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Optimization of Envelopes, Systems and Storage for Transition of Building Stocks to Zero Energy Districts

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Shifting from an individual vision to a community vision, also in the field of buildings, is a great challenge of our times. Notably, the deployment of energy district/community concepts is crucial to enable the energy transition with a view to sustainable urban growth. In this regard, the optimal combination of building design/retrofit, renewables, and energy storage systems, is challenging and crucial to achieve the net-zero energy district (n-ZED) and ZED targets. The latter is more stringent because it means an energy-independent district, without the need of energy from the grid. To understand how to achieve such ambitious targets, this paper addresses a real case study, i.e., a small building stock in Monterusciello (suburb of Naples, coastline, Southern Italy), composed of 29 residential buildings with poor energy performance as concerns both envelopes and systems. A comprehensive optimization approach is implemented to drive the energy transition of the stock to a community to minimize energy consumption and related environmental footprint. Accordingly, sundry scenarios are investigated to provide guidelines about different strategies to reach the n-ZED and ZED targets, including full-roof photovoltaic systems, efficient reversible heat pumps, refurbishment of building envelopes, and energy storage systems, i.e., batteries and compressed air energy storage, considering different size. Energy is shared by the buildings creating a community. The energy retrofit of the district is investigated in order to find different solutions to achieve n-ZED and ZED performance, using EnergyPlus as simulation tool and MATLAB® as optimization engine. The optimal solutions are compared to a traditional individual vision addressing the retrofit of each single building without shared energy and plants. Results show that sharing energy can be a powerful tool – if combined with optimization – enabling a more significant reduction of building environmental footprint compared to standard retrofit approaches.

1. Introduction

The transition to an eco-sustainable low-carbon economy requires fundamental transformations in technology, industry, transportation (Chuah et al., 2021), finance and, ultimately, society as a whole. To achieve these targets, it is essential to take actions to decarbonize every sector. This is a challenge and an opportunity for economic growth and employment, and in this regard, research and innovation will play a key role. One of the major contributors to World energy consumption and CO_2-eq emissions is the buildings sector.
In order to achieve the ambitious carbon neutrality goal by 2050, as outlined in the European Green Deal Report, it is pivotal to enhance building energy efficiency. The construction and operation of buildings accounted for around 36 % of global energy consumption in 2020, with a share of around 35 % for space conditioning as reported in the International Energy Agency report in (IEA, 2021).
The shift from the concept of individual buildings to that of building communities can allow to overcome some limitations and constraints, as concerns building use, size, on-site renewable energy availability, and cost, offering the possibility of upgrading to the zero-energy target, as shown in the works of Marique and Reiter (2014). Accordingly, the focus of researchers is moving toward the applicability of zero energy goals on a larger scale, which usually corresponds to a city or neighborhood as illustrated by Ullah et al. (2021).

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An interesting review has been written by Sharifi and Yamagata (2016) about the concept of urban energy resilience. Energy resilience implies the involvement of the entire city community in an urban regeneration process that focuses on improving the energy consumption of urban buildings. A key role in the energy transition process is played by cities, with the integration of different renewable energy sources (RES). The transposition of the concept from individual buildings to groups of buildings opens the potential to achieve energy self-sufficiency at city level. This can support the rise of sustainable prosumer communities.
In this vein, there is room and need for novel and worth scientific research. Indeed, the very recent (2021-2022) scientific literature proposes sundry studies unveiling the advantages of a district approach in building applications, as shown by the comprehensive review of Heendeniya et al. (2020). Mavrigiannaki et al. (2021) analyzed the real data obtained from the first year of monitoring of a pilot zero energy neighborhood. A comprehensive monitoring framework, with a Web-GIS monitoring platform at its core, has been developed for the measurement and verification campaign. Performance analysis has shown that the pilot neighborhood has achieved the targets set for the net regulated consumption, renewable energy production, and cost. Laitinen et al. (2021) investigated as a case study the Kalasatama district, in Helsinki (Finland), to find cost-optimal technical solutions for districts with high energy self-sufficiency rates. Two methods were applied, i.e., a rule-based method and an optimization one, in order to find the renewable energy system capacities for local centralized wind power, solar photovoltaic, battery, heat storage, and heat pump, aiming at minimizing lifecycle costs. The results showed that the full energy self-sufficiency target requires very high investments in renewable energy systems. It is economically and technically more feasible to achieve a positive energy district or net-zero energy district instead of full energy self-sufficiency. An extensive study of renewable energy communities and their potential impact on the electric distribution grid was conducted by Weckesser et al. (2021). Different distribution grids (i.e., city, suburban, village), energy community configurations, operating strategies, and battery placements were investigated.
For what concerns this paper, the novel contribution is to show how moving from an individual to a community vision can bring benefits not only in the creation of new cities but also in a retrofit perspective. To this end, a real case study is analyzed: indeed, a small building stock in Monterusciello (suburb of Naples, coastline, Southern Italy) is involved by a deep energy retrofit, to see the differences, using centralized or private energy systems, in energy demands, carbon footprint, operational costs.

