Building Management System in an Energy Positive House

– Case study: EFdeN House from Solar Decathlon

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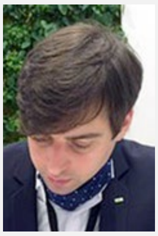

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The present paper presents the active and passive strategies implemented in the EFdeN project, a house which represented Romania at Solar Decathlon Europe 2014. The study focuses on the BMS system logic presentation which integrates all the systems implemented in the project and correlates all the active and passive strategies in order to achieve the optimum IEQ with minimum energy consumption. Using experimental measurements of sound pressure levels, air temperature, CO_2 levels, relative humidity and energy consumption a clear view on the advantages of these strategies was possible. The implementation of all the passive & active strategies combined with the BMS control prove to be an excellent combo for achieving perfect indoor environmental quality parameters (IEQ) with minimum of energy spent. Moreover, the energy production using PV panels exceeded the energy use thus the EFdeN house can be classified as an energy positive building.

After COP21, one of the most important United Nations Climate Change Conference in the history of human beings [1]., the member countries decided to do what it takes to limit the world average temperature increase bellow the value of 1.5°C above the values registered during the preindustrial period. WMO (acronym for World Meteorological Organization) [2] highlights that in 2015 the critical threshold of 1°C above the pre-industrial level was reached, the last four years represented the hottest period in history and 2019 became the 2nd warmest year on record. Finally, according to the European Commission climate and energy framework [3], until 2030 all the European Union member states must achieve at least: 40% cuts in greenhouse gas emissions, 27% share for renewable energy and a 27% improvement in energy efficiency.

Moreover, DEPB (acronym for Directive 2010/31/EU of the Energy Performance of Buildings) [4], mentions that beginning with this year, 2020, all the new buildings constructed must achieve the nZEB standard (nearly zero energy building).

Considering all these alarm signals and arguments, in order to achieve these goals and to prevent the global warming devastating impact, it is mandatory to build energy-efficient sustainable buildings with highly efficient and performant materials [8]. Moreover, in order to reduce energy consumptions for heating, cooling and ventilation which are the most important consumers in a household it is important to implement intelligent systems which are using renewable energy sources.

The current study was conducted on the EFdeN prototype (**Figure 1**), a project realized by a team of Romanian students from several universities from Bucharest which has represented Romania at Solar Decathlon Europe 2014. The energy-efficiency strategies of the building and the systems were implemented by the students of the Technical University of Civil Engineering under the coordination of their professor. This team conceived, designed, analyzed and effectively built the prototype which now became a Research Center for Comfort Conditions and a study HUB for students within our campus.

The EFdeN prototype is currently built by students in the courtyard of the faculty, where we are testing and monitoring the comfort conditions (**Figure 1**). The building consists of two floors – ground floor and first floor, with 2.5 m floor height, with the following destinations: residential building and exhibition pavilion. Furthermore, the house is open to public for social awareness, for promoting the reduction of energy consumption in buildings and lower CO_2 emissions, also for the promotion of green and NZEB buildings in Romania, after all, having a strong socio-economic impact.

Moreover, the project is perfectly suited to the European directives promoting energy performance of buildings and transposes them perfectly, even transcending them. In the current context of high energy consumption in the buildings and the EU's 20-20-20 target, it is imperative to implement energy efficient solutions and to use the right materials in order to reduce energy consumption, subject treated in this article.

The building consists of two floors – ground floor and first floor (**Figure 2**), with floor height of 2.5 m, with the following destinations: residential building and exhibition pavilion. The house has a total footprint of 96 m^2, a 170 m^2 built surface area, 118 m^2 heated area and 400 m^3 total volume. In order to achieve this goal, we have implemented a lot of active strategies and passive strategies. The active strategies used in order to reduce energy consumption are: air to water heat pump (HP) with maximum COP of 4.02 for heating, cooling and domestic hot water, vacuum tube collectors (VTC) for domestic hot water and heating, cold water tank, domestic hot water tank, heating tank, radiant panels in walls and ceilings, heat recovery unit (HRU) with maximum efficiency of 94%, LED lamps, shading system, photovoltaic system (PV) with 5.5 kW installed power, water cleaning system for photovoltaic panels, electronic taps used in order to reduce water consumption and a building management system (BMS) that integrates all the strategies and assures the communication between all the systems implemented.

