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Passive Cooling Through Ventilation Shafts in High-Density Zero Energy Buildings: A Design Strategy to Integrate Natural and Mechanical Ventilation in Temperate Climates.

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ABSTRACT

Zero Energy Buildings require airtightness and mechanical ventilation systems to provide air changes and energy saving. These requirements contrast with the principles of natural ventilation. Through a case study located in Modena, Italy, a design strategy is proposed as a solution to integrate natural and mechanical ventilation systems at different times of the year to reduce the energy consumption in a newly designed high-density ZEB. The internal comfort evaluation for the warm season is then verified with a multizone dynamic simulation and a CFD analysis.

The proposal consists of two different approaches, the cold season and the warm one. For the cold season, a mechanical ventilation system with earth tubes and heat recovery has been designed, together with airtightness, solar greenhouses and high thermal mass and insulation. For the warm season the design allows a free-running use: open trickle ventilators applied to windows which provide background ventilation, mass and insulation mitigate the heat loads, vertical ventilation shafts support natural ventilation and free night cooling. The ventilation shafts have been designed with aerodynamic principles to provide each apartment with additional (and maximised) differences of pressure due to the stack effect. The indoor comfort conditions in the warm season are then evaluated according to the ASHRAE 55 adaptive model for free-running buildings.

The results of the study confirm that in the warm season acceptable indoor comfort conditions can be achieved in a free running building. The ventilation shaft has an important role for the free cooling of a ZEB and can also be adopted in the renovation of existing buildings.

Keywords: Integrated design, hybrid ventilation system, Zero Energy Building, adaptive thermal comfort, temperate climate

1. INTRODUCTION

A Zero Energy Building (*ZEB*) is a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies.

The efficiency required to achieve the zero energy goal leads to many design strategies, including airtightness to avoid infiltration and mechanical ventilation systems with heat recovery to provide air conditioning and indoor air quality (*IAQ*). Natural ventilation systems generally contrast with the principle of mechanical control of indoor environment.

The designed energy balance of a *ZEB* can however be invalidated with an improper use of technologies by occupants, such as opening windows, changing the operative temperature or not providing the right maintenance of systems.

Thermal comfort is defined as that condition of mind which expresses satisfaction with the thermal environment and depends on physiological and psychological aspects. The former have been widely investigated by Fanger and other scholars, the latter seem to be neglected, at least in the current design. Psychological aspects of comfort involve the interaction of occupants with the environment and vary with latitude, cultural and social factors. Adaptive thermal models, essentially valid for free running buildings, are based on the assumption by Humphreys and Nicol: '*if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort*'. These models are entirely focused on psychological aspects and allow wider tolerances of indoor thermal comfort conditions than the physiological-only ones.

The mechanical control of thermal comfort, much emphasized in *ZEBs*, aims to reduce the interaction of users with the outdoor environment and this contrasts with the principles of psychological comfort. Monitoring of ultra-low energy buildings in Italy have revealed that occupants rarely use mechanical systems properly and the energy consumption often exceeds the expected results.

The aim of this paper is to propose an integrated design strategy to integrate natural and mechanical ventilation systems in a high density *ZEB* at different times of the year, overcoming airtightness related problems and thermal comfort ones. Energy and comfort evaluations are then estimated according to current standards.

2. PRESENTATION OF THE CASE STUDY

The Case Study is located in Modena, Italy, in a typical temperate climate. Winter is typically not very cold, with temperatures rarely under 0°C. Summer can instead be slightly hot, with the average of daily temperatures in the warmest months around 30°C. Wind speed is generally low at all times of the year, with values around 1,5 m/s, except for some gust at 5-8 m/s. The site of the building has 2258 Degree Days.

A high-density building is designed according to the best practice principles for a ZEB:

- Energy Saving through Building Design;
- Energy Efficiency of Mechanics and HVAC;
- Energy Production from Renewable Sources.

The integrated design of a building concerns all these principles at the same time, with choices that have influences on the whole system. The aim of the case study is to investigate the possibilities to adopt a natural ventilation strategy of use of high-density residential buildings, reducing or cancelling the energy consumption in the warm season of temperate climates, in a Zero Energy Building viewpoint. The strategy adopted for the case study are listed below.

