The E4 brickhouse of Romania – a local proved nZEB

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Abstract. The nZEB concept, intensively required by the European directives, is intended to include buildings with very low energy consumptions from fossil fuels and it will be mandatory for all new buildings starting with 2021. This paper explores the design stages of a process that meets the requirements of the “E4 program” initiated in Europe by the Wienerberger company for buildings intensively using ceramic elements. The 4 Es stand for Energy, Economy, Ecology and Emotion. Therefore, the paper presents a house in terms of architecture and installations for a healthy, energy efficient, environmentally friendly and affordable home, where ceramic building elements simultaneously stand for increased thermal and mechanical resistance and thermal mass. Energy performance assessment is accompanied by economic analysis and primary energy calculations. Once the building has been completed and occupied by the owner family of 2 adults and two children, the energy use and indoor comfort were monitored for two years. The real energy performance could thus be assessed and compared to the design stage estimate. Results indicated an over-compliance with the nZEB criteria set for Romania. The study reflects the value of simulations at the building design stage and the differences that occur between statistical approach and real building performance.

1. Introduction

Buildings are responsible for 40% of energy consumption and more than 50% of carbon dioxide emissions in the European Union countries. The number of residential buildings in Romania is constantly increasing in recent years, although at a lower rate due to the economic crisis. The reduction of energy needs and the increased use of energy from renewable sources are very important, not only in terms of costs or reduction of entropic greenhouse gas emissions, but also to ensure a sustainable development. Directive 2010/31/EU (EPBD2) for energy performance of buildings specifies that the Member States shall ensure that, by 31st of December 2020, all new buildings are “nearly zero energy buildings” (NZEB) [1]. The NZEB concept refers to a building that has a very high energy performance, in terms of energy needs and use of fossil fuel energy as well. As a consequence, the low amount of energy required to ensure proper indoor comfort all year round has to be covered to a very significant extent from renewable energy sources, wherever possible with equipment placed on-site or nearby, to reduce transportation and storage losses. The calculation and performance evaluation methodology of NZEB is provided by each Member State with guidelines from the EPB2 and associated European documents [2].

Noteworthy as well, most people in urban areas spend about 90% of their time indoor of buildings (homes, offices, stores, etc.). The proper comfort, not only from the thermal point of view, but also from the many other aspects, including emotion, is crucial when a type of building is intended to have success on the market.
The present paper illustrates a house designed and built to be at nZEB level, using ceramic elements, as specified in the “E4” program defined by the Wienerberger company [3]. The 4 Es mean Energy, Economy, Ecology and Emotion. “Energy efficiency” is achieved through the minimization of energy consumption by an optimum design of a highly thermally insulating building envelope built with clay blocks. The design also seeks to use innovative heating and cooling technologies that would lead to a referenced nZEB. For “Ecology”, it is based on intensive integration of equipment based on renewable energy sources: solar radiation, geothermal heat, and/or biomass. For “Emotion and health”, this pilot project is intended to guarantee widely accepted indoor climate quality for many generations, using mostly natural building material such as clay products. “Economy” for the concept means affordable construction and maintenance costs for the users’ comfort, otherwise said, it means economic efficiency.

2. The E4 concept applied in climate conditions of Romania

The E4 House concept uses the principles of the major energy efficient building design approaches, paying attention to the cultural differences and the local climate adaptation. In architectural terms, the building elements designed for energy efficiency are also most visible and therefore must connect to the local tradition and culture. Therefore, the design included the pitched roof covered with ceramic tiles, the massive brick walls, terraces covered with ceramic elements, large windows for the day time area, and balanced textures and colors for outside and inside finishing.

The house is designed as a two-storey building for a family of four, and provided with an attic that can be partially used as living area. It is located in the South of Romania, in a village surrounded by forest and with a climate having the statistical minimum temperature of -15°C. The structure is made of reinforced concrete frames and ceramic blocks and ceiling beams. A pitched roof with a variable shape is positioned on top of the house. PVC-framed windows and roof windows with triple glazing were used. The windows mounted on South and West façades are equipped with exterior shutters. Total built area of the house is of 228.15 square meters (attic not included). Figure 1 presents a view from the courtyard of the Romanian E4 house, as built, showing all the main spaces facing South (bedrooms, living and dining room). In the right side, a vertical section shows the extended use of clay-based products.

