Scenarios for the energy renovation of a residential building

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Abstract. In this paper, the results of the energy renovation of a residential building, aimed at introducing it into a Renewable Energy Community (CER), are presented. A case study located in Florence (Italy) is discussed. Static and dynamic energy models have been used to evaluate the energy performance of the building, to compare different scenarios based on heat pumps (independent or centralised generator) and to evaluate them under the perspective of EPBD parameters. A comparison has been made concerning energy consumption and CO_2 emissions. In its current state, the building presents an energy performance index of 129.8 kWh/(m^{2}year) (class D). The energy refurbishment with heat pump (A4, 24.7 kWh/(m^{2}year)) and VMC system (A4, 39.3 kWh/(m^{2}year)) ensures a strong reduction in CO_2 emissions, respectively 5.5 kg/(m^{2}year) and 8.7 kg/(m^{2}year) against 24.4 kg/(m^{2}year) with the current gas fired boiler. The centralized heat pump configuration allows to further reduce the energy consumption. With the same thermal energy requirement, the results show a reduction of 14% of the power needs (without total recovery), thanks to the better sizing of the generator. Furthermore, the centralized heat pump opens a perspective of direct self-consumption of the energy product by the photovoltaic system into a CER configuration. The paper shows that the energy renovation with a heat pump is an effective way to reach the EPBD objectives and decarbonize the residential heating and cooling sector.

1 Introduction

Greenhouse gas emissions from the residential sector in Europe are significant, accounting for 35% of total European emissions in 2021, mainly due to energy consumption for heating, cooling, lighting, and the use of household appliances in households. Although the residential sector has contributed to the European emission reduction target with a 31% reduction between 2005 and 2021, significant improvements are still needed for the residential sector to contribute to the emission reductions envisaged in the European Green Deal (Fit for 55 package). Recent recovery and transformation plans, including the Green Deal, the Renovation Wave Initiative, the NGEU, and national plans up to REPowerEU, all underscore the need for further enhancements in energy efficiency. These efforts operate within the framework of the Energy Performance of Buildings Directive (EPBD), initially introduced into EU legislation in 2002 and subsequently updated in 2010 and 2018. Currently, the directive is undergoing renegotiation for a new version. The future EPBD is anticipated to

mandate Member States to take decisive actions aimed at improving the energy efficiency of the entire residential building stock, ultimately leading to a zero-emissions stock by 2050. The Energy Performance of Buildings certification system, introduced by the EPBD, serves as a primary reference for assessing the efficiency of buildings. This certification system classifies buildings based on their energy efficiency and provides recommendations for improvement. Moreover, the preliminary versions of the new EPBD outline a comprehensive vision for the complete electrification of residential buildings energy uses. This includes the phased-out of natural gas boilers and the establishment of a precise transition strategy for the residential sector. These measures align with the broader goals of reducing carbon emissions and promoting sustainability in the European residential stock.

In this context, energy scenarios proposed by major organizations and agencies [1] anticipate a significant increase in the adoption of heat pumps for residential air conditioning [2]. Numerous scientific studies delve into the utilization of these devices within residential settings, examining their correlation with the local environment, broader regulatory framework [3, 4, 5], and the effective harnessing of renewable resources in urban areas [6, 7]. Additionally, various articles explore the optimization of renewable energy production and self-consumption systems for air conditioning. These analyses encompass both thermal [8, 9] and electrical [10] storage systems. Furthermore, there are studies assessing the integration of renewable electricity in Renewable Energy Communities, investigating the sharing dynamics within such communities [11, 12].

This paper suggests energy retrofit measures for a condominium building, with the primary goal of achieving full electrification of HVAC (Heating, Ventilation, and Air Conditioning) and DHW (Domestic Hot Water) production throughout the entire structure. In all proposed scenarios, the adoption of heat pumps as the main system for the building's heating and cooling requirements will be explored, effectively eliminating the reliance on methane gas for energy purposes. After evaluating the current state of the building, which was constructed in the early 2000s, the focus of energy requalification efforts is exclusively on the HVAC and DHW systems. Renovation of the building envelope is deemed unnecessary in this context. As results of energy analysis, retrofitting of the building envelope appears unnecessary. Instead, options for fully electrifying thermal energy supply are investigated, driven by the impending end-of-life cycle of the existing wall-mounted boilers. Furthermore, the potential for participating in a Renewable Energy Community (CER) initiative and the increasing adoption of heat pumps to mitigate emissions from fossil fuels are being evaluated. The study introduces and compares solutions for both individual and centralized generation units. For the latter, an optimization approach will be outlined, incorporating electrical and thermal storage systems. Additionally, the proposal involves leveraging self-consumption through a photovoltaic system installation on the building's roof. This opens the possibility of participating in energy sharing within the framework of a Renewable Energy Community.

The study begins with an assessment of the current, utilizing the standardized methodology employed in Italian energy certification. Subsequently, it moves to a dynamic hourly energy calculation, enabling a comprehensive comparison of various scenarios and a thorough understanding of the outcomes based on the proposed optimization criteria.

2 Methodology

2.1 Quasi-steady analysis

The examined building is a condominium situated in the "Isolotto" district of Florence, comprising of 34 units - 28 residential and 6 office-like units - constructed in the early 2000s.

The floor area of the building is equal to 4768 m^2, for a heated volume of 11921 m^3. Using standard quasi-steady calculations and focusing on a case study apartment, the energy performance certificate was assessed, analysing the critical aspects relating to the individual unit, and proposing improvement interventions. The calculations highlighted an energy response of the building envelope essentially in line with current requirements, leading to the exclusion of costly and less impactful building retrofit interventions. On the other hand, the energy system equipment, featuring individual heating through a traditional gas-fired boiler combined with domestic hot water and high-temperature radiators for heating, presented significant issues concerning energy performance and CO_2 emissions balance. Consequently, various assumptions for plant retrofit were explored, consistently referring to a typical apartment. Performance indicators, environmental impact assessments, and estimated intervention costs were then calculated.