2. Case Study

The Monterusciello district has been built after the bradyseism volcanic phenomenon, that has been manifested in Pozzuoli (surroundings of Naples) since 1983. Here, possible interventions of eco-energy regeneration applied to this social housing district are presented. It is located in a low seismic risk area, and the project was entrusted to the Faculty of Architecture of the Università degli Studi di Napoli Federico II. The project and construction phase were completed in 1984, while the first apartments were delivered in 1986. The real estate portfolio consists of 5,000 units divided into 21 lots. The eco-energy retrofit concerns the lot 2 of Monterusciello, composed by 29 buildings, each belonging to one of 5 building typologies, as shown in Figure 1.

Figure 1: Building types of lot 2 of Monterusciello (Naples, Italy)

The 29 buildings are classified into 5 different typologies, as can be seen in Table 1; these were built with heavy prefabricated elements. The building types of lot 2 are the so-called:

- A1 (1-5, 8-11): three-storey building with a roof area of 354 m^2;
- A2 (26-29): three-storey building with a roof area of 330 m^2;
- B1 (6-7, 19-20): three-storey building with a roof area of 375 m^2;
- B2 (22-25): like B1, but mirrored concerning the west-east axis;
- C (12-18, 21): four-storey building with a roof area of 375 m^2.

The eco-energy upgrading of the buildings in the neighborhood of Monterusciello is necessary to fulfill the standard of nearly zero energy building, mandatory in case of deep refurbishments, as required by the Italian Ministerial Decree D.M. of June 26, 2015. The buildings, in their current state, need at least two types of intervention: the insulation of the external envelope due to the high transmittance of both opaque and transparent envelopes, and the replacement of air conditioning systems (traditional boilers and chillers with low-efficiency coefficients). The plant interventions considered for heating and cooling are air-water heat pumps with fan-coils as heat exchange terminals. In particular, 5.6 kW heat pumps are provided for larger apartments, and 4.2 kW heat pumps for smaller ones. The plant interventions implemented to produce domestic hot water are solar thermal panels, while photovoltaic solar modules are considered for the on-site conversion of electricity.

Table 1: Buildings description for Monterusciello district

Buildings category	Number of buildings in each category	Single building surface (m^2)	Total surface (m^2)
A1	9	774	6,966
A2	4	698	2,792
B1	4	791	3,164
B2	4	790	3,160
C	8	1,099	8,792
TOT	29		24,874

3. Methodology

To analyze different building typologies, it is necessary to carry out modeling and simulations of their energy performance. The software used for the geometric and thermal modeling of the buildings is DesignBuilder®, while EnergyPlus is used as simulation engine. DesignBuilder® is also used to carry out the analysis of retrofit interventions. In fact, the analysis can be carried out directly employing this software, which uses EnergyPlus as a computing engine. MATLAB® is used to run optimization algorithms and for data processing because of its great programming opportunities and capabilities. In this work, the aim is to highlight the differences between a single building approach simulation and a district approach. This comparison concerns energy, environmental and economic indicators.