2.1 Building Design

The Energy Saving goal is achieved through several passive Building Design strategies, as shown in Figure 1, which include both formal and technical features:

- Orientation, shape of building, tilt angle of roof and shadow analysis;
- The exposed surfaces of facades are relatively limited compared to their inner volume, with a ratio of 0,3;

- Optimisation of solar gains through greenhouses;
- Strategies for passive cooling: cross ventilation for all apartments and shafts for additional ventilation just in the warm season;
- Increase of green surfaces for climate mitigation;
- Air tightness windows with additional trickle ventilators(to be opened in the warm season);
- Choice of materials as reported in the table 1.

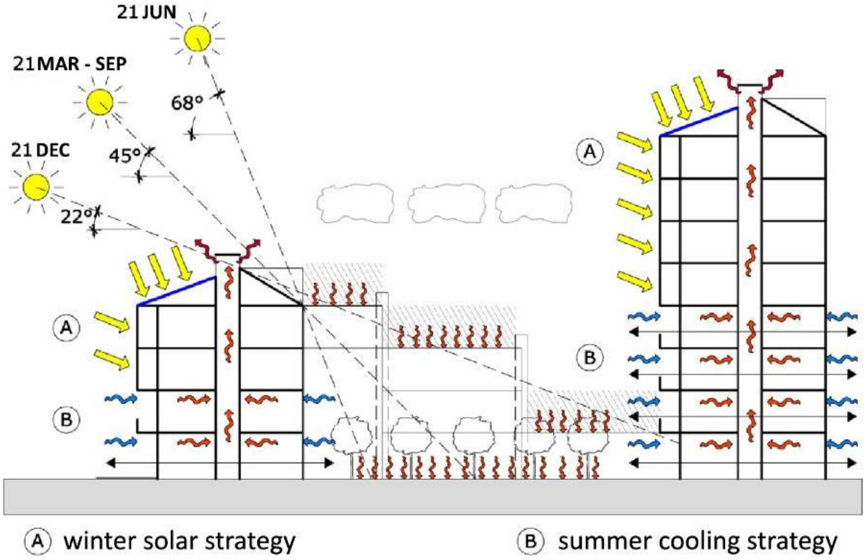

Figure 1: Building Design Strategies

Table 1: Materials

Element	**Materials**	**U-Value (W/m^{2}K)**
External wall	10 mm internal plaster 250 mm perforated bricks 320 mm rockwool panels 20 mm reinforced external plaster	0,107
Outer floor	30 mm finishing flooring 50 mm sand-cement screed 240 mm concrete floor 320 mm rockwool panels 20 mm reinforced external plaster	0,109
Roof	70 mm terracotta shingles 320 mm rigid rockwool panels 240 mm concrete floor 10 mm internal plaster	0,110
Windows (general)	Triple glazed 3x4mm, 14 mm air gap	1,00
Windows (on greenhouses)	Double glazed 3x4mm, 14 mm air gap	1,30

The ventilation shaft has been designed to maximise the indoor-outdoor difference of pressure in all the apartments for a better ventilation in the warm season, applying the stack.effect equation:

$$\Delta p_s = (\rho - \rho_i) \cdot g \cdot (H_{NPL} - H) = \rho \cdot \left(\frac{T_i - T_e}{T_i}\right) \cdot g \cdot (H_{NPL} - H) \qquad (1)$$

The height of H_{NPL} has been estimated according to Ashrae guidelines, with values typically of 0,7 of total height of the shaft. To optimise its effect, the shaft has been divided in two separate portions, the former for the lower stories, the latter for the two upper ones, as shown in Figure 2. The difference of temperature from the inlet to the outlet of the shaft has been initially settled at 25 °C. The pressure of wind has been also calculated at the various stories:

$$\Delta p_w = C_p \cdot \rho \cdot \frac{U^2}{2} \qquad (2)$$

C_p coefficient has been estimated through both empirical tables and CpCalc+ software. As shown in Figure 2, in the climate of the building site, the effects of wind pressure have little relevance compared to the stack effect ones.