2.2 Positioning

In this study, we aim to analyse the possibility of centralizing energy production for the energy service of an existing building equipped with individual heating systems. This choice can be justified not only by the superior efficiencies of a centralized system but also by the prospects that centralized production can offer in terms of harnessing potential renewable energy resources to be installed in the communal part of the building (roof), as well as integrating into the context of a Renewable Energy Community. We intend to compare a system retrofit for each apartment with one involving centralized production. The quasi-steady analysis is not suitable in this context, so a dynamic energy model has been implemented to obtain hourly energy needs. This allows for evaluations concerning the external temperature value and photovoltaic production. The hourly approach enables a detailed assessment of the obtained data. To simplify the calculation, residential units have been divided into two groups of equal size, modelling two different types of standardized programming related to system activations, tenant presence in the apartment, their habits, and thermostat-set temperature points.

The positioning of the apartment inside the building was varied, to estimate the difference in thermal loads dependent on dispersions across the boundaries of the building. The time schedules were obtained from the electricity consumption curve based on the habits of users, defined by TerMus-Plus. Through the hourly energy model of the apartment, hourly requirements for each unit were derived and then summed to obtain the building's overall energy demand. No contemporaneity factor has been directly considered but is implicitly considered within the different DHW consumption curves inserted in the users. The calculated data strongly depend on the type of modelled unit, as a method closely tied to user-specific programming has been used. To differentiate the observed consumption patterns, two distinct types of tenants were selected, each representing a different demographic group. Hourly profiles of presence and system activation were modelled based on the habits of these groups: a family with children (14 units) and an elderly couple (14 units). In the case of the family with children, a larger apartment area was considered, featuring a second floor above the first. Within the groups of users there are different virtual model referring to users with the same characteristics relating to the numbers of members and habits. The heat exchanges with the external environment and with the neighbouring real estate units were varied, taking into consideration the different position of the stairwell in the building, also varying the apartment's exposure to solar radiation. All the data are summed to obtain the graphs that follow. This choice reflects the spatial characteristics and needs of a larger household. Conversely, a separate model was applied to the six office-like units, considering their distinct usage patterns and requirements.

Specifically, the following profiles were created using the data obtained from the predefined profiles from the dynamic simulation software, TerMus-Plus:

- Presence profile in the apartment, defining internal contributions from people, lighting, appliances and windows opening periods for ventilation.
- Activation profiles for the air conditioning heat pump.
- Hot water usage profile.
- Solar shading opening profile.
- Temperature setpoint values.

Once the energy values required for air conditioning and domestic hot water production were known, it was possible to size the heat generator and terminals to be installed within individual housing units. Currently, each housing unit in the building is equipped with an independent heat generator using a standard boiler for winter heating and domestic hot water production, with no cooling systems in place. The objectives for the proposed interventions can be identified as follows:

- Implementation of cooling systems for the summer period.
- Electrification of consumption in the perspective of energy transition.
- Installation of a photovoltaic energy production system on the building's roof.

Two proposed solutions were considered:

- Individual "thermal cooling" hydronic system with reversible heat pump and fan coil units, thermal power 6 kW, cooling power 5.2 kW, with an inertial tank and storage for domestic hot water, one for each unit.
- A centralized hydronic system featuring a reversible heat pump with fan coil units, boasting a thermal power of 80 kW, cooling power 74 kW, and equipped with a heat recovery function for both winter and summer DHW production. Additionally, it incorporates DHW management through an additional hydronic heat pump with a thermal power of 20 kW, linked to storage tanks. This system can be divided into three distinct zones: generation, the heat pumps are located at roof level; distribution, connecting the external unit to the thermal plant (situated in the basement) and subsequently to the apartments; and emission, employing terminals like an independent system within each considered unit. A thermal/cooling energy meter system is need.

The utilization of a heat pump effectively caters to both heating and cooling requirements within the apartment, facilitated by the calculated low peak load. Whether implemented individually or in a centralized manner, such a machine positions the user for seamless integration into the process of energy distribution electrification, particularly in an urban setting. Considering the potential benefits, the feasibility of installing a centralized system was explored, aiming to capitalize on potential photovoltaic production for self-consumption and thereby significantly diminishing the building's reliance on external electricity sources. The decision to install a photovoltaic system was contingent upon having a shared condominium meter. This choice was made because the limited available roof area (220 m^2, 36 kW of installed power), when compared to the total number of users, did not guarantee a sufficiently substantial amount of energy production to warrant the division of the entire system into separate portions.

Using PVGIS software, the annual production of the system was meticulously calculated, considering various exposures depending on the chosen side for panel installation on the roof. The annual production is shown in Figures 1 and 2. This thorough assessment provided insights into the system's potential energy output and informed decision-making regarding its implementation. The PV system has the following characteristics:

- Crystalline silicon.
- Total peak power installed: 36 kW_p;

- System loss: 14% (PVGIS tools standard value).
- Slope angle: 20% (slope of the roof pitch).
- 50% of the modules exposed to Northwest, 50% to Southeast.
- Yearly PV energy production: 37746 kWh.

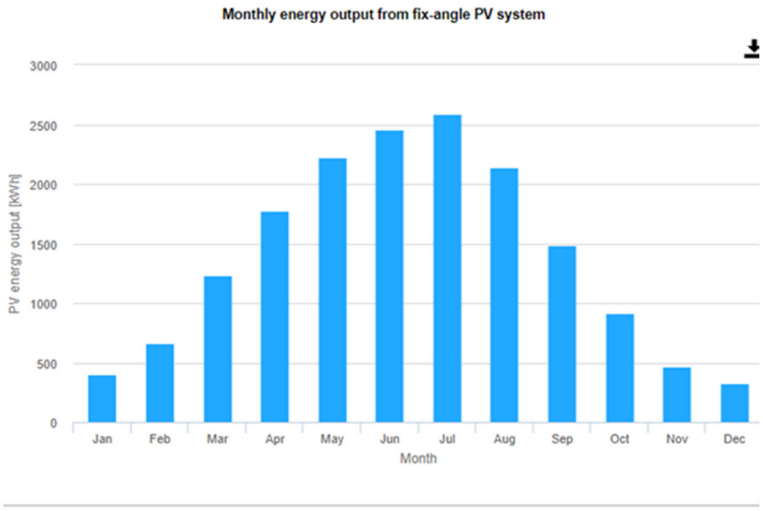

Fig. 1. Photovoltaic System Production- Northwest-facing Exposure. Data source: PVGIS tools.

