Design and testing of I-ZEB, a zero energy laboratory for the integrated evaluation of the performance of building components and HVAC systems

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Abstract. The scientific community, along with the worldwide governments, debate about the performances of buildings for decades and today the subject is still of topical interest. The recent regulatory framework requires increasingly high energy-efficient buildings in order to reduce the overall impact of building sector and to improve the user’s well-being. Several stakeholders are called upon to contribute to this end. The collaboration between the professional, industrial and scientific sectors is an engine of this challenge. Following this path, the Construction Technologies Institute (ITC) of the National Research Council of Italy (CNR) has recently developed a zero energy laboratory with the aim of creating the best platform where companies of the building sector and research bodies can share their expertise for the development and the test of products and systems to reach the Zero Energy Building (ZEB) standard. The paper focuses on the design and testing phases of the laboratory. High performance envelope, efficient HVAC and renewable energy systems are the technical pillars of the laboratory. Several characterization tests have been carried out in order to choose the most suitable technical solutions. The integrated solutions (products and systems) are tested through a continuous monitoring: energy and the Indoor Environment Quality (IEQ) variables measurements are performed.

1. Introduction
The Directive 2010/31/UE and the recent Directive 2018/844/EU identify building sector as key actor in the European energy policies, promoting both the construction of high energy efficient buildings and a long-term cost-effective renovation strategies for the refurbishment of the existing stocks toward near zero energy target, with a strong attention to health and well-being of building users [1].

The attention of professional and research sector to this issue has grown over the years with a twofold approach: the former aimed at designing buildings meeting the requirements of the current legislative framework, the latter aimed at developing innovative materials and methods for improving buildings’ efficiency. Studies and experience have shown how the design of a near Zero Energy Building cannot be reduced to a simple combination of individual systems. The complex interactions between different systems need to be considered systematically [2].

Design of a high performance building is an iterative process from the conceptual design up to the final process, where the use of advanced computer-based tools play a central role [3] and [4]. Meanwhile, great attention must be paid to construction phase in order to verify that the design choices are correctly implemented. Finally, the monitoring of the real behaviour of building in real working conditions allows to verify the compliance with the design requirements under the action of real forces. This complex schema requires the collaboration of several professionals, with different skills. In order to encourage dialogue between different stakeholders and to analyse the complex
interaction among building elements and the behaviour of a building as a whole, research bodies have realized and made available full scale facilities capable of reproducing real building operation [5] - [7]. Following this path the Construction Technologies Institute (ITC) of the National Research Council of Italy (CNR) has recently developed a zero energy laboratory with the aim of creating the best platform where companies of the building sector and research bodies can share their expertise for the development and the test of products and systems to reach the Zero Energy Building (ZEB) standard.

2. Laboratory design

The ZEB laboratory, located near Milan, consists of an existing single-storey structure that simulates an office building. The external dimensions are about 7 x 8 x 4 m (length x width x height), with 2 windows on the South-East facade and 1 window on the North-West facade. The laboratory is internally divided into three spaces: two are intended for office use (A1 and A2) and the small one (A3) is dedicated for the installation of plants.

![Figure 1. a) Plan of the laboratory; b) External view of the laboratory post operam](image-url)

The refurbishment of the laboratory is carried out through an iterative process during which different envelopes solutions combined with plants and RES solutions can be tested and validated in order to identify the most suitable design configuration in terms of energy consumption, indoor well-being and costs. The first step was to identify the envelope and system solutions to achieve the Zero Energy Building (ZEB) target starting from the Ministerial Decree 26th June 2015 directions and simultaneously calculate electricity consumption and acoustic performance in accordance with EN 15193 and ISO 12354, respectively. This configuration has been optimized through dynamic simulation programs with the aim of achieving the maximum IEQ (EN 15251) and the ZEB target. The model was set up in Design Builder V5.5 and EnergyPlus 8.9, then exported in Radiance and Daysim to deepen the aspect related to natural and artificial lighting. Using a specific module based on NSGA2 algorithm, the optimization phase figured out the best scenarios verifying both energy consumption, indoor comfort conditions and economic feasibility.

2.1. Envelope

The envelope refurbishment of the existing office building is based on the following objectives: a. minimization of thermal losses with the reduction of the existing thermal bridges and the thermal transmittance by ETICS; b. conservation of the thermal mass; c. increase of the acoustic insulation; maximization of the daylight; d. prevention of overheating risks; e. increase of the indoor air quality level. To reach these objectives the following envelope solutions have been chosen:

- External walls: mineral wool for the realization of external thermal insulation composite systems with different widths and density as a function of the existing thermal bridges and the required thermal and acoustic performance. On the southeast, a ventilated facade is installed.
• Roof: external thermal insulation, applied to minimize the existing thermal bridges, is covered by a waterproofing membrane with outstanding hail impact resistance. The roof is painted by single-component white coating pigmented with titanium dioxide, consisting in a water-based emulsion of polymers and special additives, reducing heat absorption (cool roof).