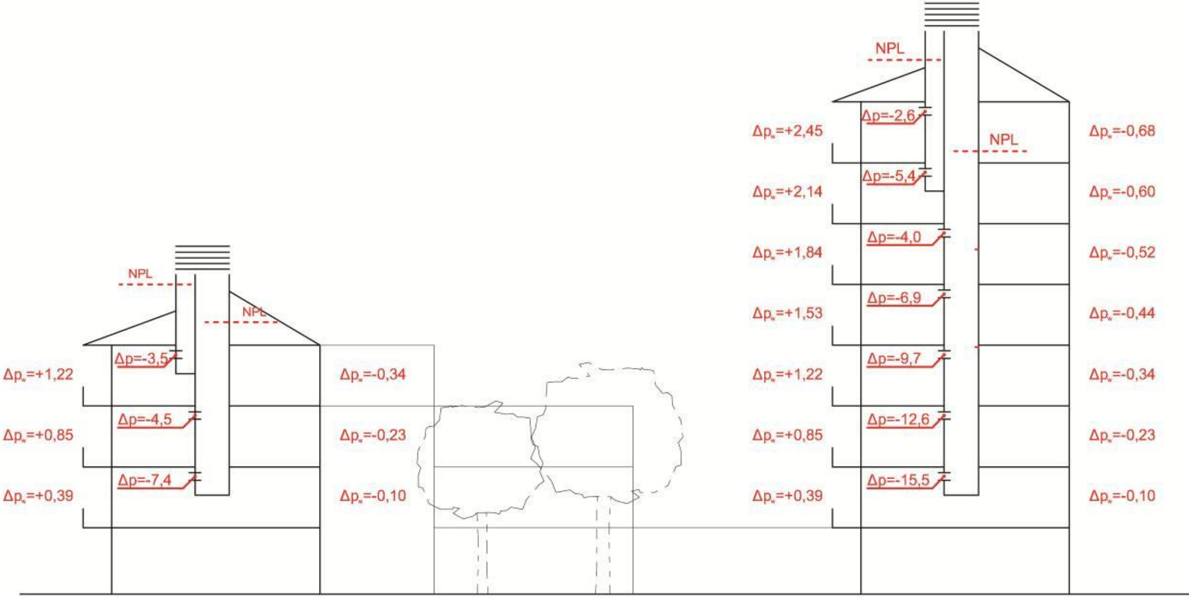

Figure 2: Differences of pressure due to wind and stack effect. Shaft optimisation.

Once Δp have been known, the airflows are calculated by the equation:

$$Q = C_d \cdot A \cdot \left(\frac{2 \cdot \Delta p}{\rho}\right)^{0,5} \qquad (3)$$

C_d is a discharge coefficient for the sharp-edged orifice, taken as 0,61. The areas of the inlet openings in the shaft are set as 0,06 m^2 (30cm x 20 cm). By applying the equation (3), a first empirical verification shows that the airflow through the shaft at each story allows a air change rate of at least 1 volume per hour. The same results are given for a reduced difference of temperature between inlets and the outlet of the shaft of 10°C.
The results suggest that a free running use of the building guarantees at a good IAQ.

2.2 Mechanics and HVAC

Energy Efficiency is achieved by the choice of high performance systems together with the entire design of the building. Designing a ZEB means to choose technologies apt to reduce, save and optimise the energy consumption, and the choice of HVAC systems is strictly related to this scope. A first overview of the project highlights questions to be solved:

- The surfaces for PV and solar thermal collectors of roofs are relatively small related to the numbers of apartments, and the energy production does not supply all the needs of the building;

- An additional and renewable system of energy production has thus to be provided to achieve the Zero Energy goal;
- The heating system of the cold season should be able to operate in reverse even in the warm season, so that a single mechanical system serves the building;
- HVAC should be shut down in the warm season in behalf of natural ventilation;
- IAQ has to be guaranteed at all times of the year, despites air tightness of windows.

The choice adopted for the building consist of a mechanical ventilation system equipped with earth tubes, heat recovery and a heating unit. During the cold season the system provides heating and ventilation in each apartment (the ventilation shaft is closed). During the warm season HVAC system should be off in behalf of natural ventilation: the background ventilation is then provided by the trickle ventilators in windows and the open shaft. In case of extreme climate conditions the HVAC system can be turned on and the ground-coupled heat exchanger provides cool and de-humidified fresh air. Hot water for domestic use and heating and electricity are then provided by a Combined Heating Power System (CHP), where PV and solar thermal collectors are not sufficient.

The Figures 2 and 3 show the operational scheme of the system in the cold and warm seasons. Figure 4 shows a relevant section of the building, Figure 5 the ventilation system scheme.