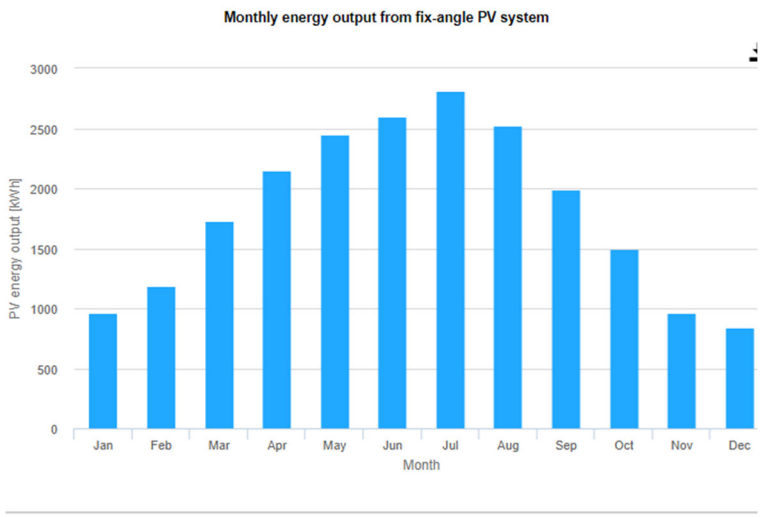

Fig. 2. Photovoltaic System Production - SouthEast-facing Exposure. Data source: PVGIS tools.

3 Results

3.1.Quasi-steady analysis results

The results of quasi-steady analysis are summarized in Table I. All data refers to a single apartment, being an analysis aimed at the energy calculation of a single heating system.

Table I. Summary of results from the quasi-steady analysis of the current situation and proposed plant retrofit for a typical apartment of the building.

Generator and emission unit type	Annual consumption	Energy Rating	CO2 equivalent annual emission	Estimated investment cost
Standard wall-mounted boiler Radiators (actual situation)	1'422.8 Sm^3 (No space cooling)	E	2772 $kgCO_2eq$	-
Condensing boiler with radiators DX Chiller	883.6 Sm^3 847.1 kWh	B	2018 $kgCO_2eq$	20'000 €
Condensing boiler Underfloor heating DX Chiller	805.6 Sm^3 847.1 kWh	B	1936 $kgCO_2eq$	25'000 €
Hydronic heat pump Fan coils	2343.4 kWh	A3	1012 $kgCO_2eq$	25'000 €
Hydronic heat pump Underfloor heating	1584.0 kWh	A4	685 $kgCO_2eq$	28'000 €
Mechanical Ventilation Heat Recovery (η=0.8) with heat pump hydronic module	2519.7 kWh	A4	1091 $kgCO_2eq$	30'000 €

The summary table indicates that interventions involving a heat pump achieve the highest possible energy class and optimal operating efficiencies for the generators. Additionally, a summer cooling service, previously absent, is introduced as part of these interventions. In cases where heat pumps are proposed, the generator remains unchanged, resulting in very similar efficiencies. The discrepancy in consumption and, consequently, the energy class is attributed to the presence of electric auxiliaries required for the system's operation. Among the various retrofit proposals, the chosen reference solution for subsequent analyses involves fan coil units. This choice is motivated by reduced invasiveness, evaluating the preservation of the existing distribution system with the addition of a condensate drain system, and the lower overall cost. This approach often enables the retention of the current distribution system, with a simultaneous evaluation of cooling pipeline diameters. Through quasi-steady analysis, it becomes evident that significant system efficiencies can be attained with interventions focused solely on the system. This reaffirms that additional measures to enhance the thermal transmittance of the building envelope would not be cost-effective. The chosen solution strikes a balance between effectiveness, cost-efficiency, and minimal disruption to the existing infrastructure.

3.2.Dynamic energy model

Once the values of thermal and refrigeration loads were obtained, the generation efficiency values for the heat pumps were derived using operating curves obtained through the Coolselector simulation software by Danfoss. Third-degree polynomial equations were derived, dependent on the evaporation and condensation temperatures, as well as the compressor RPM. Using the provided equations, inserting the values of thermal or cooling demand, along with the temperature gap between the sources and saturation temperatures of the refrigerant fluid at the heat exchangers, it was possible to determine the HP efficiency value on an hourly basis, thereby calculating the electricity consumption. Some advantages and disadvantages can be highlighted for each of the systems under consideration. In the case of an independent heat generator for single user:

- Users maintain direct control over the system, with the ability to program different activation times within preferred intervals.
- The system is more streamlined, and interventions can be made regarding individual apartments without interacting with other residents.
- A single meter for each condominium user with low-voltage supply is sufficient, even though a 6 kW power is required.
- Distribution losses are almost negligible, considering that the network is mostly located in a temperature-controlled environment.

The need to provide an inertial tank to manage machine defrosting phases and storage for domestic hot water, at least 300 liters for families of four, requires the availability of a space of considerable size for their placement, in this case, located on the apartment's terrace.

The generation efficiency of small-sized machines is lower than that of a centralized heat pump.

It is not possible to take advantage of the self-consumption of photovoltaic energy if choosing to install a photovoltaic energy production system. In cases like this, the provision of individual systems for each apartment is to be discarded because the building's roof would not provide sufficient surface area to achieve a tangible benefit.