Energy efficiency passive strategies in the building design include the placement of building into the available site, its orientation relative to the cardinal points and, as well as to the predominant wind, placement and properties of the transparent and opaque parts of the envelope, as well as the utility of spaces facing different cardinal points. As partially illustrated in figure 2, the design considered:

- Orientation of the main façade towards South, to facilitate solar gains for the living room area and the bedrooms, which represent the main living area of the house. All secondary spaces (technical room, bathrooms, stair and circulation halls) that have limited daily use are facing North, lacking significant use of solar radiation, but protecting the main area from the outdoor conditions.
- Use of large windows facing south for direct passive solar gain and small windows on the north façade in order to minimize the thermal losses. Few windows were positioned on the East and West façades in order to control overheating during summer period.
- Protection against overheating using consoles above the transparent doors of the dinning area and a recessed external solar shading to eliminate excessive heat gains inside the bedrooms.
- Use of the attic as a buffer space against overheating in summer and against cold in winter.
- Opening windows both in external walls and roof for natural ventilation wherever possible. Night-time cross-natural ventilation of the building, to cool the structure in hot summer conditions.
- Unobstructed air paths across the house because of the void above living room and the stair case that alongside with the use of heavy thermal mass with a high surface area (i.e. clay products and concrete structure) exposed to the internal airstream, stabilise internal temperatures.
- Enhanced gain of natural light using roof windows and transom dormer windows for rooms on the first floor. Also the use of relatively narrow circulation zones to ensure that daylight levels are high.
- Greenhouse effects from glass panels mounted in front of the French windows of bedrooms; the gap between panels and the wall allows for hot air circulation during summer, when the greenhouse effect is not desirable.

![Figure 1. Southern view of the Romanian E4 house, as built.](image)

The energy efficient architectural design of a NZEB also focuses on the building materials. The considerations for the materials used included as a key element recyclable or recycled, as well as locally available materials. The main materials (bricks, concrete, glass, wood) have high recycled content and have to be regionally available, thereby reducing transportation/manufacturing energy. The design team made a good selection of materials, as exemplified below:

- High levels of thermal insulation for foundations and ground floor slab, for façades and under the consoles, for the attic slab and roof.
- Additional insulation for thermal bridges.
- Use of metal consoles and insulation to minimize the thermal bridges usually generated by concrete ground slabs (for terraces).
- Terrace slab from the first floor is recessed in order to gain additional insulation space and keep a comfortable walking level from indoor to outdoor.
- Intelligent adaptive membranes with active moisture management at the attic surfaces.
- Energy performant triple-glazing windows and doors, with frame made of PVC.

![Figure 2. South-North Sections showing the orientation of spaces and passive strategies.](image)
Energy efficiency active strategies in the building design added more value in the overall energy performance of the building. The systems implemented are described below and partly illustrated in Figure 3:

- a heat pump, which uses the underground as an energy source or sink, as it may work reversibly to produce heat in the winter or cooling in the summer. If indoor conditions allow, the heat pump may provide passive cooling by simply running the underground water of 7-12 °C through indoor or built-in-walls tubes. If a heat pump cannot be used for technical, environmental or economic reasons, an alternative option may consist of using a biomass boiler on pellets.
- solar collectors that supply heated water to a buffer storage unit to partially support the preparation of the domestic hot water and/or the hot water used for space heating. The innovation of the buffer tank is that it stores thermally stratified water that transfers heat to the coils with domestic water flows. This solution avoids the risk of developing germs and micro-organisms in the domestic water and thus various possible diseases.
- low-temperature heating pipes that are placed underfloor and walls with built-in tubes used for both heating and cooling along various seasons.

![Figure 3. General view of the energy systems used.](image)

- a central home automation technology that allows users to control heating/cooling levels, window shading devices, on/off lighting, as well as security elements and video cameras. This system may register indoor temperature and humidity levels in real time or various energy consumptions over predefined time intervals, educating thus the users into what experts usually call „energy behaviour”.

Innovative strategies in the building consists here in the use of a Trombe wall, optimized to provide additional heating, cooling, or just fresh air by a combination of greenhouse and thermal mass effects. The Trombe wall is placed on the Southern surface of the living room, where the solar radiation has highest levels and the heat stored in the ceramic elements may be exchanged with the indoor air during day time and night time as well.