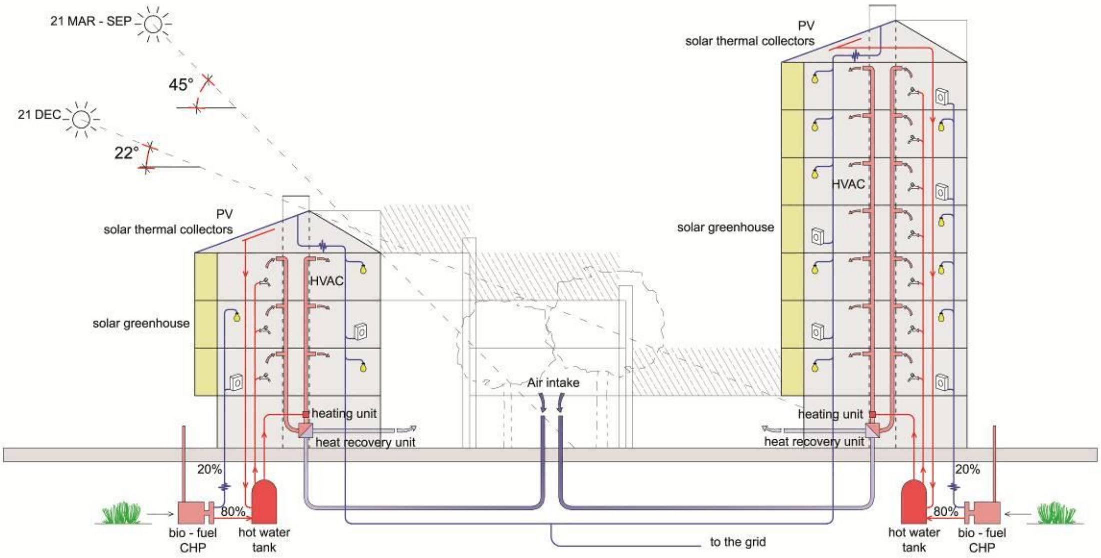

Figure 2. Operational scheme in the cold season.

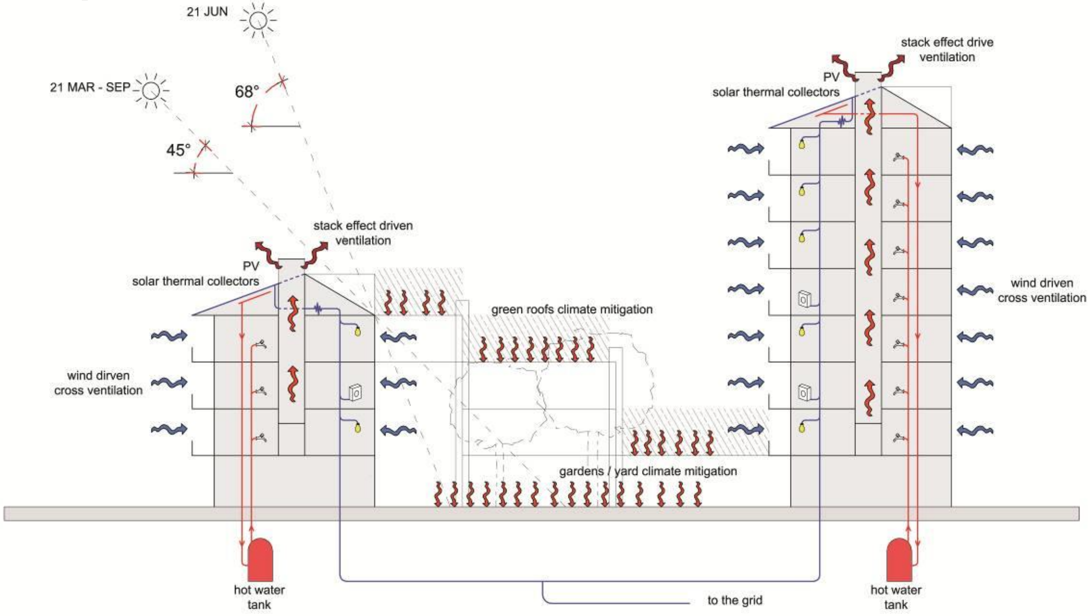

Figure 3. Operational scheme in the warm season.