• Ground floor: particular attention was paid to the connection node between the external walls and the ground floor. The floor is higher than the ground level so the space below is insulated. An innovative raised hot/cold radiant system floor is dry installed.

• Two glazing systems (W) with specific Solar Factor, U value and Light transmission suitable for the orientation are installed with the aim to minimize the overheating risks and the loads losses on the southeast and northwest side, respectively.

2.2. HVAC and Energy production
The plant solution installed involves the integration of low consumption generation and distribution systems integrated with RES. In particular, a system plant constituted by a 4.4 kW air to water / air to air heat pump integrated with tank and solar panels supplies thermal energy for heating, cooling and domestic hot water. Additionally a split air to air, the heat recovery systems with dehumidification function [8] and a floating radiant floor with built-in hot/cold radiant system are installed. In order to balance the energy need with the energy delivered and respect the ZEB requirements an on-grid 3kW solar PV system was installed on the roof. Furthermore, a solar thermal panel has been installed to provide heat water to the heat storage system for the DHW. Other prototypes are installed in the laboratory to produce electricity from energy harvesting even at low efficiency. In particular a thermoelectric system allows to recover heat from those thermal wastes coming from, for example, air conditioning systems, a Dye-sensitized solar cell (DSSC) like an efficient type of thin-film photovoltaic cell to generate current and a Luminescent Solar Concentrator (LSC) for concentrating solar radiation to produce electricity placed on the window.

2.3. Lighting systems
Within the laboratory three types of lighting systems are installed: LED lighting (LLP), artificial daylighting (AD) and daylighting solar tube (DST). The LLP consists in 14W LED spotlights recessed in the suspended ceiling in A1 (8 spots) and A2 (4 spots) with a design illuminance value of 300 lx and in a fluorescent ceiling light in A3. The overall installed light power density is about 5 W/m². The spotlight in A1 are fully dimmable in order to compensate the use of daylighting. In A1, an innovative ceiling artificial window that reproduces the true effect of outdoor light and space is installed. Finally, a solar tube device is installed in A3 ceiling, in order to guarantee the entry of daylighting.

2.4. Indoor solutions
A lightweight wall (IP) was installed as a partition between the A2 and the A3, the latter acting as a service space suitable for the installation and control of technological plants. The partition consists of a plasterboard wall on metal framework with three 13 mm thick slabs and two interposed mineral wool layers of 7,5 mm. Afterwards an internal door has been installed in the partition in order to access the service space from the A2. The main performance required for both the internal partition and the internal door is the sound reduction index R’, in order to reduce the transmission of the noise generated by the equipment located in the service space.

Between A1 and A3, a passive modular system using hydroculture felt with embedded loop irrigation and fertigation networks, both regulated by a remoted automated monitoring and control system, is installed. In fact interior green wall (GW) is one of the new frontiers [9] - [12] to enhance energy saving, through the evaporative cooling potential of plants, the balance and control of indoor temperature and air humidity level [10], and the improvement of indoor air quality [12], through plants phytoremediation potential to purify air from CO2 and VOCs, just to mention the best-known.

3. Monitoring system
The system installed monitors some aspects of IEQ [13] and the energy consumption, the envelope component behaviour and the outdoor weather conditions. Figure 2 a) reports the weather station
installed near the laboratory. It is composed by a thermo-hygrometer for the measurement of the air temperature (Pt-100, -40 ÷ +60°C, ±0,1°C at 0°C), and related relative humidity (0÷100%, ±1%), a three axis ultrasonic anemometer (0÷70 m/s, ±2%; 0÷360°, ± 1°), 1 pyrheliometer for the direct solar radiation (0-2000W/m², 250-4000 nm, ±0.5%), and two pyranometers for the global and diffuse solar horizontal irradiance (0 ÷ 2000 W/m²), 2 luxmeters for the global and diffuse horizontal illuminance (2000-200000 lx and 0-150000 lx, <8% accordance with standard photopic curve V(λ)) and 1 rain gauge sensor (0 ÷ 300 mm/h, ±2%). Two microphones are installed to be placed in front of the facades for the measurement of the outdoor noise level $L_{den}$.

![Image](image1.jpg)

**Figure 2.** a) Weather station; b) One test configuration in room A1

In each room two data-loggers, a sound level meter and different sensors are placed with the possibility to be modified and organized into a customizable grid according to the specific test configuration. They can be installed on tripod at different heights or positioned on the desk surface: Figure 2 b) reports a typical configuration of A1 room with: 3 thermohygrometric sensors and 3 globotermometers (-40÷+60°C, ±0,1°C), 3 hot wire anemometers (0÷5 m/s, ±0,2 m/s), 1 CO₂ concentration sensor (0 ÷ 5000 ppm, ±50 ppm), 1 VOCs concentration (0÷100% air quality, ±20%), 9 luxmeters (6 low range, 20÷2000 lx, 3 high range, 200 ÷ 20000 lx), 3 microphones for the measurement of the Acoustic Quality (AQ) parameters $L_{den}$ and STC. A movable solution composed by one HFP01 heat flux plate and 2 Pt100 surface temperature sensors is used to assess, in real working conditions, the heat flux passing through the building envelope and anemometer and barometer are added to measure the performance of the ventilated façade. Portable measuring instruments (e.g. luxmeter or camera photometer) are used to make punctual measurements. Three energy meters with impulsive output are connected to the plant and to a data-logger.

