A general approach for retrofit of existing buildings towards NZEB: the windows retrofit effects on indoor air quality and the use of low temperature district heating

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***Abstract* — The European Union, through the Energy Performance of Building Directive (EPBD), has recently set the minimum requirements in order to reduce the energy consumption of existing buildings and achieving nearly zero energy buildings (NZEBs). In order to comply with these requirements different aspects of the building sector have to be dealt with. In the present paper two different aspects related to the energy and environmental performances of the existing building towards NZEB are analyzed: a) the use of the Smart Energy Systems with particular regard to the heat sharing systems, and b) the effect of the window retrofit on indoor air quality.**

Keywords — NZEB; retrofit; ventilation; Smart Energy Systems; Heat Pump; IAQ

I. INTRODUCTION

A key challenge for European Countries, like Italy, characterized by a rich building heritage (mostly identified as Historical Buildings), is the energy retrofit of existing buildings in order to make their energetic performances as close as the NZEB ones. This is even more important for buildings erected after World War Two through novel techniques, characterized by the use of reinforced concrete and prefabricated building components, with respect to the traditional ones. Actually, as the days go by, building quality resulted poor: e.g. the reinforced concrete turned out to be not everlasting, the walls shown major issues in terms of energy performances, the whole building did not result earthquake-proof (this is a main concern in Italy where high standards are required due to its seismic risk [1]).

Summarizing, the Italian building heritage should be deeply retrofitted, such retrofit should be synergic as it should take into account simultaneously the different criticalities of the buildings [2]. Despite the priority actions to be carried out in terms of seismic risk, an integrated approach in building retrofitting should be used in the transition towards the NZEBs. This is even more important for building reconstruction in the towns of Central Italy recently hit by a devastating earthquake.

Retrofit actions can obviously concern both the building envelope and the HVAC system [3], but not always can be performed contemporarily. In fact, very often existing buildings show several constraints (e.g. historical and/or

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architectural) and, consequently, it is impossible to retrofit the envelope. In other cases, unfortunately, combined actions on building plants and envelope, which theoretically can lead to huge energy consumption reduction, are nullified by poorly effective retrofit interventions.

Different methods have been developed for mapping buildings energy consumption in order to better target, model and plan the needed interventions [4-7]. Furthermore, several innovative solutions have been proposed to improve the energetic performances of existing buildings such as the use of hydrogen [8], innovative CO_2 methanation processes to be used in storage systems [9], solar assisted heat pumps [10], Smart strategies applied at district level [11,12] as well as particular solutions tailored to historical buildings [13,15].

In this context, thermal storage has been identified as one of the most promising solutions [16] and its potentialities are already being exploited by means of Heat Pumps (HPs) and District Heating (DH) networks. DH in particular are gradually moving towards lower working temperature in order to reduce heat losses and ensure a more efficient waste heat recovery, also in line with the "EU Strategy on Heating and Cooling (2016)" where the deployment of the so called 4th generation of District Heating (low distribution temperatures, assembly-oriented components and more flexible pipe materials) is promoted. Such networks come along with the growth of low-energy buildings, since such low-temperature networks are feasible only for low-temperature indoor heating systems that are not present in most of the existent building stock in EU and globally.

Moreover, Heat Roadmap Europe has identified district heating and cooling networks as an essential component to increase the heating system efficiency in a sustainable and economic way [17]: it is clear though, that future networks will have to be completely different from the ones used today [18].

In the present paper, the authors analyze how the Smart Energy Systems (SES) approach through the innovative "heat sharing" principle can be partly nullified by the incorrect realization of the retrofit. As for example, windows retrofit, which in theory presents low cost and great potential in energy consumption reduction, are strongly affected by the installation effectiveness.

II. Methodology

A. The use of the smart energy systems and the heat sharing approach

In the present work, a preliminary analysis to evaluate the energy savings achievable by applying an innovative Smart Energy Systems (SESs) based on the concept of heat sharing has been analyzed. SESs are characterized by the usage of clean local Renewable Energy Sources (RES), the presence of storage energy systems of all energy vectors and of monitoring and control systems able to optimally manage the energy production and consumption. SESs need to merge the different energy consumptions and interconnect the energy vectors where possible. The particular SES analyzed in this paper merges the electric and the heating demand by applying an innovative approach to the use of Heat Pumps (HPs).