Figure 1. EFdeN House currently built in the courtyard of Faculty of Building Services Engineering in Bucharest, Romania.

The passive strategies (**Figure 2**) used in order to reduce energy consumption without operational costs are: the house form (cubic), orientation (generous glass areas on the southern facades), natural and night ventilation, taking preheated fresh air from the greenhouse (especially in the transition periods), the use of thermal mass surfaces (granite located in areas where sun radiation penetrates the building), thermal buffers (room that are positioned strategically), ventilated ceramic facade, shadings and the use of phase changing materials.

The house also presents excellent insulation as it can be seen from **Table 1**.

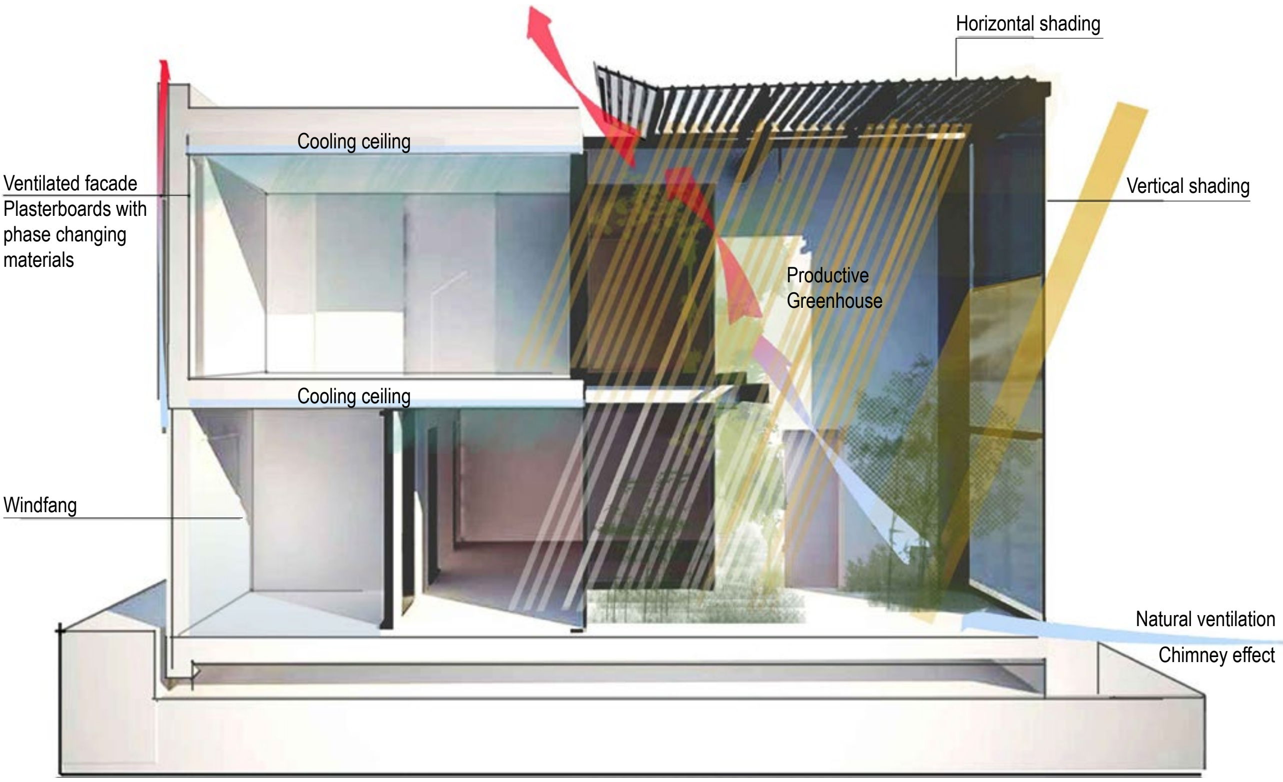

Figure 2. Overview of the passive strategies implemented within the house prototype.