In the case of a centralized heat pump:

- The heat generation efficiency is higher.
- The central production configuration allows various choices aimed at ensuring production reliability and the ability to cope with potential failures, such as the choice of multicompressor machines or dividing the required power between two or more different machines.
- The system is much larger in terms of distribution network, requiring construction work in common areas for the system's implementation, making it more expensive and impactful when it comes to energy retrofit work on existing buildings. In this case, a distribution in the stairwell was considered from the rooftop heat pump to individual users, with a single metering system in between.
- A heat metering system is, therefore, necessary for consumption recording and heat cost allocation.
- The management system must interface with each user to detect the conditions set inside each apartment.
- Activation hours are established for all residents at specific times and cannot exceed twelve total hours per day. This could also be an advantage in terms of machine efficiency in case the decision is made to concentrate most of the operating hours in intervals advantageous in terms of temperature.
- Possibility to install a centralized photovoltaic system on the roof, directly connected to the meter that also powers the heat pump, covering part of the consumption.

— It is necessary to provide a three-phase centralized meter to satisfy the large amount of electrical consumption present after retrofit interventions.

The possibility of using self-consumed energy in the case of a centralized heat pump makes the installation of a photovoltaic system advantageous. For the system sizing, reference was made to the total available surface on the building's roof, amounting to a total installed power of 36 kW. The dynamic simulation program's calculation results exhibit trends closely dependent on the chosen programming for different types of users when referring to the daily habits of tenants. An example of a typical winter day is shown in Figure 3, and a typical summer day in Figure 4. Observing the results obtained for the annual calculation (Figure 5), the highest demands are related to heating, due to the greater temperature gradient compared to the ambient temperature. This is reflected in the energy peaks required to ensure the overall building's energy loads, which are visible in the graphs depicting the trends of a typical day.

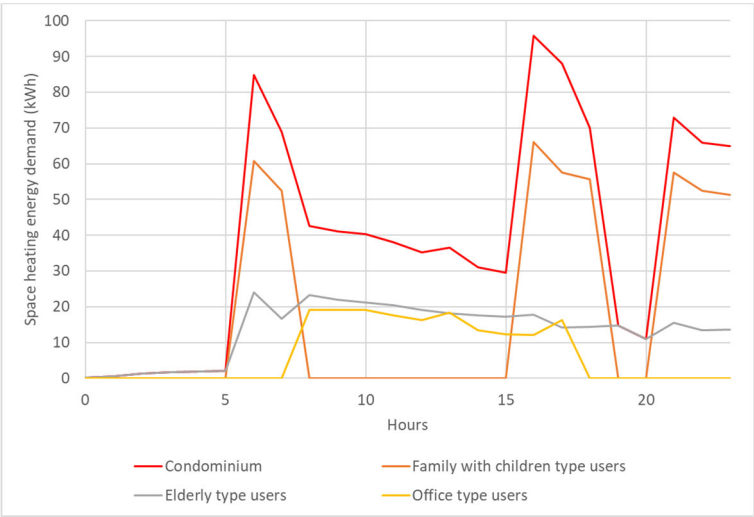

Fig. 3. Typical Winter Day 17/01. The curve representing the centralized demand is obtained by summing the others, referring to the sum of the individual users considered. The curves referred to the different types of users are the sum of the entire group (14 family users and elderly users, 6 office-like users).

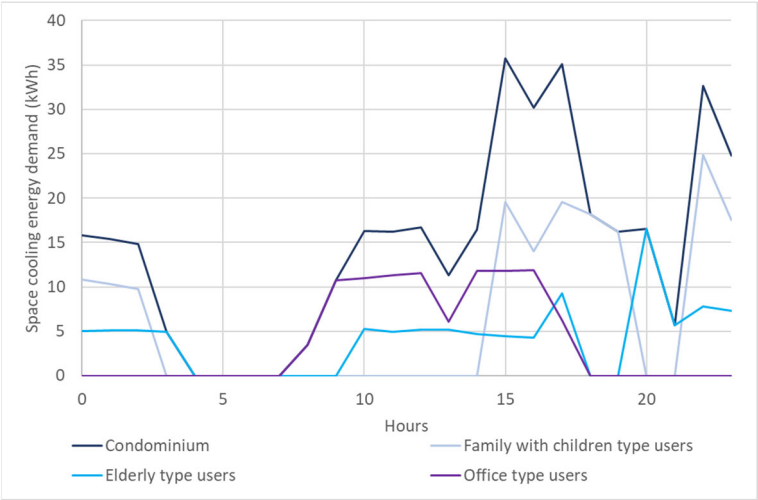

Fig. 4. Typical Summer Day 17/07 - The trend of summer energy demands is different from that of winter. The curves referred to the different types of users are the sum of the entire group (14 family users and elderly users, 6 office-like users).

The pattern of energy demands during the summer exhibits distinctions from those in winter. In the context of cooling, activations are significantly influenced by the presence of individuals within the housing unit. Moreover, given that the calculations are grounded in varying user profiles, there is contemplation of the potential for extended activation of the generator. This consideration extends beyond the 12 hours typically allowed by current regulations while still adhering to the established demand profiles of individual users. The exploration of extended activation aligns to optimize system performance and address specific user requirements, even if it exceeds standard regulatory limitations.

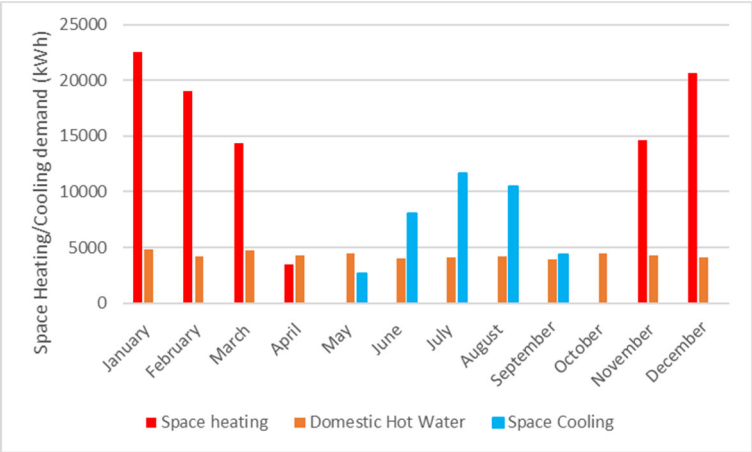

Fig. 5. Annual energy demands of the condominium building.