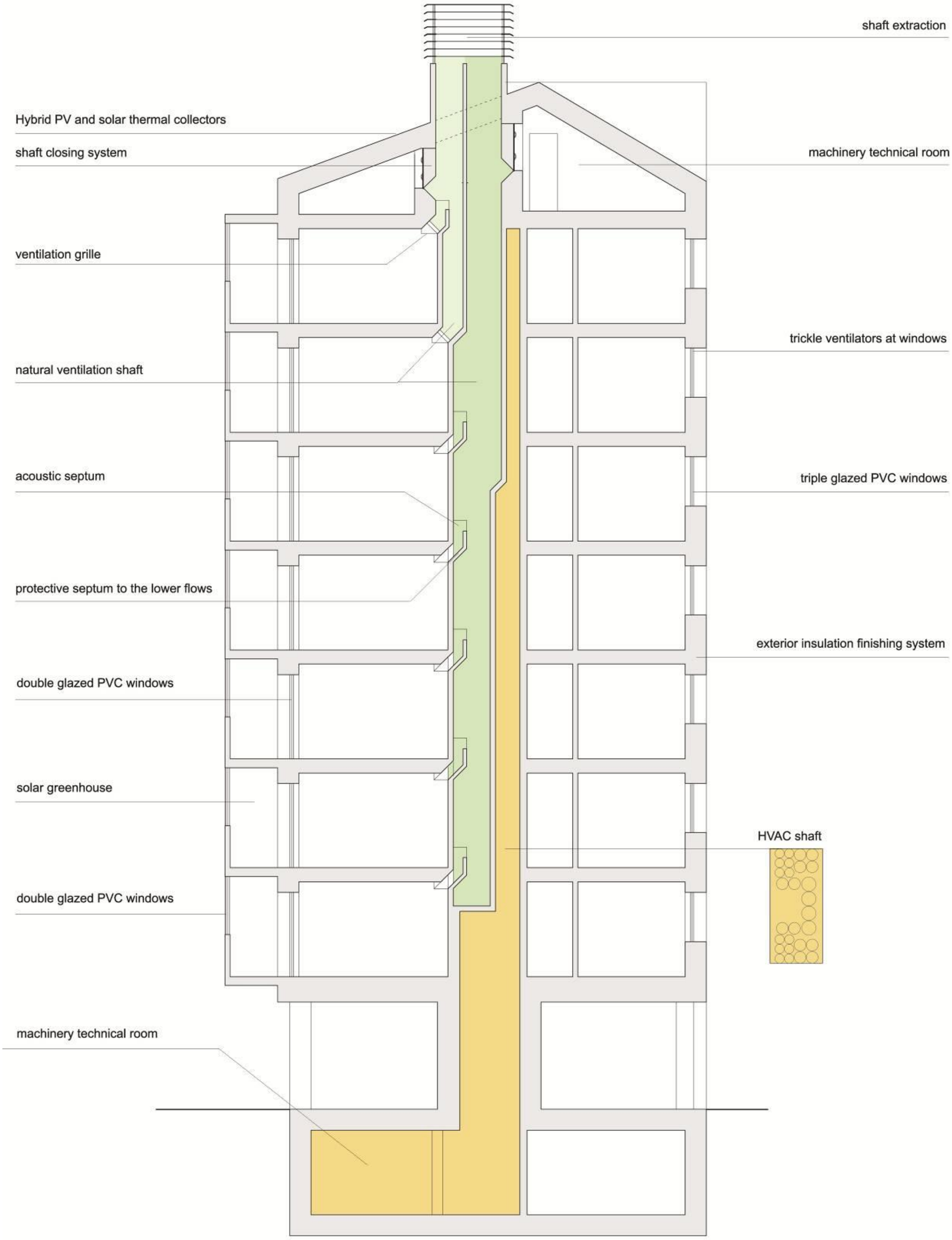

Figure 4. Relevant section of the ventilation shaft and the HVAC system shaft.