Table 1. *Construction elements and their properties.*

Name of the construction element	Main layers	U [W/m²K]
Exterior wall	Ceramic panels 3 mm, Air layer 6 cm (ventilated façade), OSB panel 12 mm, Mineral wool 25 cm, OSB panel 12 mm, Mineral Wool 10 cm, Gypsum plasterboard / PCM/ Radiant panel	0.129
Interior wall	Gypsum plasterboard / PCM/ Radiant panel, Mineral Wool 15 cm, Gypsum plasterboard / PCM/ Radiant panel	0.39
Terrace	Waterproof layer 3 mm, Stone wool 5-15 cm, OSB panel 12 mm, Mineral wool 25 cm, Gypsum plasterboard / PCM/ Radiant panel	0.121
Floor above ground	OSB panel 12 mm, Mineral wool 25 cm, OSB panel 12 mm, Parquet + Cork/Granite 3 cm	0.124
Exterior windows	Triple glazing low-E	0.8
Interior windows between the house and the greenhouse	Triple glazing low-E	0.8
Exterior windows between greenhouse and exterior	Double glazing low-E	1

The present paper focuses on the BMS system logic presentation which integrates all the systems implemented in the project and correlates all the active and passive strategies in order to achieve the optimum IEQ with minimum energy consumption.

The present study objectives are to:

a) design and monitor a self-learning building management system for maintaining a high level of thermal comfort
b) monitor the indoor environmental quality (thermal, visual, acoustic, air quality) using experimental campaigns.

Self-learning Building Management System for enhanced energy efficiency

The BMS is the system implemented to make the inhabitant's life easier, more comfortable, it helps to optimize consumption and, of course, helps us monitoring the house. By putting together a large variety of sensors such as temperature, CO_2, humidity, light level and presence detection for both monitoring the comfort parameters and learning the users behaviour; actuators and the central control unit, the BMS is able to monitor many parameters at short intervals of time, synthesize all incoming data, take decisions according to algorithms and user-defined parameters and actuate different household elements in order to make the most comfortable environment possible with the least amount of energy, making sure almost none is wasted. The BMS system has a link with the other house systems with the help of analogue and digital inputs and outputs. The KNX network was the perfect solution that allowed us to integrate all equipment and systems from various manufacturers, having the flexibility to adapt the BMS to the situations that we faced. We integrated subsystems with remote user interface, in a single decentralized system, stable and extendable (**Figure 3**).

The light intensity in the environment is monitored by light intensity sensors and gives feedback to dimming ballasts, in order to maintain a constant light level throughout the day. Also, the light level can be controlled from the push-buttons and remotely, from the user interface. For switching light control we used switching actuators, presence sensors and push-buttons, this type of control being used for the greenhouse, exterior, technical rooms, lobbies and bathrooms lighting. Human movement sensors are used to detect presence in a certain area in order to command the lightings to turn on and off and are also used to learn the behaviour of the occupants. We integrate the TV and audio systems to control them remotely via the KNX network from the user interface due to IR to KNX gateway.

An important feature of the electrical system is the automatic shutdown. In case a fire breaks out, a differential temperature detector will trigger the emergency and immediately the central control unit shuts down electrical power to the stove and oven, while to the user is given a message to be made aware of the situation.

High air quality is maintained by the house ventilation control system, which is linked to temperature, CO_2 and humidity KNX sensors. The fresh air (taken either from outside or from the greenhouse) is heated/cooled using the HRU equipped with a heating battery (the thermal fluid comes from a buffer tank linked to VTC, HP). The air is introduced in each room via air dampers, controlled individually by KNX actuators. The temperature comfort is assured by radiant panels controlled by zone. KNX heating actuators controls by set point each valve's zone. The thermal agent comes from the same buffer tanks.