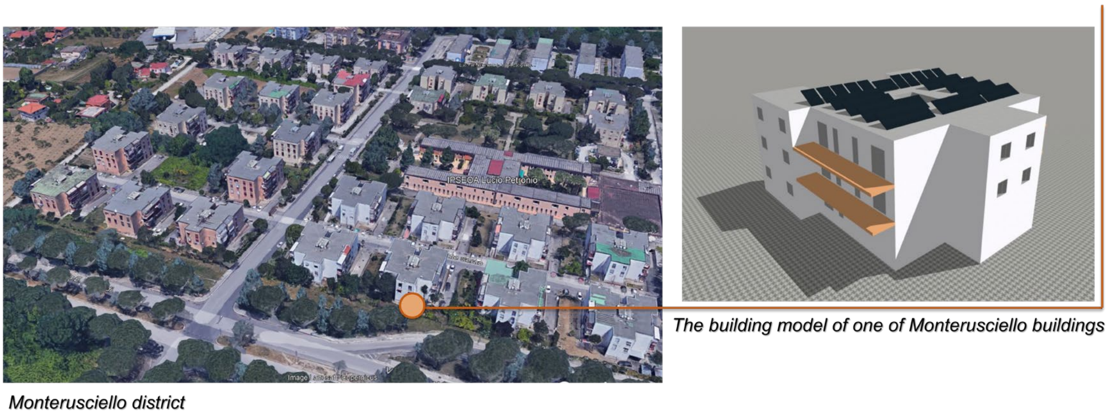

Figure 2: Example of a modelled building in DesignBuilder®

This investigation is developed both for current buildings (the "as is" condition) and for buildings subjected to retrofit. In particular, the single building approach is developed in DesignBuilder® and EnergyPlus, while the district approach is developed in MATLAB®. By means of DesignBuilder® the building envelopes are modeled, the wall compositions of the various building elements are defined, and the location is set by using an associated weather data file. Notably, the user can also define the thermal zones of the building and finally the heating and cooling systems. An example of the geometry of one of the buildings modeled in DesignBuilder® is reported in Figure 2. The energy, environmental and economic indicators considered as outputs are: a) primary energy consumption (*PEC*) (kWh/m^{2}y); b) CO_2-eq emission (kg/m^{2}y), c) running cost (*RC*) (€/m^{2}y).
After the energy simulation phase, developed in EnergyPlus, the heating, cooling and electricity demand values obtained for each hour of the year are imported into MATLAB® to perform the study of the following four cases:

- Current state buildings: "single building" level analysis;
- Current state buildings: "district level" analysis;
- Building retrofit: "single building" level analysis;
- Building retrofit: "district level" analysis.

In the district-level analysis, the district heating capacity is calculated by increasing the maximum value of the sum of the heating capacities of the individual buildings under investigation by 10 % and considering a centralized system. On the other hand, in the analysis at the individual building level, the total thermal capacity is calculated as the sum of the individual thermal capacity of each building category, where each building has its air conditioning system. In particular, the individual heating power of each building category is calculated as a function of the number of buildings in each category, shown in Table 1, and as a function of the number of apartments per building. Each building belonging to categories A1, A2, B1 and B2 is composed of 10 apartments and each building belonging to category C is composed of 14 apartments. As far as the cooling system is concerned, the reasoning is the same as for the heating system.
Considering a primary energy factor (PEF) f = 1.95 kWh_p/kWh_{el} (i.e., to convert from kWh electric to kWh primary), the PEC value for heating is calculated as a function of the efficiency of the traditional boiler considered, while the PEC value for cooling is calculated as a function of the energy efficiency ratio of the air chiller (EER). Considering the Italian CO_2-eq emission factors for natural gas and for electricity f_{gn} = 1.95 kg/kWh, f_{el} = 0.483 kg/kWh, reported in the Reporting guidelines SEAP and monitoring by the (Covenant of Mayors for Climate & Energy Reporting Guidelines, 2016), it is possible to calculate the annual CO_2-eq emissions. Considering the low heating value of natural gas LHV = 9.59 kWh/Nm^3 and the specific cost c_{gas} = 0.9 €/m^3, the value of the *RC* is calculated.
The retrofit study considers the installation of 321 photovoltaic solar panels to produce electrical energy, each of 230 W. The coefficient of performance of the heat pump is calculated as a function of load ratio and outdoor temperature, assessed on hourly basis.
Once completed the energy, environmental and economic analysis for the four cases under examination, it is possible to evaluate the results, in order to understand in which case it is suitable to face the refurbishment at the district level, and when, conversely, it is convenient to reason at the single building level.