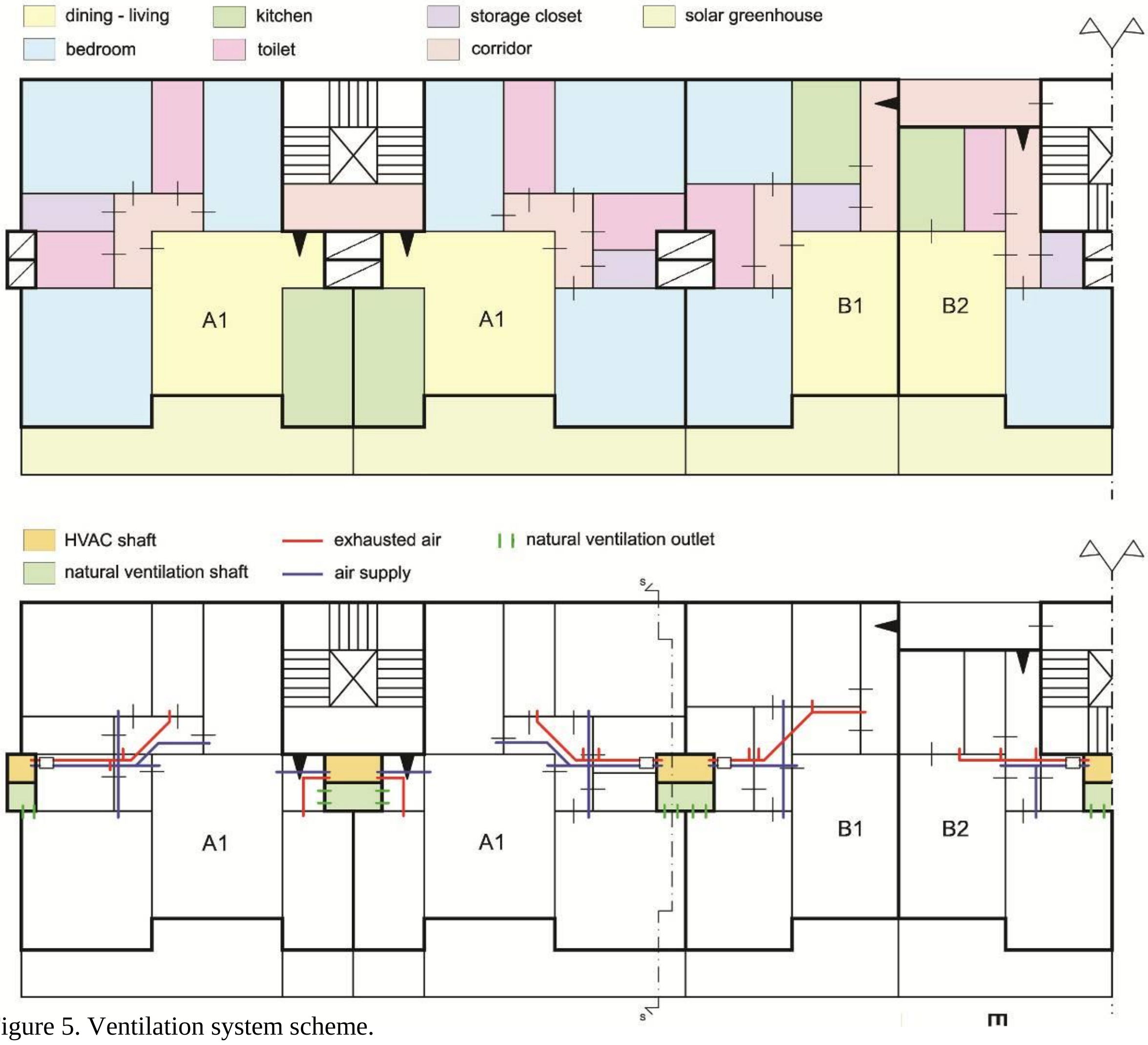

Figure 5. Ventilation system scheme.

2.3 Renewable Sources of Energy

The Energy Production in ZEBs should balance the consumption. To optimise the sun-exposed surfaces of the roofs, PV is designed to be settled for 604 m^2 while photovoltaic thermal hybrid solar collectors are designed for the remaining 250 m^2. The total energy production is about 155100 kWh per year, and the hot water production supplies all the needs of the building for the most part of the year.

The electric needs of the building are estimated in 171000 kWh per year through the SVI index (*StromVerbrauchsIndex)*, related to the number of occupants of every single apartment according to the equation 4:

$$\text{N. of occupants x 500 kWh + 500 kWh = goal value per apartment in kWh} \tag{4}$$

A CHP system supplies the electric deficit of PV and also provides hot water for heating and domestic use in the cold season. A power of 80 kW is sufficient to furnish hot water and the residual electric energy needed.

Building energy rating is evaluated according to EN ISO 13790:2008 in 7,7 kWh/m^2 per year and all the energy consumption is balanced by the production from renewable sources also with a slight surplus.

3. ANALYSIS AND RESULTS

Thermodynamic and a CFD analyses have been carried out to evaluate the effectiveness of the design strategies adopted. The main purpose of the analyses has been to estimate the indoor thermal comfort conditions, especially in the warm season when a free running use of the building is desired. The results have been so checked through the Ashrae 55 standard for buildings with no HVAC systems working.