The human machine interface is compatible with many mobile devices and operating systems, such as tablets, smartphones and pc. The web-based visualization can be accessed via internet from all over the world. We have floor plans and system diagrams (photovoltaic,

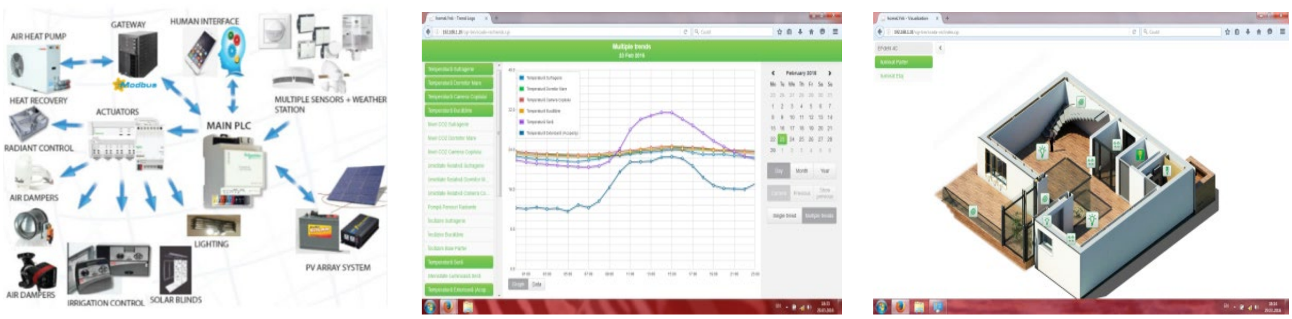

Figure 3. Equipment's integrated in the BMS system and monitoring interface

metering, heating, cooling, ventilation, sensors) both as overview and detailed screens. Trends can show overview regarding thing like energy consumption or comfort parameters evolution. Through the homeLYnk webserver we can access and control elements of the KNX system. We can monitor sensor values (temperature, CO_2, humidity, brightness, wind) or equipment status (air dumpers, heating actuators, pumps or energy meter). It is possible to control the lighting, the shading systems, the HVAC equipment's and water pumps and all these through the web interface.

Multiple energy meters are used to be able to break down energy consumption. We have meters for consumed energy, produced energy, stored energy, lighting, sockets, electrical vehicle charging, BMS, laptop/TV, plumbing, HVAC. All these meters are connected to the KNX system and can be used to interact with a smart grid. Having these data, we can do the electrical energy balance during certain periods, and after a numerical campaign the results showed us that the house produces 36% more than it consumes per year (6844 kWh produce and only 4330 kWh consumed).

Noise measurements results

In order to assess the interior environmental quality an extensive experimental study was necessary. The team measured the sound pressure level in all the rooms of the house in the case when all the systems are working at maximum capacity (heat recovery unit, circulation pumps, heat pump etc.).

Several microphones were placed in all the rooms of the house (technical room, bedroom, master bedroom, living room and kitchen and dining room) – see **Figure 5**. The results were compared with the reference values normed by the STAS 6156:1986 Romanian Standard and EN 15251:2007 [5] (under 35 dB for bedrooms and under 40 dB for living room) for all the frequencies (125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz). For the evaluation of the sound pressure levels the following equipment's were used: Bruel&Kjaer 2270 sound level meter class 1 precision, Bruel&Kjaer type 3050 6-channel input module in order to collect the data from the microphones and the Bruel&Kjaer Software Pulse Labshop v. 15.1.0 in order to collect and analyse the results [7].

Figure 5. Pictures during the measurements conducted by our team [6].