From the polynomial correlations, the seasonal average efficiency value was obtained for various types of users and the centralized generator, allowing the determination of the actual electrical consumption of the entire condominium building.

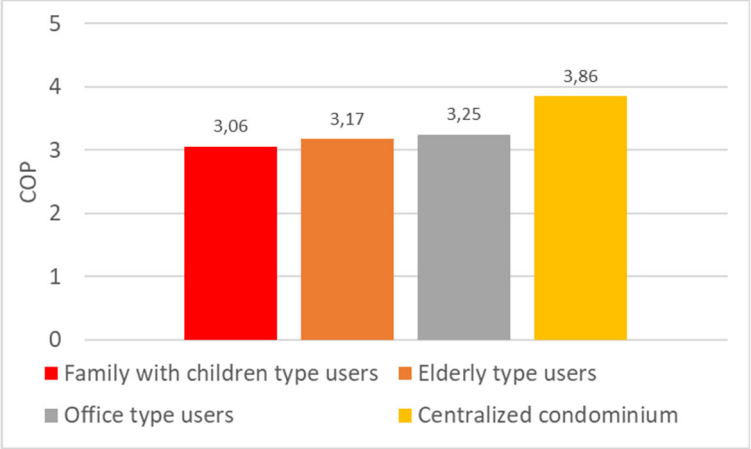

Fig. 6. Seasonal average efficiency of the winter air conditioning system.

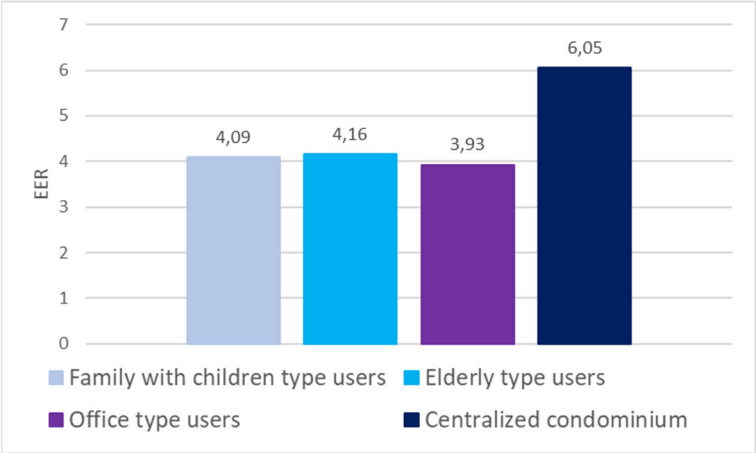

Fig. 7. Seasonal average efficiency of the summer air conditioning system.

In Figure 6 and Figure 7, the values of the seasonal average efficiencies obtained for independent systems and the centralized heat generator are presented. In the centralized solution a heat pump size well calibrated with cooling and heating loads, combined with greater control capacity, allows for an increase in the coefficient of performance, with very positive effects on the energy consumption of the building. The need to install a heat pump with a peak power of at least 6 kW, to meet domestic hot water production (despite the presence of a storage tank of at least 300 Liters), significantly reduces the heating efficiency of the machine. A comparison can also be made regarding the installed power. In the case of individual systems, a total value of 204 kW is obtained, while for the centralized system, the combined power of the two heat pumps is only 100 kW (80 kW for HVAC demand and 20 kW for DHW demand). Leveraging simultaneity enables a reduction in the size of the heat pump, resulting in a noteworthy advantage in terms of efficiency, consumption, and, evidently, emissions.

Optimizing the activation of the heat pump generation during the most favourable daily hours is a method to enhance system efficiency. This can be illustrated by examining the energy consumption patterns of commercial users. Typically, energy loads peak during

daylight hours, which are usually the warmest part of the day. Consequently, the efficiency of the heat pump improves in winter but declines in summer. Redirecting energy demands to other times of the day may pose challenges for certain users. Therefore, the ongoing study also explores the feasibility of add thermal storage, aiming to shift the activation hours of the centralized heat pump to intervals when the outdoor air temperature is more advantageous.

The energy performance of the centralized system in the presence of on-site photovoltaic production was also evaluated. As highlighted in Figure 8, the gain obtained is quantifiable at about 25 MWh of energy, which already provides a significant reduction in consumption. The significant advantage is achieved with the presence of a centralized photovoltaic production system, which allows for a roughly 50% reduction in energy consumption. It is worth noting that the simulation only considers the needs for regulating the indoor air temperature of buildings and domestic hot water production, without considering any additional needs from different types of appliances inside the homes.

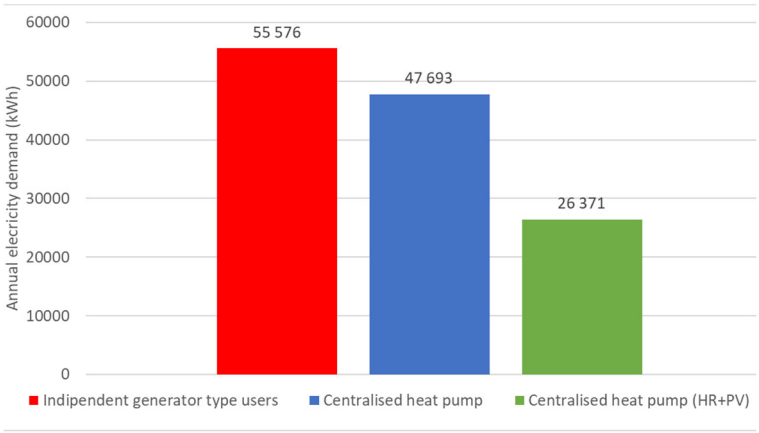

Fig. 8. Annual electrical consumption of the different proposed system configurations.