In particular, a standardised and turn-key version of hybrid SES has been considered, accounting for the major part on energy production devices and consumers typology by implementing a low-grade heat water distribution pipeline using an innovative approach that allows the system construction and operation independently by the used technologies, starting from the basic principle of district heating network along with the hybrid systems concept.

The heat sharing concept is based on the well-known concept of District Heating (DH), thanks to the introduction of Building Integrated Heat Pumps (BIHP) it is possible to lower the grid temperature, thus lowering the thermal losses, without increasing the pipes diameter and thus the infrastructure costs.

The SES is constituted by a central HP supplying low-temperature fluid to buildings, in each building is then installed a water-source BIHP that raises the fluid temperature to the one needed for inner space heating and Domestic Hot Water (DHW) production. In this layout, the BIHP use the low-temperature network as a thermal sink thus sharing the heat.

The proposed solution was analyzed from an energetic and economic point of view and it has then been compared to traditional systems in order to prove its feasibility.

B. The window retrofit

In order to enhance the energy saving of the building sector, a main approach could be represented by retrofitting existing buildings. In particular, new opaque and transparent walls could easily decrease the heat losses through the building envelope. Nonetheless, retrofitting walls could be problematic for buildings with historical constraints or aesthetic peculiarities not allowing invasive solutions (e.g. envelope insulation). On the contrary, the retrofit of the windows is easier and can also be applied in historical buildings [19] by replicating the original window frame with improved performance materials.

Since windows are mainly responsible for air permeability of the buildings, and then for ventilation energy losses, the window retrofit can successfully improve the overall energy performance by reducing the leakages. Unfortunately, more energy efficient windows can strongly reduce the building airing [20] and then the Indoor Environmental Quality (IEQ) [21-23]. Therefore, a good evaluation of the actual air exchange rate is a key aspect to estimate the indoor air quality (IAQ) in the building. Moreover, even when a mechanical ventilation system is present, is important to quantify the air infiltrations because they can lead to oversizing the ventilation system with inevitable energy waste. In fact, the ASHRAE Standard 62.2 [24] requires the reduction of mechanical ventilation if air infiltrations are higher than a certain level. The air leakages cannot be neglected in existing buildings: they should be investigated before retrofit interventions in order to reduce them. Anyway, an inappropriate installation can nullify the expected energetic benefits. In the present paper the possible installation issues during window retrofit were also analyzed.

TABLE I. CHARACTERISTICS OF THE BUILDING INVESTIGATED

Building	Year of construction	Volume, V (m^3)	Envelope Area (m^2)	Height (m)	Degree day (°C)
1	1978	178	226	12	1164
2	1951	436	418	17	1164
3	1910	138	137	14	1383

TABLE II. CHARACTERISTICS OF THE WINDOWS BEFORE AND AFTER RETROFIT

Building	Window surface area (m^2)	Window material before Retrofit	Window material after Retrofit	Air Tightness Class [25]	Retrofit technique
1	8	Wood	PVC	4	- rubber seals - substitution
2	19	Wood	Aluminum	3	substitution
3	4	Iron	Aluminum	4	substitution

The study of the effect of window retrofit was carried out performing a Blower Door Test (BDT) experimental campaign before and after different window retrofit solutions on three buildings located in the Central Italy (climatic zone C) (TABLE I.). Two window retrofit approaches were analyzed: (i) the application of a new rubber seal on the window frames (only for Building 1), and (b) the replacement of the original windows with new certified high performance windows (on all the buildings). The Building 1 was retrofitted in two steps: the application of new rubber seals to the existing wooden window frames and the substitution of windows with new certified high performance windows. In the Building 2 and building 3 was considered the substitution of the windows as retrofit solution: indeed, the wood and iron windows were replaced with PVC and aluminum thermal break windows (class 3 and 4 according to EN Standard 12207 [25]; TABLE II.).

The BDT test [25, 28] is based on the mechanical pressurization/depressurization of the building (or part of it), in particular, the airflow rate through the building envelope (q) is measured as a function of the indoor-outdoor static pressure difference (Δp) as:

$$q = C \times \Delta p^n \quad (1)$$

here C and n represent the flow coefficient and the air pressure exponent, respectively; they are evaluated through a simple linear regression. The experimental analysis was performed considering the ISO 9972 “method B”, which is the test of the building envelope with intentional opening closed or sealed [26-28]. The experimental apparatus used of the BDT is made up of a calibrated airproof fan fitted to the door, a flow rate regulation system to set the value of indoor-outdoor pressure difference, two flow rate measurement devices, a digital micro-manometer measuring the pressure differences, a thermo-hygrometer to measure air temperature and relative humidity, a hot wire anemometer to diagnose possible air infiltrations in the building during BDT.