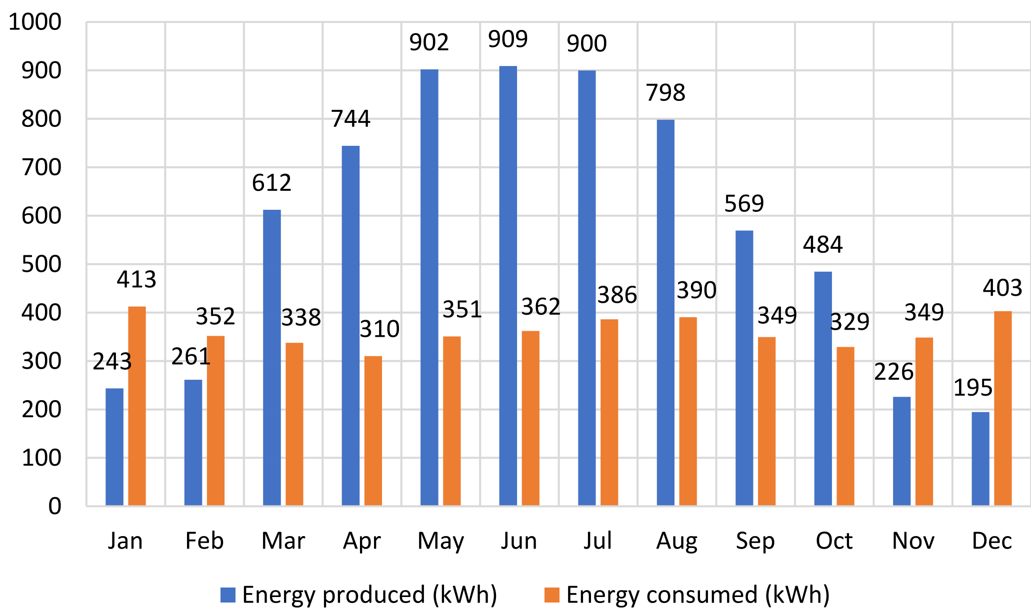

Figure 4. Monthly energy balance of the building.

As it can be observed from the **Figure 6**, the sound pressure level in all the rooms is below the maximum allowable values required by the Romanian and European Standards. This is due to the high acoustic insulation of the interior walls and soundproof of the technical room.

Indoor air temperature, CO_2 level and relative humidity are also important parameters describing the indoor environmental comfort according to the national standard and international standards like EN 15251:2007 [5]. The data presented in the figures bellow were collected during the experimental studies conducted in the EFdeN prototype during one week from one winter month (more exactly 8th – 14th February 2016). The set point for all the parameters is controlled and adjusted by the BMS or by users via a web based interfaced.

Air temperature measurements results

Figure 7 emphasize the measurements of indoor temperature in the living room, indoor temperature in the bedroom and outdoor temperature (which are highly correlated). Moreover, on the graphic we can

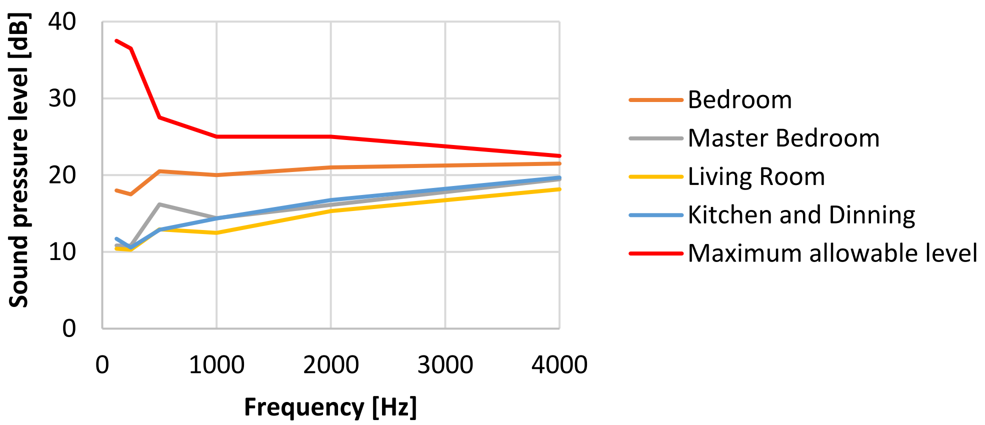

Figure 6. Sound pressure level measurement in multiple rooms.