3.3.Electrochemical storage

An electrochemical storage of approximately 220 kWh has been planned to manage the self-consumption of photovoltaic production. The graphs in Figure 9 highlight how, during the winter period, a significant amount will need to be drawn from the power grid, still managing to achieve a good portion of self-consumption. The only electricity exported to the grid comes from the months at the extremes of the heating season. In the coldest winter months, the battery will face challenges in charging due to significant thermal loads requiring a substantial amount of electricity. The limited production of solar energy during this period further adds to the constraints, making it difficult for the battery to accumulate charge on any occasion. The combined impact of high thermal loads and reduced solar energy availability during extreme winter conditions poses limitations on the charging capability of the battery system. The battery system's operating logic includes a minimum charge level to avoid premature deterioration of the storage system. As seen in the graph in Figure 10 for a typical week in January, the limited photovoltaic production results in very restricted battery charging, leaving it in an almost continuous state of discharge.

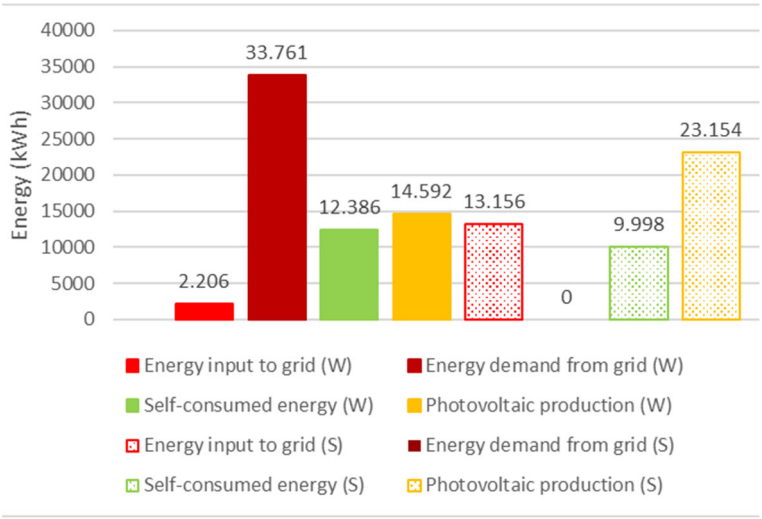

Fig. 9. Electricity balance produced by the photovoltaic system. Full color, the report for the winter period (W); dotted, the report for the summer period (S). Injection, self-consumption, and energy drawn depend on the state of charge of the electrochemical storage, consistently maintained between 20% and 80%.

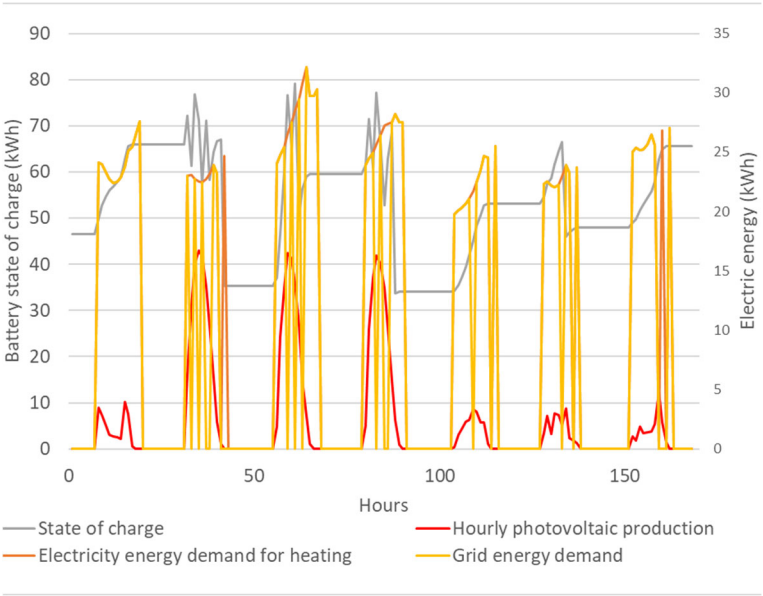

Fig. 10. Typical Winter Week 12/02 - 18/02. State of charge of the electrochemical storage about the electrical heating demand and the production of the centralized photovoltaic system.

The reduction in consumption mainly concerns the summer period, where photovoltaic production significantly exceeds the energy required for air conditioning, leading to substantial amounts of energy being exported to the grid.

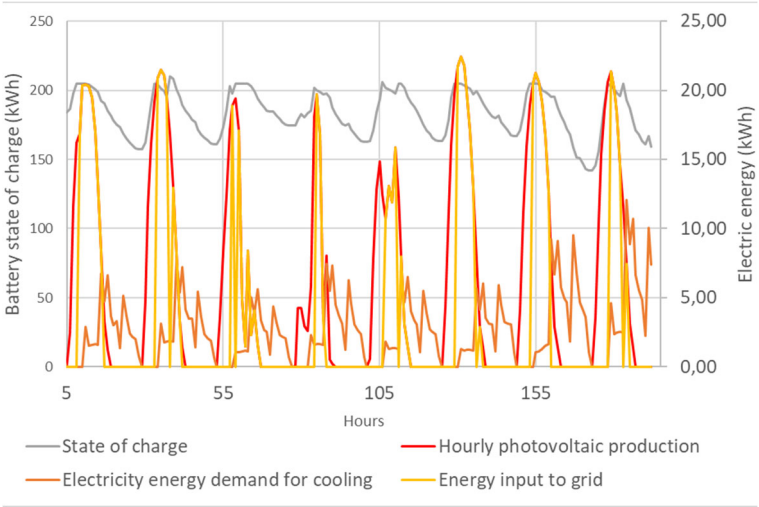

Fig. 11. Typical Summer Week 11/08 - 18/08. State of charge of the electrochemical storage about the electrical consumption for cooling. The production of the photovoltaic system is very high, so a significant portion of the electricity produced is injected into the grid, considering the reduced demand of the users.

As evident from the graph in Figure 11 for a typical summer week, the storage remains almost constantly charged, causing the energy produced by the photovoltaic system to be largely supplied to the national electrical grid.

Considering the high photovoltaic production in the summer and the need for grid injection, the possibility of implementing seasonal electrical energy storage has been evaluated to make the condominium almost entirely independent. A storage capacity of 3000 kWh was considered, but it is deemed entirely impractical in terms of space and installation costs. The analysis reveals that the gain in terms of self-consumed energy is nearly equivalent to the capacity of the electrical storage, as can be seen in Figure 12. This observation indicates that the charging pattern during the summer months and almost complete discharge in the winter months persists even for a storage system of considerable size. As a result, it is concluded that such a large storage system is unsuitable for the required seasonal use, highlighting the need for a more practical and efficient solution.

