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Retrofit of a kindergarten targeting zero energy balance

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Abstract

Old buildings that are severe energy wasters and provide low indoor environmental quality (IEQ) form a large fraction of the European building stock. These buildings represent nevertheless, an asset that should be re-evaluated in order to promote local communities development. This paper describes the study that supported the design for the zero energy retrofit of a kindergarten as part of a renovated smart district. The work will substantially reduce the energy needs for heating and cooling while improving IEQ. Prefabricated modules, including mechanical ventilation and solar shading are proposed and particular attention is given to natural, mechanical and hybrid ventilation.

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Keywords: **energy retrofit, zero energy building, hybrid ventilation, indoor environmental quality**

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1. Introduction

Presently (2013), the Italian residential building stock consists of about 11.8 million buildings, of which around 61 % constructed before 1973; the educational buildings stock consists of 52 000 buildings (around 63 % of which constructed before 1973); the directional public building stock consists of 13 700 buildings (71 % of which constructed before 1973) [1]. For space heating, residential buildings use thermal energy for almost 319 TWh/a, educational buildings use more than 9.6 TWh/a, and directional public buildings more than 4.3 TWh/a [1]. The energy retrofit of such a large and old building stock should be considered a high-priority objective to improve energy

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efficiency and to reduce energy expenditure, especially for local governments, which own and manage a considerable amount of buildings.

The European project EU-GUGLE was developed to provide evidence of opportunities of deep energy renovation in Austria, Finland, Germany, Italy, Slovakia and Spain, promoting the retrofit of some pilot buildings as an inception of renovated smart districts. In Italy, three residential buildings and a kindergarten have been selected. The present paper describes the study that informed and supported the design process for the energy retrofit of the kindergarten. The work is intended to substantially reduce the energy needs for space heating and cooling while improving indoor environmental quality.

2. The existing building

The kindergarten is a typical one story heavy-prefabricated building, constructed with concrete precast panels and low performance windows, on a concrete structural frame (Figure 1 and Table 1). It was built in the 80s, and many other similar buildings are present in the metropolitan area, under the property and management of the city government. The opportunities of replication are therefore substantial and the school could become a showcase for effective energy retrofit solutions. The building has a gross floor area of 944 m^2, a net floor area of 855 m^2 and a gross volume of 3 422 m^3 (S/V ratio equal to 0.77 m^2/m^3).

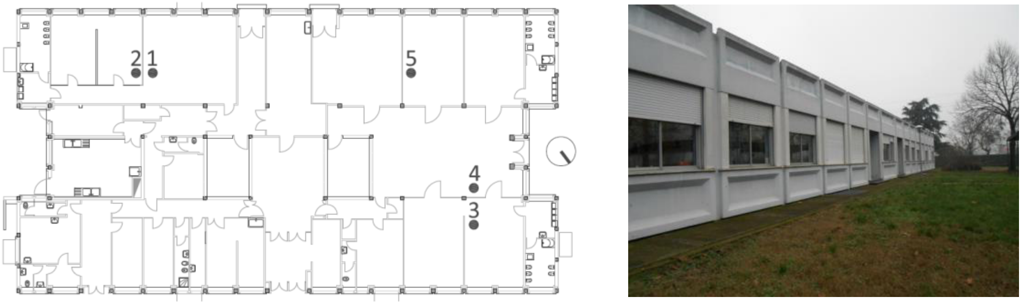

Fig 1. Kindergarten plan view including the five monitored rooms (on the left); picture of the southwest facade (on the right)

Table 1. Technical description of building envelope components pre- and post-retrofit

Component	Pre-retrofit U-value, W/(m^2 K)	Post-retrofit U-value, W/(m^{2}K)
Roof	0.9 (pre-cast concrete slab)	0.1
Vertical opaque wall	1.0 (pre-cast concrete panel)	0.1
Window	~ 6.0 (single glazing + frame)	0.8
Floor (facing unheated cellar)	0.8 (pre-cast concrete slab)	0.3

The energy required for space heating and the production of domestic hot water of the existing building, relying both on the same boiler, were normalized by using a regression model ($R^2 = 0.87$) made on the basis of the metered data and Heating Degree Days (HDD) from 2010 to 2013 (Table 2). Space heating value was substantially higher than the one of domestic hot water, therefore the correlation with HDD is motivated.

