing different possible scenarios of implementation of the identified measures;
- extension of the results from the previous point over the entire district to estimate the overall energy improvement;
- analysis and evaluation of the obtained results from the NZED/PED perspective, i.e., energy balance of the entire district, also considering some economic aspects.

A. The Case Study: The Cuba-Calatafimi Neighborhood

The case study is the Cuba-Calatafimi neighborhood located in the southwestern part of the city of Palermo in the South Italy, climatically classified as Mediterranean profile Csa according to the Koppen-Geiger categorization [37]. The entire neighborhood, whose layout and positioning within the city of Palermo are shown in Fig. 1, covers a total area of about 1.2 km^2.

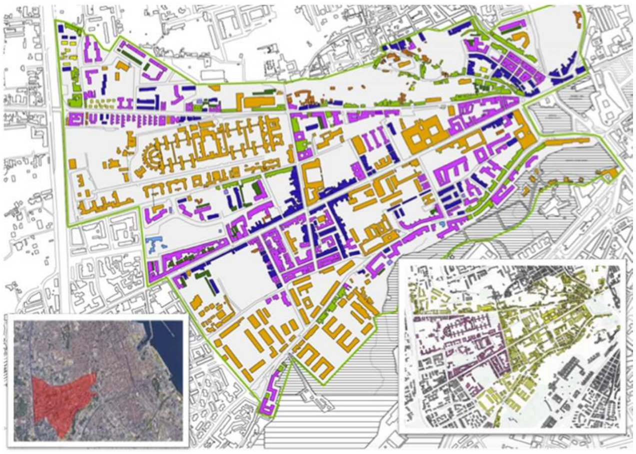

Fig. 1. Layout and positioning of the Cuba-Calatafimi neighborhood (red area) within the city of Palermo, with the identified building types indicated by different colors.

As it can be observed the neighborhood, which has been developing since the 17th century, is characterized by the presence of various building types both in terms of construction characteristics and the intended use of the buildings. In fact, in addition to residential-type buildings (such as detached houses, row houses, block houses, tower buildings, villas and social housing), there are also non-residential buildings with predominantly collective functions of urban polarity and/or monumental (such as schools, hospitals, barracks, administrative headquarters, university headquarters, commercial and craft activities, monuments, churches and organized religious buildings of various types).

In this paper, a portion of the neighborhood located to the west with an area of about 260,000 m^2 containing 200 buildings was chosen as it is considered representative of the variety of the building stock of the entire neighborhood (see Fig. 2); indeed the goal is to conduct an analysis following a methodology as easily scalable as possible to larger urban contexts.

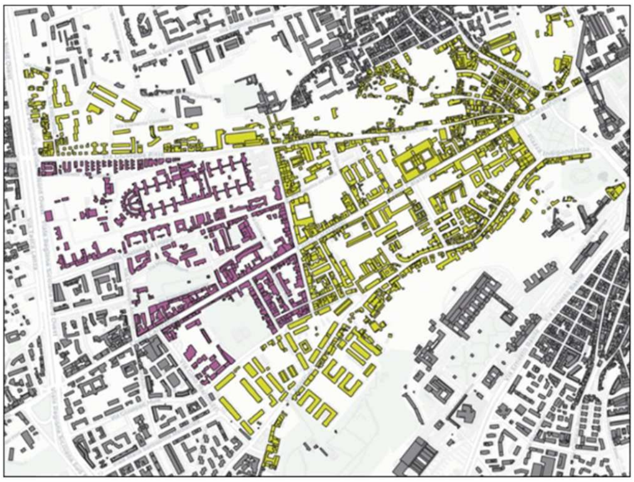

Fig. 2. Identification of the district (purple) within the neighborhood (yellow).

To implement the simulation model as closely as possible to the real conditions, by means of the data collection campaign (consisting of both consultation of documents and technical papers and on-site inspections), it was possible to identify, within the district, the buildings type classes (Table 1) based on construction period, intended use, building type, number of floors and surface/volume ratio (S/V).

TABLE I. MAIN CHARACTERSTICS OF INTEREST OF THE IDENTIFIED BUILDINGS TYPES.

