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 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 4^{th} 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*

The retrofit of existing residential stock provides significant opportunities and challenges in terms of new systems and components and in terms of the related energy saving. Operating on opaque and transparent walls is an effective strategy to reduce heat losses through the building envelope. Unfortunately, the retrofit of opaque elements is often difficult, especially when buildings exhibit historical constraints (e.g., in Mediterranean countries) or aesthetic peculiarities that avoid invasive solutions such as external insulation. On the other hand, operating on windows is undoubtedly easier and this can be applied also to historical buildings [19] by reproducing the original window frame with high performance materials.

Windows and doors are one of the main elements responsible for air leakages. Thus, window retrofits can be very effective to enhance the overall energy performance and to reduce air leakages when it is impossible to operate on opaque walls. Unfortunately, air-tight windows nullify the airing [20] and worsen the Indoor Environmental Quality (IEQ). It is well known that assuring high energy saving has to be consistent with acceptable IEQ levels in terms of IAQ and thermal comfort [21]. Regarding the IAQ, the air change rate is generally favored by air leakages, even they are unfiltered and uncontrolled [22]. On the contrary, as regards the thermal comfort, air leakages can generate a local discomfort due to draught and local temperature differences. As a result, the energy demand to obtain acceptable IEQ levels increases. This is even more important in Mediterranean countries where climatic changes result in cooler winters and hotter summers [23].

Furthermore, at the mechanical ventilation system design stage, air infiltrations are generally overlooked when the nominal air change rate of the system is calculated. Therefore, the wrong assessment of air infiltrations can lead to oversizing the ventilation system with unavoidable energy waste. Not by chance, ASHRAE Standard 62.2 [24] requires the reduction of mechanical ventilation if it can be shown that air infiltrations are above a certain level. The evaluation of energy waste owing to air infiltrations appears even more difficult. In fact, in winter, air leakages always result in heat losses, especially in the absence of heat recovery units.

An adequate mechanical ventilation system is obviously the most appropriate solution in new buildings in which air leakages could be minor if compared to air intakes. On the other hand, in existing buildings it is not possible to neglect air leakages; thus, during retrofit interventions it could be very useful to accurately investigate them in order to reduce or eliminate their main causes. Anyway, an incorrect installation can nullify the energetic benefits.

TABLE I. CHARACTERISTICS OF THE BUILDING INVESTIGATED

Building	Year	Volume (m^3)	Envelope Area (m^2)	Height (m)	Degree day of the location (°C)
1	1978	178.2	226.3	12.0	1164
2	1951	436.0	417.5	17.4	1164
3	1910	138.0	136.6	14.0	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	8.4	Wood	PVC	4	rubber seals; substitution
2	18.7	Wood	Aluminum	3	substitution
3	3.9	Iron	Aluminum	4	substitution

The investigation of the effect of window retrofit was performed through a Blower Door Test (BDT) measurement campaign before and after different window retrofits on three buildings located in the Central Italy (climatic zone C) (TABLE I.). In particular, two window retrofit techniques were investigated: (i) applying a new rubber seal on the window frames (only for Building 1), and (b) replacing the original windows with new certified high performance windows. The Building 1 was retrofitted in two steps. Firstly, a very cheap not invasive windows retrofit was consider by applying new rubber seals to the existing wooden window frames. Nonetheless, the substitution of windows with new certified high performance windows is always requested when the performance of the building need to be increased and financial incentives (or tax breaks) have to be obtained. To this end, the for all the building the substitution of the windows was investigated in this paper; in particular, PVC and aluminum thermal break windows characterized by high air-tightness performances (class 3 and 4 according to EN Standard 12207 [25]) have been used to replace the previous wood and iron windows (TABLE II.).

Air leakages through the building envelope have been measured by means of the BDT method [25, 28], based on the mechanical pressurization/depressurization of the entire building or of a part of it. In this way, the airflow rate through the building envelope q_{env} is measured as a function of the indoor-outdoor static pressure difference Δp according to the equation:

$$q_{\mathrm{env}} = C_{\mathrm{env}} \times (\Delta p)^{n} \tag{1}$$

where C_{env} and n are the flow coefficient and the air pressure exponent (estimated by means of a simple linear regression), respectively. In particular, the "method B" ("test of the building envelope" with intentional opening closed or sealed) of the ISO 9972 Standard [26-28] was applied. The experimental apparatus used of the BDT is made up of:

- a calibrated airproof fan fitted to the door by means of an extensible frame allowing the measurement of pressure differences (positive and negative);
- a flow rate regulation system able to set the value of indoor-outdoor pressure difference by varying the speed of the fan;
- two primary devices for the flow rate measurement (e.g., a calibrated orifice plate on the plate and a Pitot tube for low and high flow rate, respectively, with an expanded uncertainty of about 5% at approximately 95% probability);
- a digital micro-manometer with an expanded uncertainty of about 1 Pa at approximately 95% probability, to measure the pressure difference both indoor/outdoor and up/downstream to the primary element;
- a thermos-hygrometer for air temperature and relative humidity measurements;
- an infrared camera, a hot wire anemometer and a Pitot tube to locate the main critical air infiltrations in the building under test.

All measurement devices have been calibrated at LAMI, the Industrial Measurements Laboratory of the University of Cassino, calibration laboratory LAT No 105 accredited by the Italian National Body Accredia.