3. Theoretical performance analysis
Design team used modular systems during design phase, running several optimization scenarios in order to choose the best solution for a fast building rate, with reduced pollution, and with at least 50% less energy waste than buildings made according to the current minimal standards in Romania. The building
was not intended to be a high-tech exercise, but, on the contrary, to be friendly, i.e., traditionally operational, and affordable. The cost of nearly zero energy buildings is usually compared with that of regular buildings, and it is expected to be higher due to the better quality of envelope elements, more energy savings and/or unconventional HVAC installations. For the purpose of illustrating the advantages of the proposed design, it is presented here a comparison between a standard house and the designed one. Both have same geometry and orientation, but different levels of energy performance, as described below. Construction prices were estimated and a prognosis for energy price increase was used to evaluate the economic efficiency for each case.

- **Study Case 01: Standard new house** – built with the current national standards [4], with no renewable energy sources. It uses a gas boiler for heating and DHW and a commercial split system for cooling. This case is used as baseline for the next ones, both in terms of costs and energy savings.

- **Study Case 02: E4 design** – masonry 38 cm + 14 cm mineral wool, ground slab insulated with 10 cm XPS, consoles with 15 cm mineral wool, roof with 20 cm cellulose and adaptive humidity membranes, 20 cm XPS for terrace, PVC windows with triple glazing, solar panels for partial DHW, PV panels, Trombe wall, and geothermal heat pump for heating and cooling.

Heat transfer coefficient $U$-values [W/(m$^2$K)] for each building envelope construction are shown in table 1. For comparison, standardized value for regular Romanian buildings [4] are also included in the table. $U$-values for 2020 are not yet regulated.

The solution that induces energy savings for lighting and also brings a lot of comfort and emotion to the users remains the natural light. This means large window area, but also shading devices and low-emissivity glazing to reduce heating over the summer or thermal losses during the winter. Roof windows are used at the first floor to ensure enough light to the stairs and hall areas, as well as in the bedrooms/offices. The goal was to obtain a daylight factor in every single room a few times higher than the usual standard.
Table 1. Table with the main U-values [W/(m²·K)] corrected to account for thermal bridges.

| Structural element                      | Romanian standard in 2013 | E4 – case 02 |
|-----------------------------------------|---------------------------|--------------|
| External walls                          | 0.55                      | 0.22         |
| Attic slab                              | 0.20                      | 0.15         |
| Slab over the ground                    | 0.22                      | 0.18         |
| Window (PVC frame)                      | 1.30                      | 0.85         |
| Roof window                             | 1.30                      | 0.94         |
| Slab over exterior (e.g. arcade/bowindow)| 0.22                      | 0.22         |
| Flat roof                               | 0.33                      | 0.19         |
| Slab between first floor and attic      | 0.33                      | 0.22         |
| Roof                                    | 0.20                      | 0.17         |

Table 2. Energy and environment performance of the two study-cases.

| Heating kWh/(m²·y) | DHW kWh/(m²·y) | Lighting kWh/(m²·y) | Cooling kWh/(m²·y) | TOTAL kWh/(m²·y) | difference % | CO2 kg/(m²·y) | difference % |
|--------------------|----------------|-------------------|--------------------|------------------|--------------|---------------|--------------|
| SC 01              | 106.8          | 23.5              | 4.4                | 6.3              | 141.0        | 0%            | 35.4         | 0%           |
| 100% from natural gas boiler | | | | | | | |
| SC 02              | 10.5           | 2.2               | 2.5                | 2.4              | 17.7         | -87%          | 8.6          | -76%         |
| 5%/yr from Trombe wall and the rest from heat pump of COP = 4.0 | | | | | | | |

The energy analysis of the two cases led to the values summarized in Table 2. The calculation was performed according to the Romanian methodology for energy auditing of buildings [5]. It is a monthly-averaged approach over a statistical year in terms of outdoor temperature solar radiation. Energy need for heating or cooling considers energy transfer through building envelope (thermal resistances including thermal bridges) and air exchange, as well as internal and solar gains. Corrected degree-days for the particular house analysed could thus be calculated and used for heating and cooling demands, as illustrated in Figure 5. In this figure, $T_{int}$ is the averaged indoor temperature based on standard values [5], $T_{ext}$ is the monthly averaged outdoor temperature based on statistical data, $T_{iR}$ is the indoor temperature corrected for internal gains, and $T_{eR}$ is the outdoor temperature corrected for solar gains. The beginning and end of the heating/cooling seasons are marked by the arrows and the area closed by $T_{iR}$ and $T_{eR}$ curves represents the degree-days for heating (a) and cooling (b). Noteworthy, the cooling energy demand calculation included also the latent heat of water vapour condensed during the cooling process [5]. Noteworthy, energy needs for heating considered in details the internal load and solar loads for a South-orientation of the building in the vicinity of Bucharest. Corrected degree-days for the particular house analysed could thus be calculated and used for heating and cooling demands, as illustrated in Figure 5.