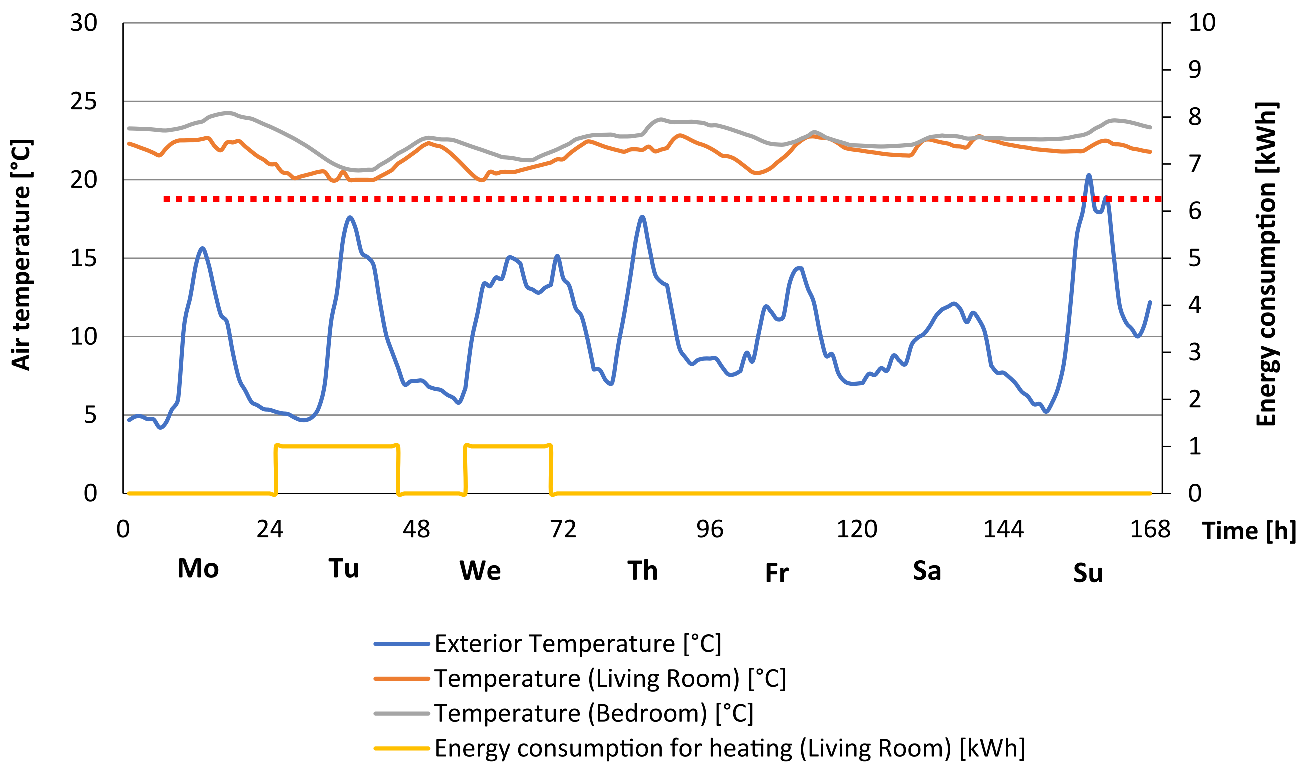

Figure 7. Temperature and energy consumption for heating during one week from a winter month.

observe the energy consumptions for heating during the seven days studied. Even if the outdoor temperature variation is between 4.2°C and 20.3°C, the indoor temperature variation is between 20°C (which is the temperature set point in both rooms) and 24°C in the bedroom, respectively 23.6°C in the living room. The amplitude variation is 16.1°C for the outdoor ambient air, while inside we obtain only up to 4°C amplitude variation. During the week studied we could observe that the heating system started during day 2 and day 3 (Tuesday and Wednesday) when indoor temperature values reached the set point. Furthermore, during this week the heating system consumed only 38 kWh during the 37 hours of functioning. Also, it can be observed that the variation of the interior temperatures, unlike the exterior temperature, is more uniform due to the thermal inertia added by using PCMs and special concrete. Thermal mass elements are crucial in case of low inertia buildings in order to store energy during the sunny periods when solar radiation is available.

CO_2 level measurements results

CO_2 levels measurements were also conducted during the same seven days analysed. **Figure 8** presents the CO_2 level variation in the two rooms studied: living room and bedroom. Moreover, the variations are related to the rotary heat recovery unit (HRU) energy consumption, equipment which starts when the indoor values reach the set point of 800 ppm. EFdeN prototype is not only a house, a prototype, but became also a Research Center and study HUB for students, so many meetings are scheduled every day, but the ventilation system was designed for a normal family occupation. This is why we can notice some peak values of CO_2 concentrations especially during four days of the experimental measurements: Wednesday, Thursday, Friday and Saturday. In order to keep the CO_2 levels below target, HRU worked for about 55 hours during one week, thus consuming only 10 kWh electrical energy. The European Standard EN 15251 mentions a limit of 800 ppm for category 1 of comfort and a limit of 1200 ppm for category 3 of comfort. During the seven days analysed the values measured are in the limits of category 1 more than 85% of the time and in the limits of category 3 100% of the period.