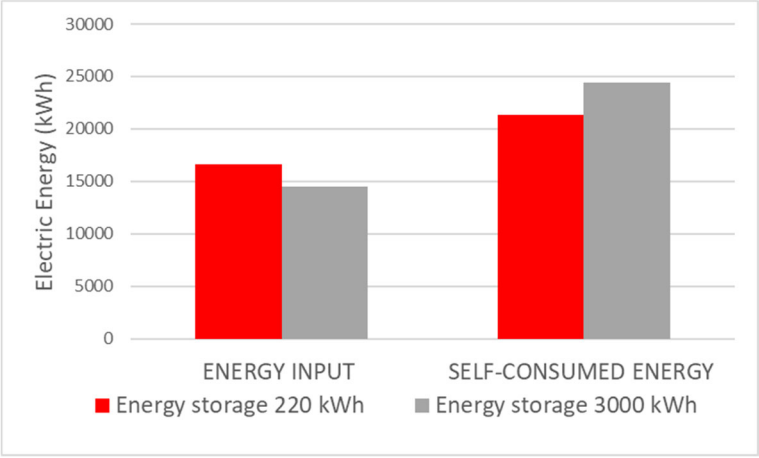

Fig. 12. Comparison of daily injected and self-consumed electrical energy for daily and seasonal storage.

3.4. Thermal storage

In the pursuit of optimization, the exploration of sensible thermal storage systems has been undertaken. This involves using hot water in winter and cold water in summer, to enhance the efficiency of the heat pump by strategically operating it during the most favourable hours of the day. The sizing of the storage system is meticulously planned to fulfil the building's energy requirements throughout the entire day. This approach enables the activation of thermal or refrigeration energy production by the heat pump at times when external conditions are most conducive, contributing to overall system efficiency – daytime in winter and nighttime in summer. This should enable an increase in the production efficiency of the heat pump. Thermal losses from the storage units to a "service room" located in the basement were estimated, considering a temperature that remains constant throughout the year and incorporating thermal insulation consistent with the specifications of commercial thermal storage units.

The same type of insulation was used to determine the heat losses of the storage tanks for domestic hot water (DHW), considering a total quantity of 4m3. The storage will be maintained at 60°C, as in the case of domestic hot water, for a total of 20m3. Figure 13 shows the trends of the storage unit temperature and energy demand by users for both a typical winter week (12/02 - 18/02) and a typical summer week (12/07 - 18/07). A clear difference in terms of energy demand for heating and cooling is observed, significantly affecting the variation in the storage unit temperature. The heat pump activation is shifted only during daylight hours in winter and during nighttime hours in summer, leaving the tank responsible for meeting the building's energy needs for the rest of the day.

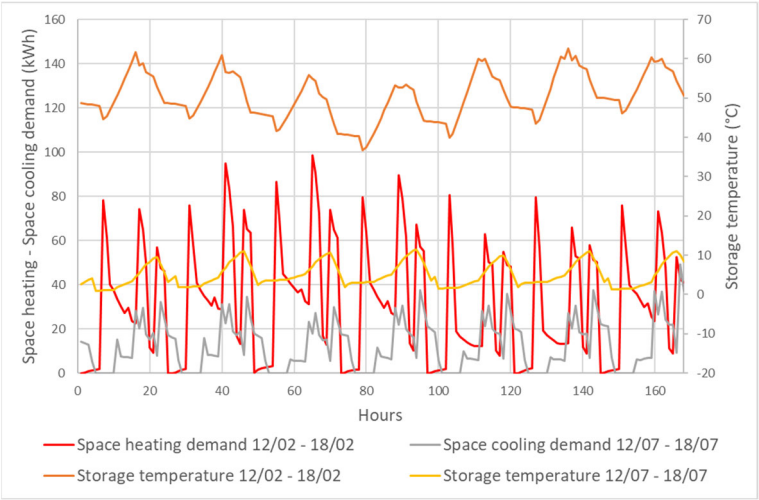

Fig. 13. Temperature trend of the inertial storage unit. Comparison between a typical winter week (12/02 - 18/02) and a typical summer week (12/07 - 18/07).

Figure 14 presents the performance coefficients of the heat pump for the typical winter week (12/02 - 18/02) in the case of a centralized system with direct use and thermal storage. It is noted that the ambient temperature equally influences the efficiency of the two different systems. The intersection between the two curves occurs when the temperature of the inertial storage unit rises enough for its condensation temperature to be higher than that of the direct

system. Analysing the coefficient of performance, it is evident that the efficiency of the heat pump is higher only during its activation compared to the continuously operating centralized generator. This observation emphasizes the importance of considering the specific operational conditions and efficiency variations during different phases of the system's operation.

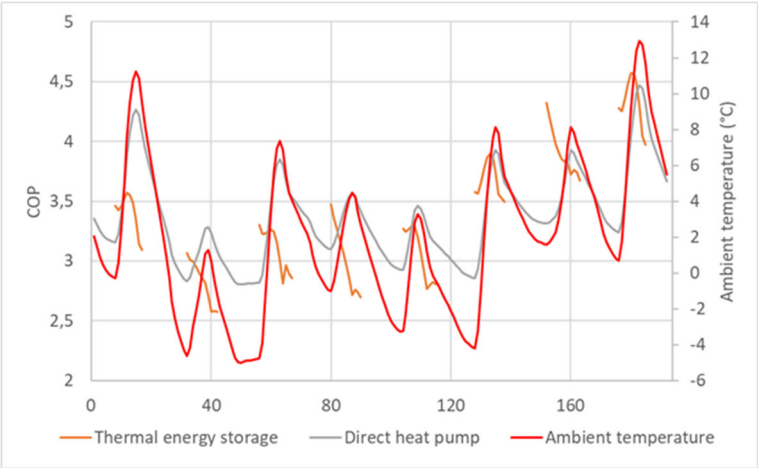

Fig. 14. Comparison of the coefficient of performance of the heat pump with and without thermal storage.