Building Type Classes	Number of Buildings (% on District)	Construction Period	Number of Floors	S/V Ratio	Glazed Surface
C1	2 (1%)	1974 - 1987	7 - 12	19%	15%
C2	66 (33%)	< 1935	1 - 3	26%	24%
C3	20 (10%)	1936 - 1956	1 - 3	32%	17%
C4	32 (16%)	< 1935	4 - 6	17%	15%
C5	5 (3%)	1936 - 1956	4 - 6	20%	13%
C6	9 (5%)	1963 - 1973	4 - 6	21%	21%
C7	13 (7%)	1936 - 1956	7 - 12	15%	22%
C8	22 (11%)	1963 - 1973	7 - 12	14%	14%
C9	28 (14%)	1974 - 1987	7 - 12	14%	20%
C10	3 (2%)	1988 - 2004	7 - 12	14%	19%

B. Buildings Simulation Model

To evaluate energy performance consequent to the application of the improvement strategies, a simulation-based approach was used. First, for each of the type buildings a dynamic simulation model was implemented using the EnergyPlus code by means of the OpenStudio interface [38], to evaluate their energy performance in terms of annual energy consumption per type of use (i.e., heating, cooling, lighting, equipment, fans, pump and water system), with and without the application of the selected improving measures. In this phase, with the aim of drawing configurations consistent with real conditions, for each building type, the thermo-physical characteristics of the buildings opaque (e.g., walls, roofs, foundations, etc.) and glazed (windows) elements have been configured coupling the data obtained during the collection campaign with those provided by the Italian buildings envelope components database [39, 40, 41]. While, the identification of the thermal zones, the internal heat gains due to the presence of people, equipment and lighting, the infiltration and ventilation rates, the HVAC system operating parameters and so on were based on previous studies concerning similar contexts [12, 42] and on current regulations/legislation on the matter [43]. Subsequently, the results of the simulations of the type buildings were extended to the district level to estimate the overall energy performances from a NZED/PED standpoint.

C. Energy Improvement Interventions

As previously stated, a mix of building envelope retrofit interventions and RES integration was considered as a possible strategy to foster the energy efficiency of the chosen district. Such measures were selected based on the climatic context and of the buildings typologies and state of conservations, finding solutions that would best suit the variety of the district's building stock, also taking into account the environmental aspects (i.e., favoring natural-based materials) and the cost-benefit ratios. Reference was made to the price list for public works of the Region of Sicily [44] and market surveys to estimate the expenses necessary to implement the interventions. Based on these considerations the following building envelope retrofit measures were identified.

- Walls Insulation – Thermal coat with expanded cork panels, for buildings built after 1945, and premixed thermal insulating plaster with a base of hydraulic lime consisting of mineral expanded aggregates and natural fibers, for buildings built before 1945. Thanks to this district-level intervention, it is possible to shift from an average thermal transmittance of 1.63 W/m^2K to one of 0.37 W/m^2K, with an average cost of 126.26 €/ m^2.
- Roofs Insulation – For flat roofs, wood fiber panels (characterized by good insulation and vapor permeability capabilities). For sloping roofs, in addition to these panels, a ventilated cavity is also envisaged to further reduce the summer heat load. Thanks to this district-level intervention, it is possible to shift from an average thermal transmittance of 2.53 W/m^2K to one of 0.23 W/m^2K, with an average cost of 120.47 €/ m^2.
- Fixtures Replacement/Refurbishment – In buildings built after 1945, replacement of existing fixtures (mostly single-glazed wooden/aluminum windows) with high-efficiency thermal break aluminum ones. In buildings built before 1945, instead, replacement is assumed only where made necessary by the advanced state of deterioration. Otherwise, opting for the repair of existing fixtures is preferred, since based on the achievable performance, it results to be a more environmentally sustainable choice (the energy improvement would not justify the environmental and economic costs to produce new components and

dispose of removed ones [45-48]). Thanks to this district-level intervention, it is possible to shift from an average thermal transmittance of 4.86 W/m^{2}K to one of 1.98 W/m^{2}K, with an average cost of 373.86 €/m^2.

- As for RES, photovoltaic (PV) integration was opted for. Specifically, for buildings built after 1945, PV panels with a nominal power of 360 W, measuring 1.50 x1.00 m and electrically connected in series, were chosen. While, in the case of buildings built before 1945, the implementation of solar cell PV tiles with nominal power of 125 W was chosen, as in this case they are more suitable and less impactful than classical PV panels. In addition, in the case of flat roofs, an available area equal to 70% of the total was considered, taking into account the possible presence of obstructions (such as elevator locals) and spaces required for maintenance. Whilst, in the case of inclined roofs, an available area equal to 50% of the slopes with southern, southeastern or southwestern exposure was considered, also taking into account any shadows brought on these areas. Thanks to this district-level intervention, it was estimated that it would be possible to obtain an electric power production of 228.58 kWh/year/m^2 to be used to cover part of the energy needs of the district., with an average cost of 287.44 €/m^2.