A good strategy in order to limit the values reached during meetings is to start the HRU with certain time before the start of them, or to lower the set point to 750 ppm, thus determining higher energy consumption.

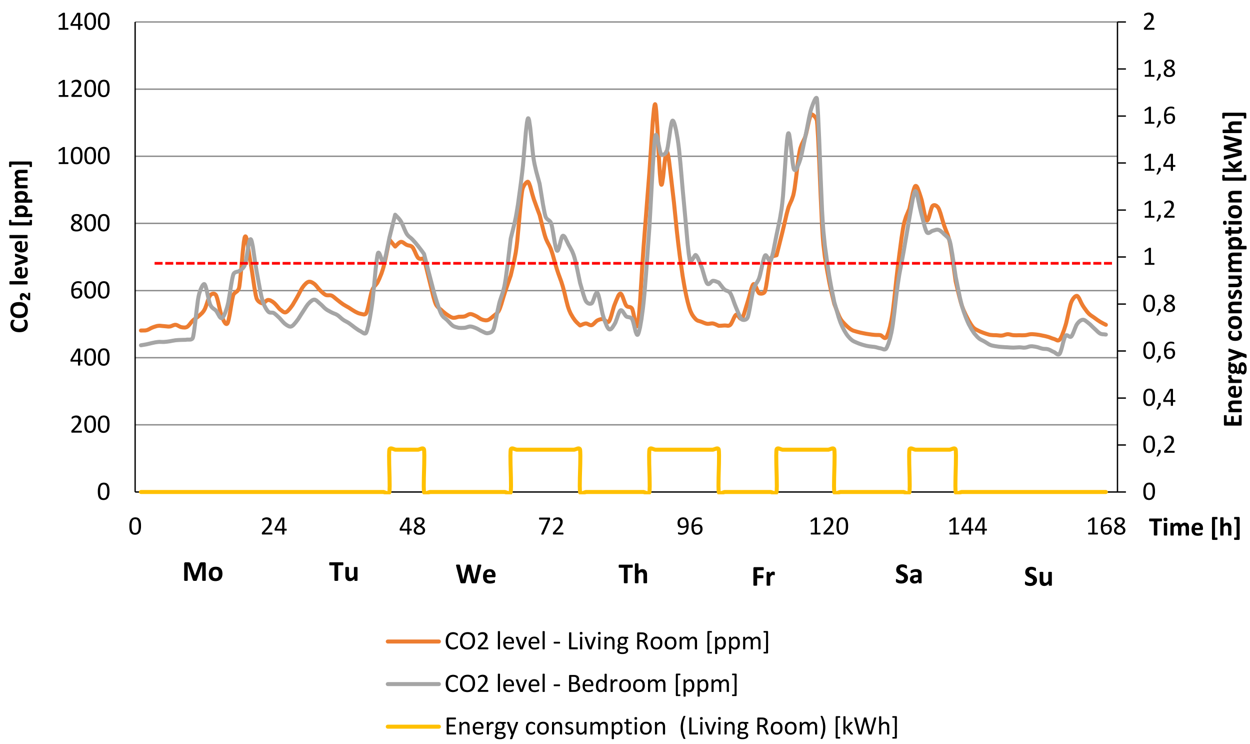

Figure 8. CO_2 level and energy consumption for HRU during one week from a winter month.

Relative humidity measurements results

Figure 9 highlights the relative humidity levels for the week studied. As it can be observed the values are within normal limits, except some short periods correlated with the meetings above mentioned which determined increased humidity and CO_2 levels. The values measured for the two rooms are between 34% and 51.5% in the bedroom case, respectively between 34% and 55% in the living case where the occupation level was higher also. The relative humidity was also controlled by the HRU used in order to reduce CO_2 levels inside the house.

According to the EN 15251 Standard, a relative humidity ratio between 30% and 50% corresponds to category 1 comfort level, while a ratio between 25% and 60% corresponds to category 2 comfort level. By taking this into account, in more than 86% of the time, the relative humidity values are in the range proposed for category 1, while in 100% of the period studied, the values are in the range proposed by the standard for category 1 of comfort.