Air and operative temperatures were monitored from July 2014 to December 2014 in five reference rooms (Figure 1), in order to identify potential thermal discomfort issues (operative temperature only in room 5). Summer of 2014 has been quite unusual, with low outdoor temperatures and many rainy and overcast days; hence summer discomfort issues may have been underestimated compared to a more typical summer situation. Slight overheating discomfort conditions (compared to Category I according to the adaptive model of standard EN 15251 [2]) were recorded only in a few early days in July (Figure 2), although interviews to the teachers revealed that overheating discomfort was experienced as an important issue in former years, especially in rooms facing southwest, e.g., room 1, 2 and 3. In fact the building has no effective external solar screen (only security roller shutters), and it has no mechanical cooling or ventilation system. Moreover, the building was unoccupied for the whole month of August.

Table 2. Existing building energy consumption per net floor area

Energy carrier (energy service)	Delivered energy kWh/(m^2 a)	Primary energy conversion factor	Primary energy kWh/(m^2 a)
Fuel (space heating and production of hot water*)	202.07	1.00	202.07
Electricity (lighting, laundry, kitchen, equipment)	35.32	2.18	77.00

*Energy used for space heating and production of domestic hot water are corrected according to the HDD of the test reference year used for energy simulations, on the basis of the regression model developed on real monitored data.

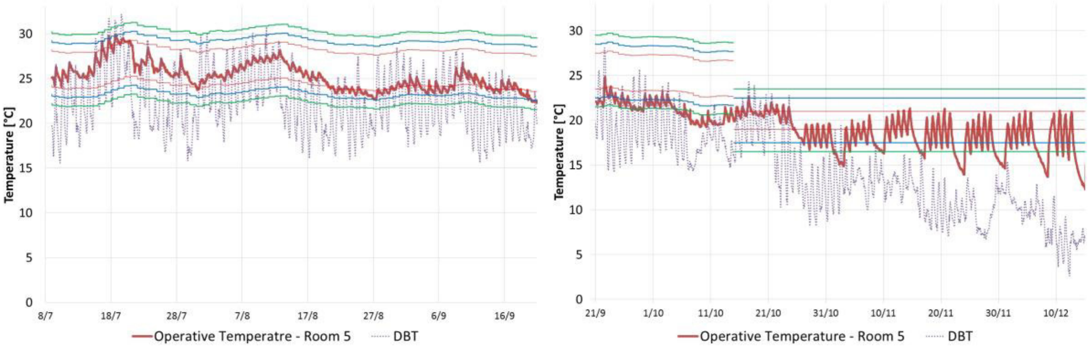

Fig 2. Operative temperature in room 5, and outdoor dry-bulb temperature (DBT) between 8/7 and 20/9 (on the left) and between 21/9 and 15/12 (on the right) compared to EN 15251 comfort limits (red, blue and green lines corresponding to the limits for categories I, II and III, respectively)

During the mid-season, from September up to the 15th October (when heating season started), the indoor temperatures, during occupation time, were typically between the Category II and III limits (blue and green lines in Figure 2), according to the adaptive model of standard EN 15251 [2] that was used as a reference. This condition is usually considered acceptable in existing buildings. Nevertheless, the building is occupied by very sensitive and fragile persons (children between 3 and 36 months), and Category I might also be assumed as a reference.

Since the recorded temperatures were always below the lower limit for Category I (red lines in Figure 2), they show a potential thermal discomfort due to under-heating during this period. Only after the 11th November, the heating system was able to provide acceptable indoor temperatures, equal or above the set point temperature of 20 °C, during the whole occupied time.

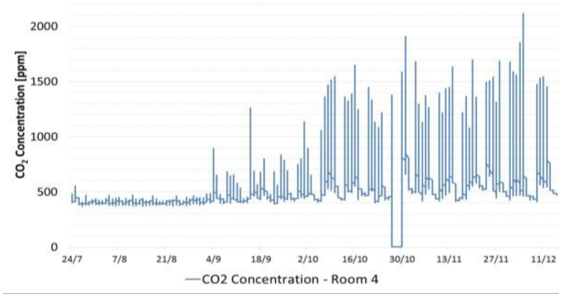

Fig 3. CO$_2$ concentration in room 4, with noticeable peaks after September (missing data from 27/10 to 30/10 are due to a technical problem to the energy supply of the equipment)

The temperatures were nevertheless dropping as soon as the heating system was turned off (Figure 2), providing evidence of the low performance of the building envelope in terms of thermal insulation. Constant thermal comfort limits reported for kindergartens in Table A.3, Annex A, of EN 15251 are plotted since the 15th October, because, according to EN 15251 specifications, the adaptive model limits cannot be used when the heating system is operating. CO_2 concentration was monitored in room 4 (Figure 3), a common space where pupils play and spend a considerable part of their time. During August, the building was unoccupied so the average value of 400 ppm may be assumed as the background outdoor level. After September, noticeable peaks are recorded in the room, with values which substantially exceed the reference value of 700 ppm above the background level [3], i.e. beyond 1 100 ppm. This evaluation should be made under steady-state conditions, however, the recorded peaks go far beyond the threshold, showing that the building needs a better ventilation strategy.