3.1 Multizone Thermodynamic Analysis

A relevant portion of the building has been modelled and analysed in the typical design summer week. The internal environments have been modelled in different ways to evaluate the influence of the shaft on performances. The settings of the simulation included air infiltration for 0,5 volumes per hour in each apartment, a night cooling program of 5% windows openings between 8pm and 7am and an advanced mathematical pattern for ventilation calculation. The output results of the simulation are copious and detailed. Hence the main and interesting outputs are presented. A global overview of the internal temperatures, presented in Figure 6, shows that the average values range between 25°C and 28°C, despites the daily temperature fluctuations.

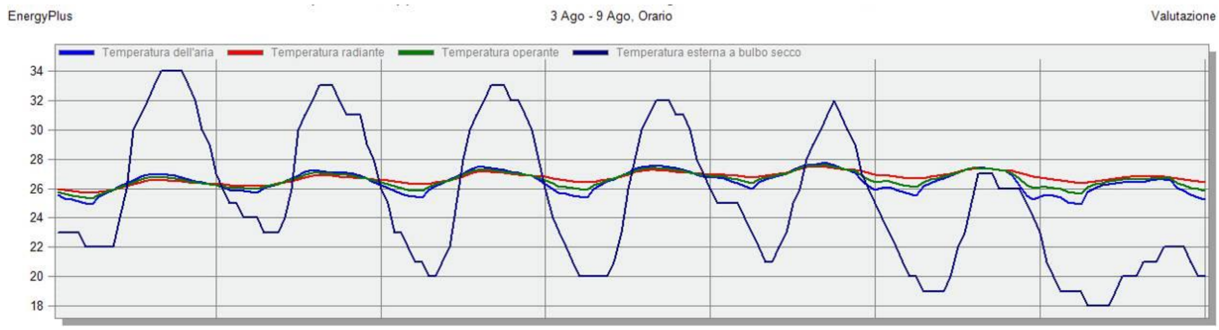

Figure 6. Internal and external temperatures in the typical design summer week.

A detailed analysis of the various zones shows that local temperatures vary at each story. If the lower stories are the cooler ones, with temperatures of 1°C below the building average, the upper floors reach in the hottest hours of the day temperatures of 29°C.

The entire results for each story and zone of the model have been evaluated according to Ashrae 55 standard and are reported in Figure 7. As it is clearly visible, thermal comfort conditions are satisfied within a 80% of acceptability limit in the hottest days of the year.

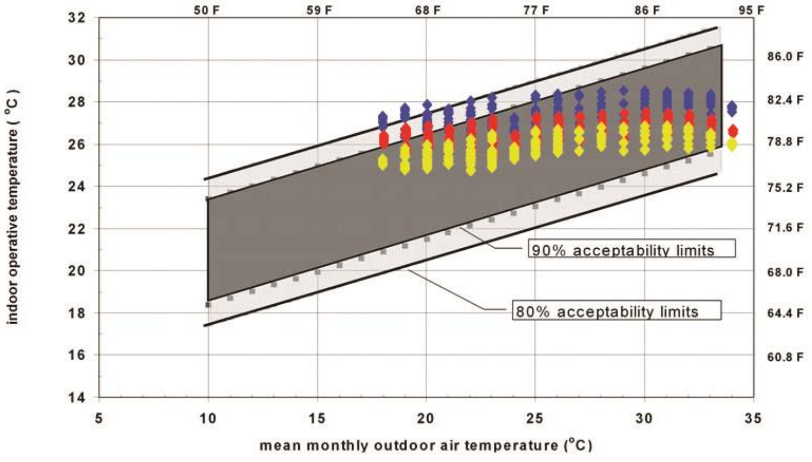

Figure 7. Internal comfort conditions in Ashrae 55 adaptive model chart. In blue the upper floor, in yellow the lower floor, and in red the average of the whole building.

3.2 CFD Analysis

A more accurate analysis has been led for the rooms served by the shaft to check the internal conditions of comfort. A simplified model of seven rooms, one for each story, and the annexed ventilation shaft has been analysed. The boundary conditions have been set adopting the output of the thermodynamic simulation in a typical situation of night cooling, at 4am of 7th August, when the outdoor air temperature is about 20°C and the average of the whole building is 26,5°C. The grid used for the model has steps of 0,1m, with 0,05m subdivisions close to the openings, the shaft and the surfaces of walls and floors.

The results of the simulation show the temperature gradient across the height of the building, as expected, and the air speed, never exceeding 0,25m/s in the rooms (Figure 8). The air speed and the temperature in the shaft are instead much higher and this causes the cooling effect in the rooms. A further detailed look at the results in every single room of the model shows the convective movements of air just adjacent the floor and the walls, with the air speed in the middle of the rooms quite little.