From a total overall estimate, implementing the selected interventions to improve the energy efficiency of the district would, therefore, require a total expense of around 61 Millions€, of which 85% (around 52 Millions€) to implement the envelope retrofit interventions and 15% (around 9 Millions€) for the PV installation. In this case it was estimated that, such expenses can be amortized for a percentage comprised between 55% and 65%, thanks to incentives and tax deductions specifically aimed at improving the energy efficiency of buildings [30, 31], thus obtaining a deduction equal to 56% of the overall investment cost with a payback-time of 14 years.

III. Results and Discussions

As mentioned above, the simulations related to the behavior of the type buildings were initially carried out, to estimate their energy needs in terms of Energy Use Intensity – EUI (kWh/m^2) on annual basis. The results of these first simulations, reported in Fig. 3, are characterized by differences that reflect the diversity of the district housing stock. In fact, it is possible to notice how reductions in EUI vary significantly (from about 10% to 30%), depending on the building characteristics that significantly affect envelope retrofit interventions, i.e., age of construction, floor area, S/V ratios, and percentages of glazed surfaces. For the sake of completeness, it should be noted that the results shown in Fig. 3 refer to the total demand; however, the actual reduction in energy consumption here is mainly related to the building air conditioning (heating and cooling), whose weight on the total demand in the ten classes represents not only the largest consumption item, but also the one most affected by building envelope retrofit interventions. A separate discussion deserves the RES integration; in fact, while the PV installation does not actually affect the energy savings of a building, it allows to produce an amount of energy able to cover part of the building annual needs, from 6% to 48% depending on the building class.

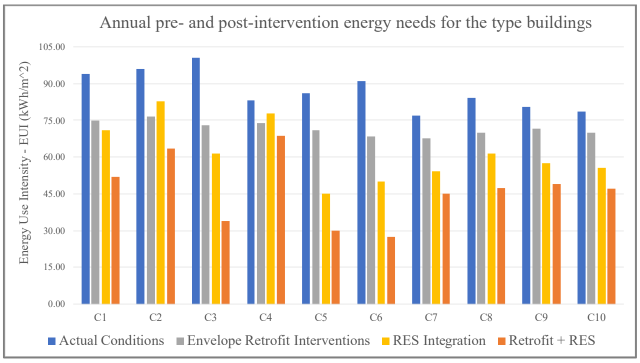

Fig. 3. Pre- and post- intervention energy consumption values of the ten identified type buildings.

The results of the energy simulations carried out for the ten type buildings were subsequently extended to the entire district. Fig. 4 shows the obtained results at the district scale broken down by building class. Once again it is possible to observe some variations, which in this case are due not only to the characteristics of the buildings but also to the weight of the class on the entire district. For example, class C9, while being the third in terms of numerosity, accounts for more than a third of both total consumption and total PV energy production. While classes C2 and C3, which together represent more than half of the district, are responsible for about 20% of the district consumption and contribute to only 7% of energy production. These circumstances are also reflected in the implementation costs of the energy efficiency measures. For instance, it turns out that class C2, although having the lowest per single-building retrofit price (about 150,000 €/building), at the district scale entails retrofit costs comparable to those of class C9, i.e., the one with the highest per single-building retrofit cost (about 500,000 €/building).

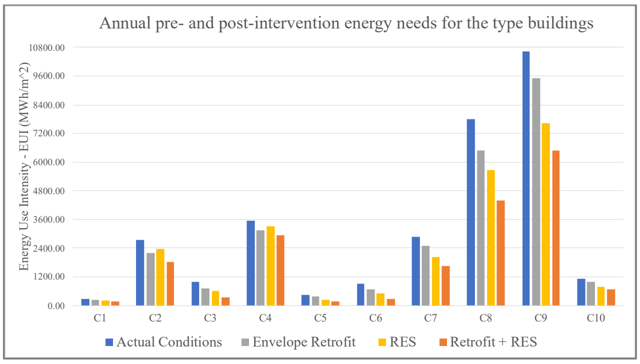

Fig. 4. Pre- and post- intervention energy consumption values of the entire district.