3. Methodology

The energy metering and the indoor environment monitoring provided evidence of the low performance of the existing envelope, heating and lighting systems; furthermore in the existing building no solar control strategy is implemented and this may determine overheating risk during the hot periods. Finally, the kindergarten shows poor ventilation conditions and a potential low level of indoor air quality (IAQ).

The energy retrofit strategy was therefore defined targeting the following goals:

- reducing energy needs for space heating;
- reducing all the final energy uses by improving the efficiency of building systems;
- adopting passive strategies whenever possible, while avoiding the installation of active cooling systems;
- installing new generation systems using renewable energy sources;
- improving IAQ, by developing a ventilation strategy;
- guaranteeing adequate thermal comfort condition all year long;
- reducing both construction time (to limit the disturbance or interruption of the educational service) and cost (to make the intervention feasible).

A numerical model of the building was developed to:

- optimize the selection of opaque and transparent envelope thermal insulation;
- optimize the ventilation strategy;
- define a solar control strategy;
- check energy needs and uses to implement a zero-energy approach;
- check indoor environmental conditions.

4. Energy simulation

The energy simulation of the building was performed using the building performance simulation tool EnergyPlus [4], version 8.1.0. The physical models and algorithms for calculating heat exchanges have been selected with a trade-off between precision and computation time. The heat conduction through the opaque envelope was calculated *via* the conduction transfer function method with four time steps per hour. Natural ventilation in the classrooms and corridors through window openings was simulated using the airflow network model. The minimum outdoor ventilation rate was set according to national standards [5]. School working schedule, number of occupants, equipment and lighting operation were based on interviews with teachers and the building manager. The metabolic activity rates were calculated according to the definition of a "standard kid" [6].

Two models were developed, one representing the building before the retrofit and the other after the retrofit. The latter was used to test different design solutions. Before running the energy simulation, the major thermal bridges were identified and studied *via* a finite element analysis. All the identified thermal bridges were reduced by properly applying external insulation. The design team has developed *ad hoc* prefabricated modules which include windows, solar screens and ventilation systems, to be installed on the outdoor face of the existing building envelope. These modules will be carefully connected to the new highly-insulated flat roof and, if economically feasible, the thermal insulation will extend 1.5 m below the floor level, disconnecting the outdoor pavement from the structure of the building. In order to substantially reduce energy needs for space heating compared to the existing building, a 30 cm thick thermal insulation layer was chosen for the roof and the vertical opaque panels. Moreover, triple glazing systems with Argon filling and an innovative frame included in the opaque part of the prefabricated module were selected. A glazing g-value of 0.47 and outdoor movable solar screens will allow to control solar gains and glare risk by means of manual or automatic control. The building will be connected to the local district heating network, eliminating the existing low performance boilers. Two heat exchangers will be used: one for low-temperature heating and the other for producing domestic hot water. The lighting system will be renovated by installing high performance LED lamps controlled *via* automatic systems. The control of the lighting systems was simulated establishing a target illuminance value on permanently occupied rooms of 300 lux [7], providing adequate visual comfort conditions for pupils. No cooling system is included in the concept of the renovated kindergarten and the indoor thermal comfort and air quality will be guaranteed by a hybrid ventilation system operated either *via* automatic or manual control. The strategy includes operable windows and decentralized ventilation units with heat recovery.

4.1. Ventilation strategy

Poor ventilation conditions were identified in the existing building. In order to reduce exposure of pupils to low IAQ levels, while keeping energy use for ventilation low, two ventilation strategies were analyzed:

A. mechanical ventilation based on the minimum required outdoor airflow rates including heat recovery;
B. hybrid ventilation with automatic/manual-controlled operable windows and night-time cooling ventilation.

Scenario A considers minimum ventilation air changes as defined by national standards [5], provided by decentralized ventilation systems with high-efficiency heat recovery units with a nominal sensible efficiency of 85 %, used in winter and bypassed in summer. The mechanical ventilation is working all year long following occupation schedules (i.e. when a room is empty no ventilation is provided) and natural ventilation is excluded.