4. Results and Discussion

Figure 3 shows, for the district approach, the hourly and cumulative values of the three indicators. The indicators under analysis are closely related. The trends of PEC, CO_2-eq and RC show local maximum and minimum in the same hours. Considering the current state, the cumulative PEC (*i.e.,* yearly) reaches the value of 167.8 kWh/m^{2}y. The hourly trend reaches its maximum in December, right at the maximum heating demand value. The maximum hourly values of CO_2-eq and *RC* are at the same hour which is the maximum hourly value of PEC. Obviously, for all the hours of the year, the three indicators analyzed are always greater than zero because in the current state analysis the plants are not powered by renewable sources and then there is always a primary energy consumption greater than zero that involves CO_2-eq emissions and running cost. The retrofit implies, compared to the current state: a) a PEC reduction around 101.3 kWh/m^{2}y reaching the cumulative PEC value of 66.48 kWh/m^{2}y; b) cumulative CO_2-eq emission achieves the value of 17.81 kg/m^{2}y with a saving of 24.77 kg/m^{2}y; c) a final cumulative RC value of 8.51 €/m^{2}y with a saving, compared to the current state, equal to 11.24 €/m^{2}y.
Figure 3 shows that there are certain hours of the year, after the energy retrofit, in which all indicators (namely, primary energy consumption, CO_2-eq emissions, and running costs) are nullified. This does not happen, never, for the current buildings, always interested by energy demands, CO_2-eq emissions and costs. Finally, the retrofit leads to hours where primary energy consumption is zero since plants are powered merely by renewables.

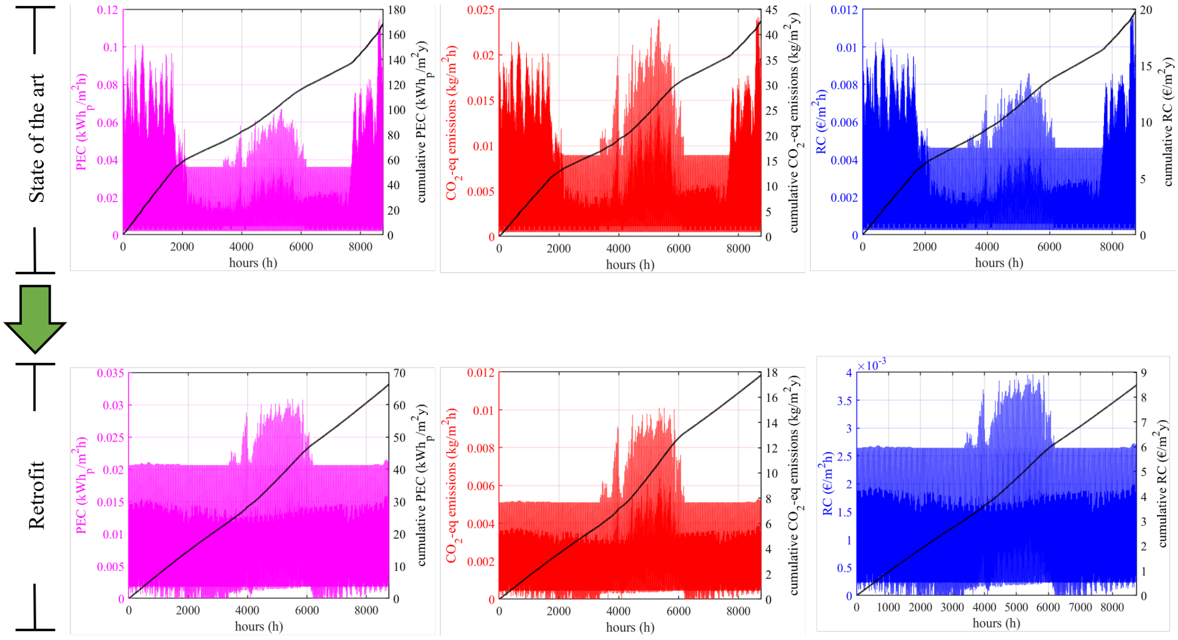

Figure 3: District approach: cumulative values of performance indicators for current and retrofit state

In addition, the shown trends unveil that all maximum values provided by the retrofit solution are lower than the maximum values found in the current state. Post-retrofit, the cooling and heating loads are concentrated in fewer hours of the year compared to what happens in the current state.

Figure 4 shows the case of the single building approach, where only the cumulative trends, in different colors for each building category, are represented for the three considered indicators. It is important to note that the indicator values are normalized (→ to a single m^2) and the weighted average should be considered when comparing to the district level. The cumulative curves refer to the sum of all buildings belonging to a single category.