From the BDT test results, the main air-tightness parameters (q_{50}, n_{50}, q_{a50} *and* w_{50}) were calculated using the following equations in which q_{50} is calculated from (1) using Δp = 50 Pa and evaluating C_{env} and n at the standard values for air temperature (20 °C) and barometric pressure (101.325 Pa) [24, 28-30]:

$$n_{50} = q_{50} / \mathrm{V} \tag{2}$$

$$q_{a50} = q_{50} / \mathrm{A_E} \tag{3}$$

$$w_{50} = q_{50} / \mathrm{A_F} \tag{4}$$

The natural airflow rate (n_{nat}, also called "effective flow rate") was estimated from the air change rate (n_{50}) through the equation [31]

$$n_{nat} = n_{50} / N \quad (5)$$

where N ranges 10 to 30 [32], depending on the type and the age of the building, windows and the other openings, the ventilation systems, etc. Here a 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°), 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).

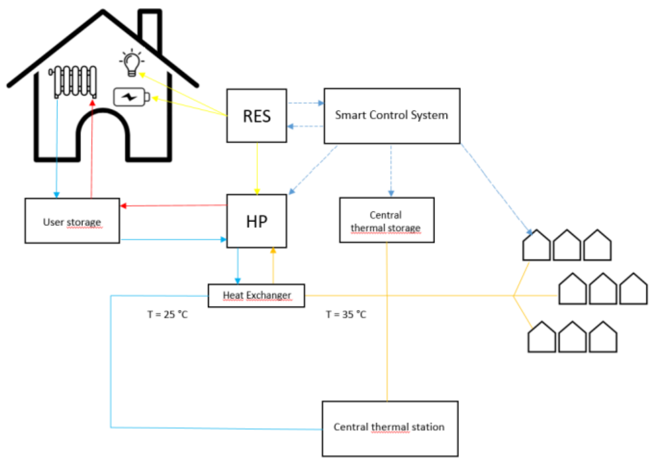

Fig. 1. Layout of the heat sharing smart energy system

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.

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*

Results of the window retrofit methods adopted in the present studies were summarized in TABLE III. and TABLE IV. : in particular, the experimental results are reported in terms of air leakages and related energy demand for ventilation, respectively. For the energy analysis, the air change rate (n_{50}) reference value of 0.3 h^{-1} was used as prescribed by law for residential buildings in Italy.

TABLE III. EXPERIMENTAL RESULTS FOR THE INVESTIGATED WINDOW RETROFITS

Building	Windows Retrofit	Leakage Rate (m^3/h^1)	n_{50} (h^{-1})	n_{nat} (h^{-1})	w_{50} (m/h^1)	q_{a50} (m/h^1)	Excess of Natural Ventilation (h^{-1})
1	none	2513	14.1	0.71	42.3	11.1	0.41
	rubber seals	1889	10.6	0.53	31.8	8.3	0.23
	substitution	4918	27.6	1.38	82.8	21.7	0.88
2	none	5968	13.7	0.68	49.3	14.3	0.38
	substitution	5126	13.0	0.65	42.3	12.8	0.35
3	none	1005	7.3	0.37	20.2	7.4	0.07
	substitution	629	4.6	0.23	12.6	4.6	-0.07

When the new rubber seals were applied to the window frames of the Building 1, the air change rate n_{50} decreased by 24.8% compared to simple wooden windows. This is probably due to the previous ineffective seal guaranteed by the existing wooden windows, which in some cases presented visible interspaces between the window and the frame. On the contrary, an unexpected increase of building permeability ($n_{50,}$ increase of 95.6%) was detected for a complete substitution of windows with new certified PVC windows. The substitution of windows in Building 2 and 3 resulted in a reduction of the air leakages (4.9% and 37.4% in terms of n_{50}). This improvement resulted in a reduction of the energy demand (TABLE IV.); nonetheless, it could lead to unforeseeable effects on the indoor air quality (in the absence of a ventilation system).

TABLE IV. ENERGY DEMAND DUE TO AIR LEAKAGES (WITHOUT MECHANICAL CONTROLLED VENTILATION, VMC)

Building	Windows Retrofit	Actual Energy Demand (MJ/yr)	Energy Demand per Surface Area (kWh/(yr·m^2))	Excess of Energy Demand (MJ/yr)	Excess of Energy Demand (%)
1	none	4254	19.89	2444	57.4
	rubber seals	3198	14.95	1388	43.4
	substitution	8323	38.92	6513	78.3
2	none	10121	23.21	5183	56.2
	substitution	9620	22.07	5675	53.9
3	none	2026	11.28	361	17.8
	substitution	1269	7.06	-397	-31.3

Summarizing, the complete substitution of windows leads to different results in for the three buildings analyzed: an increase of air permeability in the Building 1, a minimum reduction of the leakages in the Building 2, and a significant reduction of the leakages in the Building 3. These conflicting results, can be due to possible installation issues: indeed, a post-hoc investigation on possible air leakages through windows by means of a hot wire anemometer, showed that some windows were incorrectly installed in the Building 1 and 2. Therefore, window retrofits sometimes lead to a worsening of the air-tightness performance despite the use of air-tight–certified windows, due to evident installation issues.

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 confirm that possible not-fully-effective 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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