BDT results provided the airflow rate through the building envelope at a pressure difference of 50 Pa (q_{50}); such value allowed to evaluate the main air-tightness parameters, such as the air exchange rate at 50 Pa (n_{50}) [24, 28-30]:

$$n_{50} = q_{50} / V \quad (2)$$

Moreover, the natural air exchange rate (AER) was estimated from the (n_{50}) through the equation [31]

$$AER = n_{50} / N \quad (3)$$

where N ranges 10 to 30 [32], depending on the type, age, height, orientation of the building, as well as on the type of windows/other openings and the possible presence of the ventilation systems, etc. Here a commonly accepted N value of 20 was considered.

III. RESULTS

A. The use of the smart energy systems and the heat sharing approach

The considered SES will allow the temperature of the working fluid flowing through the network to be around 35-40 °C thus strongly decreasing the amount of energy losses along the pipes and allowing to get better thermal comfort and indoor air quality as well as an increased simplicity in exploiting local RES. To do so, a central Heat Pump (HP) (e.g. air/ground/seawater-source HPs) will supply the main energy carrier i.e. low-temperature water. The thermal energy flowing through the pipes will work as a shared heat-sink for further water-source HPs which will be integrated in the buildings. In such a way, the building integrated HPs will boost the fluid temperature to make it suitable for high-temperature applications, needed by the most common inner space heating systems.

Both central HP and BIHPs work with very high COP thanks to the two temperature levels required by the system. Thermal losses in the network are strongly reduced compared to a traditional DH network thanks to the lower temperature in the pipes. Furthermore, the energy needed to run the pumps for the fluid transport is not increased since the energy gap created by a lower temperature in the network is not filled by an increased flow rate but it is supplied in form of electricity to the BIHP.

The system will exploit the basic principle of district heating network to implement a low-grade heat water distribution pipeline (water envisaged temperature around 35-40 °C), thus ensuring a more efficient system without jeopardising comfort and indoor air quality.

As detailed in Figure 1, the thermal energy flowing in the grid will work as a shared heat-sink for water-source HPs integrated in the buildings that will raise the fluid temperature to make it suitable to the most common heat emission devices used in the inner space heating systems (i.e. radiators, HVAC, radiant floor heating system, fan coils).

This layout allows HPs to work with the optimal heat-sink temperature along the whole year and thus with the highest CoP during the heating season and Energy Efficiency Ratio (EER) during the cooling season. Furthermore, thanks to the presence of HPs, the low temperature in the grid will not implicate an increase of the flow rate: by consequence, the network size and cost as well as the energy needed for fluid transport will not increase. In fact, the grid will have to transport an amount of energy that is about ¼ of the one of a traditional DH network since the remaining energy will be supplied in form of electricity. An HP will be used in the central thermal station; it will work with a limited temperature range (between 20 °C and 40 °C accordingly to the grid layout and losses) and thus with a high CoP.

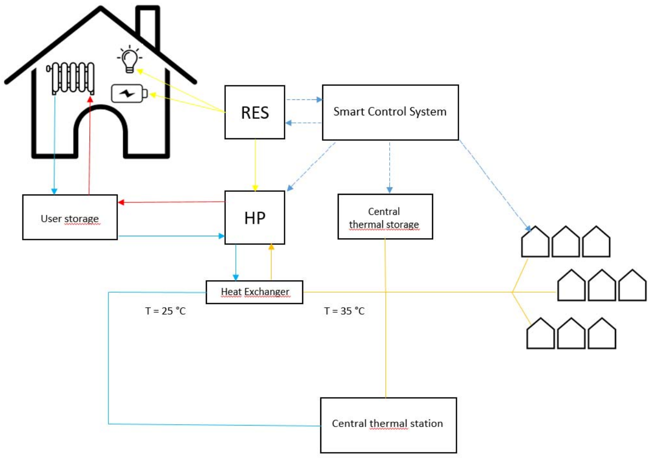

Fig. 1. Layout of the heat sharing smart energy system

A hybrid energy system designed in this way will allow the conversion of the electric energy in excess into thermal energy, thus creating the possibility to store it in thermal storages both as central thermal energy storage (TES) or user TES, which are particularly advantageous for the reasons detailed in what follows: thermal storages are significantly cheaper than traditional electric ones; thermal energy can be stored at relatively low temperature (35 °C) thus reducing heat losses.