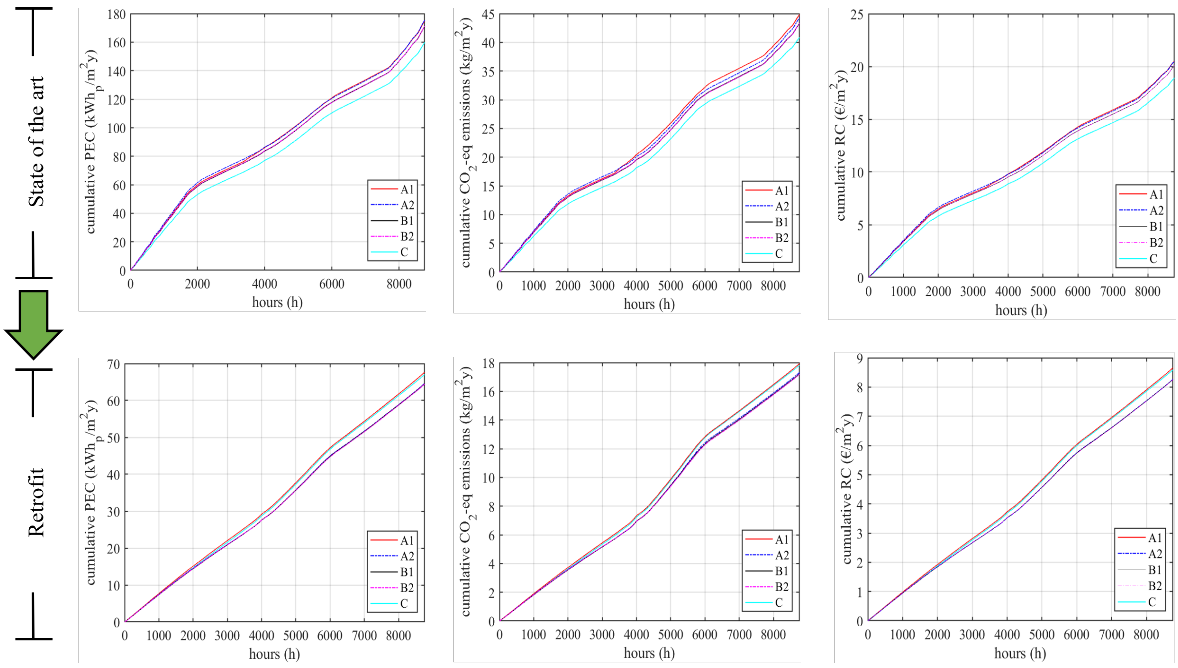

Figure 4: Single building study: cumulative values of performance indicators for current and retrofit state

The comparison between the two different level analyses (district and single building) is carried out in Table 2. It is possible to see that the saving (%) achieved by retrofitting buildings is greater at district level than at individual building level. Retrofitting buildings and using larger and more efficient heat pumps than those used in current buildings reduce PEC values and then the other indicators: at part load conditions, the heat pump works better than the traditional boilers presently installed. The results show the importance of the use of a district level analysis in the energy field. This is the only way, for the available technologies, to be exploited at the maximum, ensuring the minimization of primary energy consumption.

Table 2: Comparison between the two different analyses

		DISTRICT APPROACH			SINGLE BUILDING APPROACH		
		Current	Retrofit	Saving (%)	Current	Retrofit	Saving (%)
PEC	$(\frac{kWh_p}{m^2y})$	167.80	66.48	60.38	160.60	67.73	52.82
CO_2-eq	$(\frac{kg}{m^2y})$	42.58	17.81	58.17	41.36	17.62	56.39
RC	$(\frac{€}{m^2y})$	19.75	8.51	56.91	19.10	8.47	55.65

5. Conclusions

The minimization of primary energy consumption is crucial, as it allows also to minimize CO_2-eq emissions and *RC*, reducing the impact of buildings on the environment, which currently is very high, considering that the construction sector requires, in Europe, about 36 % of primary energy consumption as reported by the European Green Deal Report.

To achieve sustainability, it is necessary to act no longer as disinterested consumers but to become protagonists in the construction of energy communities, i.e., a coalition of users who collaborate and manage energy with the aim of self-produce and providing renewable energy at affordable prices to its members.

The results achieved in a district approach show how thinking no longer as individuals can lead to greater savings not only in energy but also in costs.

Future development of the present study, which is under investigation, will consider even more renewable energy production systems. The aim is to demonstrate, furtherly, the advantages that can be achieved by sharing the energy surplus or deficit, to optimize the energy flows and costs at the community scale.

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