The greenhouse`s effect as thermal buffer was a key point of the energy reduction strategy while the BMS "decided" in many cases to use the preheated air from the greenhouse instead of radiant panels to heat the building. In conclusion, all the passive and active strategies implemented in this building were correctly designed to achieve optimum values for indoor comfort and energy consumption.

Conclusions and perspectives

Following the experimental studies conducted it can be concluded that the passive and active strategies designed and implemented in the EFdeN energy-efficient building were complementary and well combined in order to achieve the indoor environmental quality with minimum energy consumption. The main element of the house, the BMS system, was found to be the necessary asset in linking these strategies. Other conclusions are mentioned:

- the indoor air temperature variation is uniform during the entire period;
- the sound pressure levels were below the maximum acceptable limits thus the indoor acoustic comfort is considered very good;
- the CO_2 levels were in the limits proposed by EN Standards in almost 85% of the time and classified in very low polluting;

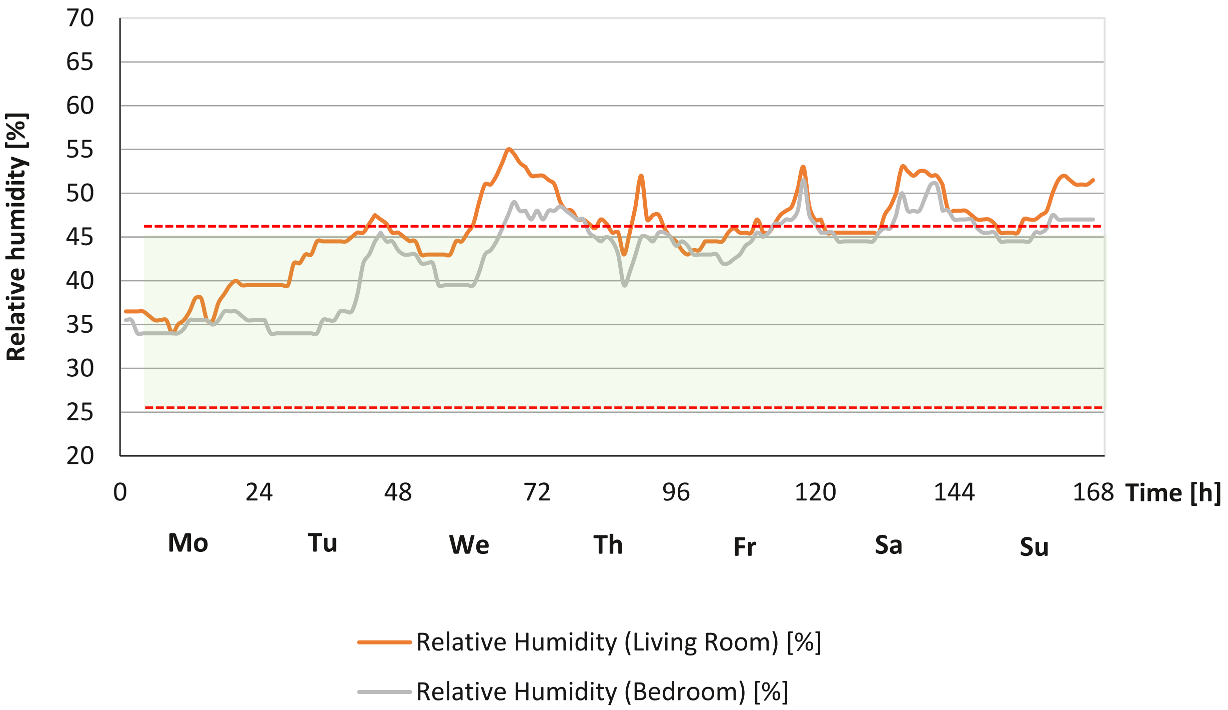

Figure 9. Relative humidity variation during one week from a winter month.

- the relative humidity levels were also in the good accordance with the standards with 86% of the time classified in category 1;
- the energy consumed in order to maintain IEQ was exceeded by the energy produced by the photovoltaic panels therefore the building can be mentioned as an energy-positive house. ■

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