Thanks to a preliminary parametric analysis of the main components relative cost, it is possible to say that the number of BIHP installed is the most important variable to be considered when designing the system. In any case, the system presents economic cost that are, in the worst case, comparable to traditional solutions.

Finally, it will be possible to implement a power-to-heat strategy to store and use the potential renewable excess, thus allowing, by logical consequence, the merging between electric and heating sectors. Furthermore, when renewable energy excess cannot be exploited instantaneously, thermal storage devices can be integrated in the heat sharing SES. In such a designed system, each building can be connected to a given distribution network and become at the same time a node able to produce energy locally (i.e. buildings as prosumers).

B. *The window retrofit*

In TABLE III. and TABLE IV. the main results of the BDTs performed both before and after window retrofit on the three buildings are reported. In particular, the air leakage parameters and related energy demand for ventilation are summarized. The comparison with the reference value of natural ventilation ("Excess of Natural Ventilation"), as well as the energy analysis of the building, was performed considering an air change rate (n_{50}) reference value of 0.3 h^{-1} (value prescribed by the Italian regulation on residential buildings).

TABLE III. RESULTS OF THE DIFFERENT RETROFIT SOLUTIONS CONSIDERED IN THE THREE BUILDINGS.

Building	Windows retrofit	Leakage rate (m^3 h^{-1})	n_{50} (h^{-1})	AER (h^{-1})	Excess of natural ventilation (h^{-1})
1	pre-retrofit	2513	14.1	0.71	0.41
	rubber seals	1889	10.6	0.53	0.23
	substitution	4918	27.6	1.38	0.88
2	pre-retrofit	5968	13.7	0.68	0.38
	substitution	5126	13.0	0.65	0.35
3	pre-retrofit	1005	7.3	0.37	0.07
	substitution	629	4.6	0.23	-0.07

TABLE IV. BUILDING ENERGY DEMAND DUE TO AIR LEAKAGES.

Building	Windows retrofit	Energy demand (GJ yr^{-1})	Excess of energy demand (GJ yr^{-1})	Excess of energy demand (%)
1	pre-retrofit	4.25	2.44	57.4
	rubber seals	3.20	1.39	43.4
	substitution	8.32	6.51	78.3
2	pre-retrofit	10.12	5.18	56.2
	substitution	9.62	5.68	53.9
3	pre-retrofit	2.03	0.36	17.8
	substitution	1.27	-0.40	-31.3

The cheapest retrofit solution adopted on the Building 1, i.e. applying the new rubber seals, reduced the air change rate (n_{50}) of 24.8% with respect to the pre-retrofit value. This improvement is likely due to the previous ineffective seal of the existing wooden windows. The second retrofit solution on the Building 1, i.e. substitution of windows with novel certified PVC ones, led to an unexpected increase of building permeability ($n_{50,}$ increase of 95.6%). Nonetheless, when adopted for the Building 2 and 3, the window substitution solution reduced, as expected, the air leakages by 4.9% and 37.4% in terms of n_{50}, respectively. This enhancement resulted in a reduction of the energy demand (TABLE IV.) with unpredictable effect on the indoor air quality (since no ventilation systems are used).

The contradictory results obtained with the complete window substitution can be ascribed to possible installation issues: to this end a post-hoc investigation using a hot wire anemometer was performed to detect possible air leakages through windows: such diagnosis confirmed incorrect installation in the Building 1 and 2. Summarizing, when not properly performed, the window retrofit can worsen the air-tightness performance of the buildings despite the use of certified windows.

IV. CONCLUSIONS

As regard the heat sharing SES, the preliminary results show that the solution proposed is energetically the best option compared to traditional DH and to traditional individual heating systems. The considered SES assures an interesting amount of carbon avoidance thanks to the electrification of the heating demand. An important impact on this result is made by the electric supply assumptions.

Concerning the effect of the window retrofit, the first results confirmed that possible wrong installation could result in an increase of air leakages and the related energy demand: such findings highlight the importance of starting an in-depth technical discussion focused on the characterization and the assessment of air leakages of windows.

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