### 4. Expected results

Respect to other case studies [14], realized to demonstrate the feasibility of constructing new buildings from zero energy, net energy, positive energy or nearly zero energy (ZEB [15], NZEB[16], nZEB[17] and PEB [18], respectively), zero emissions [19] and life cycle [20] points of view, the ZEB laboratory represents the renovation of a building in a Zero Energy perspective. The laboratory is also created with the aim of being able to modify its envelope and plants with a view to flexibility, interaction and adaptability as a function of specific requirements of companies. The laboratory activities are divided into two parts: yard and experimental phases. The yard phase consists in testing the installation of new products (e.g. different ETICS plugs, waterproofing, etc.), in terms of time, yield and correctness of exposure. The experimental phase intends to demonstrate that the laboratory respects a zero annual energy balance as design by optimising the operation of each system installed (heat pump with radiant floor, mechanical ventilation and heat recovery system, green wall for controlling humidity and concentrations of CO2 and VOCs, power generation systems, etc.). Then, unconventional experiments are carried out which only the ZEB laboratory allows and in real and non-simulated conditions, by performing listening tests and survey questionnaire. In particular they are focused on the occupants’ satisfaction in the ZEB [21][22]; measurements are carried out of all the quantities, in order to correlate the occupants’ perception to all the other different factors including building location, BA, AQ, ICQ, IAQ and ILQ. For the purpose, different tests have been scheduled to verify the IEQ and
consequently the energy efficiency (EE) as a whole to guarantee these comfort levels and simultaneously the ZEB target. The IEQ, as known, is a holistic concept including indoor thermal comfort (ICQ), indoor air quality (IAQ), indoor lighting quality (ILQ), the AQ [23]. In the Table 1 are listed indices of assessment, reference standards and relative test element on which tests are performed. Tests are completed with and/or without occupants in ZEB rooms. The acoustic class of the building unit could be evaluated according to the Italian Regulation in force and to the Italian Standard UNI 11367. An example of the BA evaluation of the internal partition can be found in [24]. About lighting, cause some innovative elements tested, an experimental campaign has been defined according the standards and personal experiences [25] and [26]. In particular, tests consider light perception and circadian stimulus comparison considering the different light’s sources (LLP, AD, DST and W) and they are conducted combining absolute values from monitoring campaign (illuminance, luminance, light spectrum, biometric parameters) and questionnaires to occupants.

| Category | Index                                      | Standard                  | Test element |
|----------|--------------------------------------------|---------------------------|--------------|
| ICQ      | PPD, PMV, local discomfort, personal thermal comfort | EN ISO 7730               | A1 and A2, GW |
|          | \(D_{2m,1T}, R'; L'_{nT}\)               | ISO 16283 all parts       | ETICS, IP, F, D, GW |
| BA       | \(L_{Aeq}, L_{Amax}\)                    | ISO 16032                 | HVAC         |
|          | \(L_{den}\)                              | ISO 1996-2                | Outdoor, A2 and A3 |
| AQ       | \(T; STI\)                               | ISO 3382-2; ISO 3382-3; ISO 9921 | A2 and A3, GW |
| PAQ      | Perceived Acoustic Quality                | -                         | A1 and A2    |
| ILQ      | Em, UGR, DGI, DGP, DF                     | EN 12464, UNI 11165, UNI 10840 | LLP, AD, DST and W |
| IAQ      | CO2, VOCs                                 | EN 13779, EN ISO 16000-26, EN ISO 16000-5 | GW |
|          | Global Primary Energy                     | EN 52010                  | ZEB          |
|          | Thermal performance                       | EN 13187, ISO 9869        | ETICS        |
|          | Hygrometric performance                   | EN ISO 13788              | IIW, R       |
| EE       | Fluid dynamic performance                 | -                         | VF           |
|          | HVAC-R efficiency                         | EN ISO 15316              | ZEB          |

5. Conclusions
The ZEB laboratory is designed to study and characterize the performance of materials and systems in an integrated perspective with the aim of optimizing energy consumption assuring high levels of IEQ both for scientific purposes and of interest to companies. The monitoring system can detect different variables in continuous for at least one year or for specific period depending on the type of test. No less important objectives are represented by the possibility of studying in an ideal yard topics that are difficult to investigate during early stage and as built such as: correct and easy installation of materials, time and workability, durability of performance over time of components [14], comparison between the performance of similar elements.

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