It should not be overlooked that the choice of having assumed for historic buildings (made before 1945) less invasive interventions, and therefore also less effective in terms of both envelope insulation and energy production, may have led to less significant improvements than those actually achievable. Nevertheless, by summarizing the obtained results at the scale of the entire district, as shown in Fig. 5, it can be seen that a 14.3% and a 25.5% reduction in energy needs can be achieved thanks to the envelope retrofit and RES integration measures, respectively, resulting in an overall energy saving of nearly 40 %.

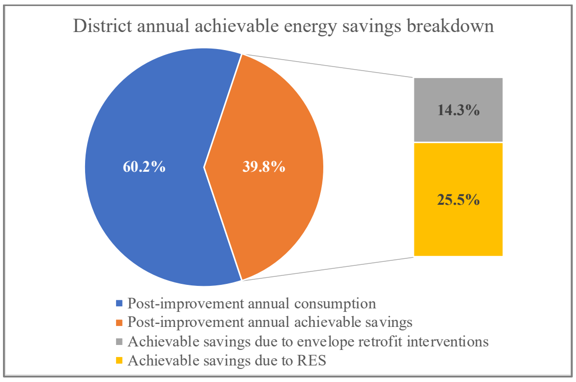

Fig. 5. District annual achievable energy savings.

The above observations were also extended to economic and environmental aspects. Specifically, on the basis of the obtained results, it was possible to estimate (i) the energy-related CO_2 emission reductions using a conversion factor equal to 0.48 tCO_2eq/MWh [49, 50], and (ii) the energy-related monetary savings considering an average energy cost of 150 €/MWh [51, 52]. The results of these economic and environmental evaluations are shown in Fig. 6.

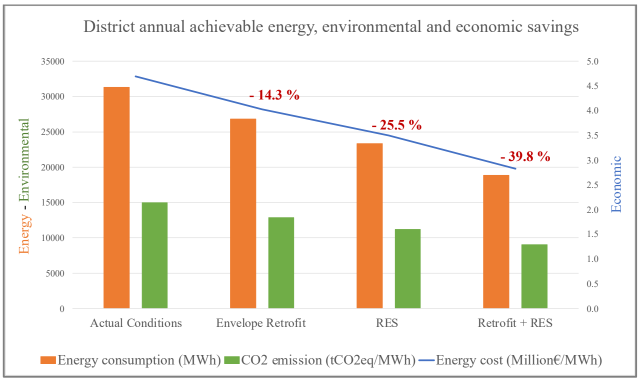

Fig. 6. District annual achievable energy-related environmental and economic savings.

IV. CONCLUSIONS

In line with the ambitious goals of energy efficiency and decarbonization of urban settings set out in current energy-environment policies, in this work some considerations have been made about the potentiality of using a strategy to foster Nearly Zero and Positive Energy Districts using a mix of buildings envelope retrofit interventions and RES integration. Such strategy has been illustrated by means of a case study that can be considered emblematic of existing and/or historic neighborhoods in Italy, in which buildings dating from various historical periods and having different structural connotations and uses coexist and are often in need of a major energy retrofit.

The outcomes of the case study put in evidence that in dense urban settings such as the one under analysis, measures of building envelope retrofit and on-site PV power generation alone do not seem to be sufficient for the purpose of achieving a net zero or even positive energy balance. In such cases, the allocation of sites in adjacent urban areas (or in surrounding regions) for additional electricity generation from renewable sources (e.g., biomass, wind or solar farms, etc.) could be considered in order to be able to aspire to cover peak energy demands.

Parallel to this, the critical question regarding the physical extension and/or the group of buildings to consider as PED (and/or Energy Community) should also be deepened and clarified. In fact, this case study made it also possible to note that in some cases it would make more sense to constitute such energy districts by building and/or user category rather than by geographic extent, more so considering that usually the geographic extents of city neighborhoods do not even coincide with the physical boundaries of the electrical power grid.

In more general terms, the proposed approach could help in setting strategies for a more efficient and smart urban energy planning to identify possible solutions for energy upgrading and decarbonization of urban areas, while also considering economic aspects. Local administrations and private citizens need, in fact, appropriate tools to better allocate their resources, making sure to employing suitable measures for the promotion of energy equity and accessibility in their territories.

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