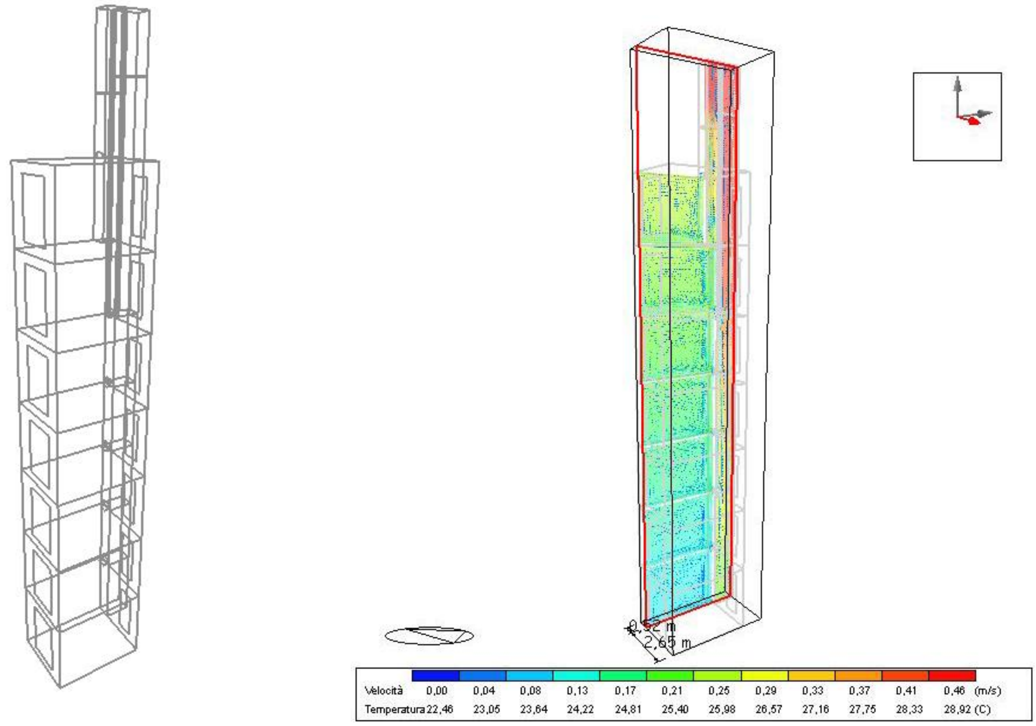

Figure 8. Model and results of the CFD analysis.

4 CONCLUSIONS

The case study presented shows the possibility to achieve good levels of comfort in Zero Energy Buildings in temperate climates through passive strategies of design, in the perspective of minimum impact on the environment and resources. The results are the sum of various systems that work together, from building design to mechanics and HVAC systems. The ventilation shaft, which is an element that characterise the project, is a part of this integrated process of design. Indeed adopting passive strategies of cooling is not a requirement to design a ZEB, as the zero energy goal can be achieved in many other ways.

If in winter heating is and ventilation are required, as the analyses have shown acceptable indoor thermal comfort conditions are still achievable even without the use of HVAC systems in the warm season. Adaptive comfort models indeed guarantee high psychological and physical satisfaction by occupants, moreover admitting wider ranges of temperature. The outputs of thermal simulations show acceptable conditions and are still preventive: indeed, a simple change of a parameter can adulterate the results. The settings have so been precautionary, e.g. the percentage of opening of the windows have just been set at 5% and could be more, or the timing of windows opening has not intentionally set in the best desirable conditions. A consideration should be also done on the possibility of using the HVAC system in the hottest days: indeed the position adopted for the project is not absolute, and in extreme climate conditions mechanics can be turned on at any time.

Hence the case study presents a strategy of integrated design of a high-density ZEB and suggests an use of hybrid ventilation in buildings: mechanical in the cold season, just natural in the warm one. In extremely hot conditions in summer natural ventilation can be assisted by HVAC systems. The ventilation shaft represents an option among the various possible. In the site of the case study its contribution to the final result is significant, as it increase the airspeed in the room and accelerates the cooling, but it is part of a complex design. For higher heights and windier locations its contribution for free cooling could be decisive.

Finally, the use of the ventilation shaft can be also adopted in the renovation of old buildings.

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