In scenario B, during daytime, both in heating and in free-running period, natural ventilation is provided *via* windows opening, when outdoor temperature is below indoor temperature and within a reference range from 16 °C to 26 °C. When these conditions are not met, mechanical ventilation is started following scenario A. This is a conservative approach for the heating season, which aims to include the effect of occupant-controlled windows on building energy performance. Furthermore, natural ventilation is prevented when raining. In free-running mode, night-time ventilative cooling is provided *via* automatic operation of dedicated openings included into the window frames, and two lightwell exhaust openings obtained covering the two existing patios, while no night-time ventilation is provided during the heating period.

The delivered energy for space heating of scenario A resulted to be 19.5 kWh/(m^2 a). Under this condition, overheating occurs for 2 340 hours, showing a substantial discomfort risk for occupants. Calculations were made according to the method B of the Annex F of EN 15251. In scenario B, the use of thermal mass inside the building, coupled with day-time and night-time natural ventilation reduced overheating period to 19 hours, with essentially the same delivered energy for space heating, i.e.19.6 kWh/(m^2 a). Making a trade-off between energy and thermal comfort performance, solution B was eventually selected.

5. Results

Results of energy simulation (ventilation strategy B) are summarized in Table 3 and Figure 4, showing a reduction of primary energy of 85 % compared to pre-retrofit conditions.

Table 3. Estimation of energy consumption per net floor area of the retrofitted building

Energy carrier (energy service)	Delivered energy kWh/(m^2 a)	Primary energy conversion factor	Primary energy kWh/(m^2 a)
District heating (heating and production of domestic hot water)	28.33	0.80	22.66
Electricity (lighting, laundry, kitchen, equipment)	8.50	2.18	18.53

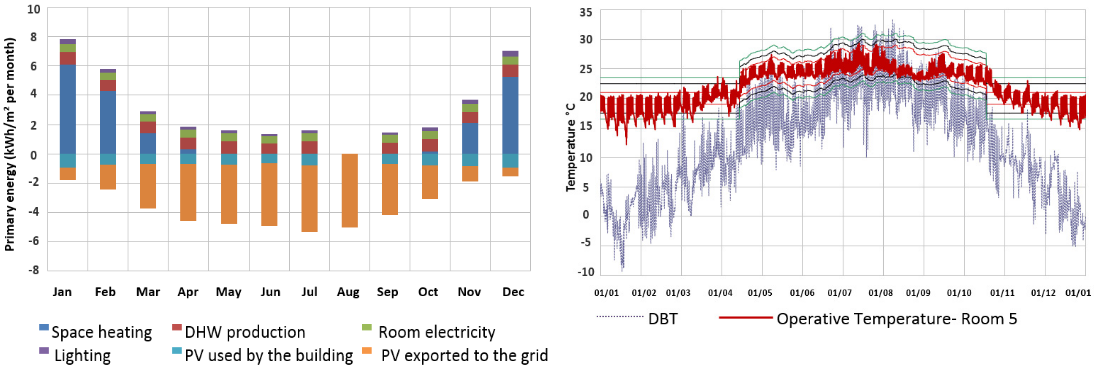

Fig 4. Energy breakdown of the retrofit building including a PV field of 217 m^2 (on the left); Operative temperatures inside room 5 contrasted with the Category I, II and III according to EN 15251 and outdoor dry-bulb temperature, DBT (on the right).

If the primary energy conversion factor for electricity produced by an on-site PV system is assumed equal to 1, then 217 m^2 of PV panels are required to balance (over one year) the whole primary energy required by the building. If instead the national primary energy conversion factor is used, i.e. 2.18 [8], then 105 m^2 of PV panels are sufficient. Both cases are feasible in term of available roof area, but they require substantially different economical efforts. Poly-crystalline cells with a nominal efficiency of 14.8 % and a nominal peak power of 285 W per module were considered. The PV system is characterized by a nominal peak power of 31.9 kW and an expected annual production of 38 737 kWh/a in the first case, and by a nominal peak power of 15.4 kW and an expected annual production of 18 483 kWh/a, in the second case.

6. Conclusion

The study that informed and supported the design process for a nearly zero energy retrofit of a kindergarten has been reported. Energy metering and indoor environment monitoring showed the low energy and indoor environmental performance of the existing building, identifying the major technical weaknesses. A comprehensive design approach has been selected, minimizing the energy needs and increasing the energy efficiency of building systems. The design team proposed to adopt a prefabricated solution that will allow to control the quality of the construction on site, while reducing refurbishment time and cost.

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