This depends mainly on the high condensation temperature that the heat pump is forced to work at. When the machine turns on, the tank will be on average cooler than during the rest of the generator's operating hours, which is why its efficiency is indeed higher. In other cases, even though the machine always operates at nominal load and exchanges with the outside at more favorable temperature values, this will not be enough to improve efficiencies. If the heat losses due to the presence of thermal storage and the consequent increase in energy demand are also added, there will be higher consumption compared to the case without storage.

In the summer period, a similar consideration can be made, yielding entirely analogous results. In this case, the evaporation temperature will be lower than in direct exchange, counteracting the advantage offered by the nighttime activity of the generator. It is noteworthy that in summer, there is a substantial amount of electrical energy available for self-consumption. Consequently, the daily operation of the machines may not pose significant challenges in terms of actual consumption. Generally, it is possible to lower the storage temperature, thereby increasing its capacity. In such a scenario, the challenges would no longer revolve around enhancing the COP value but rather focus on the space needed to accommodate the larger volume of water required. Providing a complete overview of all electricity consumption, including self-consumption when available, the following graph, Figure 15, is obtained:

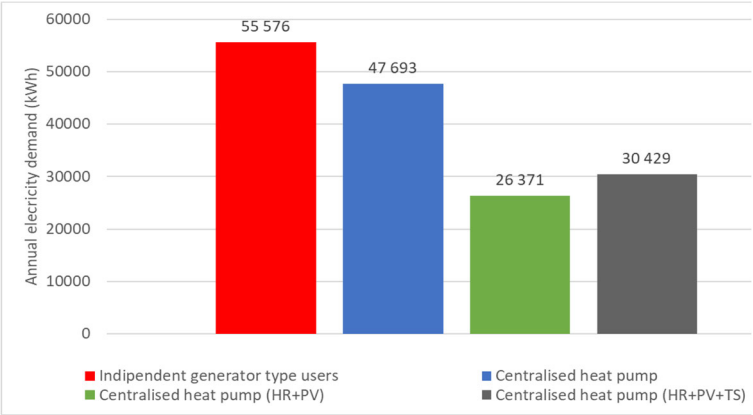

Fig. 15. Summary of total annual electricity consumption for the condominium building for all proposed scenarios

Table II. Summary of results of the energetic balance of the building for each retrofit proposal, cost estimate and money savings per year for HVAC and DHW production. The savings are calculated compared to the case with independent generators.

**$Ep_{gl,nren}$ is the standardized primary energy consumption obtained from the dynamic calculation, which is why the value of the energy classification is not reported.

Proposal	**Cost estimate**	****$Ep_{gl,nren}$**	**Savings (years)**	**Payback period**
Independent generators	953 258 €	22.71 kWh/(m^2 year)	0 €	Not calculable
Centralized heat pump (HR)	1 078 885 €	19.5 kWh/(m^2 year)	2364 €	53 years
Centralized heat pump (PV+HR)	1 347 806 €	10.78 kWh/(m^2 year)	8761 €	45 years
Centralized heat pump (HR+PV+TS)	1 411 339 €	12.44 kWh/(m^2 year)	7544 €	60 years

The results obtained show how energy savings are impressive, but the economic balance does not justify such an investment, unless heavy state incentives are considered, such as the Superbonus 110 [13], that is an economic support measure for retrofit interventions promoted by the Italians government.

4 CONCLUSIONS

From the quasi-steady energy analysis, considering different cases in the plant retrofitting, heat pump technology's excellent performance is highlighted, both in terms of efficiency and emissions reduction. For completeness, indoor air thermo-hygrometric conditions and the improved air quality guaranteed by a VMC system should also be considered, as it will likely be necessary soon. However, in terms of efficiency and investment cost, the solution with fan coils certainly offers better advantages. The study demonstrates that a centralized system, under equivalent operating conditions, provides on average higher efficiencies. This is primarily due to the exploitation of energy load simultaneity as well as the possibility of having generators with better control behaviour (such as a higher number of cascading

compressors), avoiding excessive off-design operating mode. The greater challenges in implementation, stemming from the need for main vertical columns where they are not present, and in management, due to metering and different activation schedules creating dependency among residents, continue to make centralized systems more complex. Although significant energy savings, the high costs of centralized retrofit make interventions not economically convenient without the availability of incentives.

Management of storage systems is more complex. A system that works for energy storage becomes crucial, considering that the hours of maximum efficiency of the heat pump do not always align with the availability of renewable energy or vice versa, and the accessible renewable energy might be insufficient. Electric batteries ensure complete self-sufficiency in summer and good self-consumption in winter if the dimensions of the photovoltaic system are adequate. However, they do not enable effective seasonal storage on-site due to reduced winter production. A water-based storage method does not yield optimal results. The need to operate at high temperatures, to store the maximum amount of energy while keeping the dimensions of the storage units contained, requires operating the heat pump under disadvantageous conditions, even when seeking optimal ignition intervals. An alternative system is needed to optimize the use of renewable energy by modifying the battery operation. Alternatively, a complete shift in approach with CER and the direct sharing of produced electrical energy might significantly improve the situation. However, in this case, most of the demand would still be in winter, as seen from the graphs, so solar power alone cannot be the sole source of renewable electrical energy within a Community Energy Resource due to its limited production. Conversely, in summer, excess energy might exceed demand, minimizing the need for sharing. In conclusion, typical forms of energy storage are not mature for achieve a seasonal storage system. While they can briefly shift consumption during the day, they do not allow for a real gain in terms of energy consumption and, consequently, saved emissions.

To conclude, the cost estimates for the two interventions presented are reported in Table II, making references to the regional price list of Tuscany. Furthermore, the energy performance indices achieved and the annual savings that can be obtained by exploiting the improvement in energy efficiency are shown. No considerations relating to the incentive deriving from the CER were made in the economic balance sheet. The annual saving is calculated assuming an average electricity price of 0.3 €/kWh.

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