The energy values in Table 2 are final non-renewable energies used in the building, meaning that the renewable energies have been subtracted from the theoretical values. The emissions of CO2 are
calculated using values specified in the Romanian methodology for environmental loads [5]. Below values, some brief explanations are given in order to facilitate the understanding of what changes from case to case. All differences are then expressed in percentages relative to study case 01. for both total final energy and total emissions. It must be said that, in this table, thermal and electrical energies for the four uses were added up, as it is done in some legal documents, although it is not a correct approach. For this reason, the energy and environment performance must be judged together.

Noteworthy, additional energy savings may be achieved with the design approach, as it aimed for reduction of embodied carbon-dioxide emissions, through reducing waste by modular design based on standard dimensions of each building element, prefabrication and site management.

The engineering approach is always completed with an economical evaluation of the solutions being promoted, such as to ensure marketable products. Given the long life of buildings, the instabilities of prices and fuels availability, as well as the legal increasing demands for energy and environmental performances of new buildings, careful calculations must be performed in order to show to the client the advantages of obviously more expenses designs. The client must be educated to appreciate in long term the savings that he/she can make.

In order to emphasize only costs associated with energy efficiency measures, from the total costs of the real building was subtracted the total cost of the standard case SC-01. These extra-costs were then
compared to money savings from energy savings relative to the same case SC-01 during the operation of the house over a certain period of time. In the economic efficiency evaluation presented in this paper, the annual inflation of euros and increase of energy tariffs are considered at rates of 3% and 10%, respectively. The extra-investment payback time period for the design case SC-02 resulted from calculation 17.9 years, compared to the estimated life-time of energy saving solutions of 30 years.

4. Energy performance analysis from measurements

The real performance results clearly from measurements on comfort and energy use in the built environment. For this purpose, the house was monitored for full two years. Temperature, relative humidity and illuminance levels were measured in all major rooms (living, bedrooms, kitchen), simultaneously with similar outdoor conditions, with a time step of 30 minutes. Inlet and outlet air temperatures at the Trombe wall, electricity meters for the general use and for the PV panels were also continuously registered.

For proper understanding the building energy response, Figure 6 presents the outdoor temperature and humidity levels measured in a sunny spot near the South façade of the building. This placement makes the measured temperature to play the role of TeR in Figure 5. Panels (a) and (b) are for the first trimester of 2017 (January-March) and panels (c) and (d) are for the third trimester of 2017 (July-September).

The building has a BMS implemented that ensures pre-set indoor temperatures, such as, no major problems were indicated by monitoring devices, regardless the outdoor conditions. However, for relative humidity it was noticed that high discomfort was created by high levels in the living room and dehumidifiers were installed. This was caused by the outdoor high relative humidity associated with a lot of greenery in the garden and in the nearby forest. Figure 7 indicates such measurements before and after installing the dehumidifier device.

All indoor parameters were used to compute the Fanger comfort indicators PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) and family members were inquired about their level of satisfaction, indicating very small and temporary discomfort levels in the kitchen and living room.

The daily energy use and production are represented in the figure below (Figure 8), indicating periods when production was higher than consumption (summers) and periods when production was lower (winters). In summer, cooling is of passive type, so the heat pump (PQ) does not consume much energy, with the exception of circulating water pumps.

The overall energy balanced is illustrated by the cumulative representation of energy use/production in Figure 9. It results that after two years of use, the difference between heat pump consumption and PV production is 1700 kWh, which, with a tariff of 0.1 Euro/kWh, means 170 Euro net cost with electricity for the thermal comfort conditions in the house.

When the total energy use and production is considered, a representation of terms as a function of outdoor mean monthly temperatures is significant, as illustrated in Figure 10. It is shown that at high outdoor temperatures (as measured by the weather station placed on the house external walls), the heat pump does not consume much and the electricity production in the PV panels is superior to the total electricity consumption from the national network (SEN). Other electricity users (i.e., computers, appliances, lighting and electrical correction for hot water) besides the heat pump result from the differences, assuming that all PV energy has been used.

Besides the inherent errors stemmed from various theoretical assumptions, the differences occurred also due to the following:

- The estimated cooling indicator included night cooling by additional ventilation, which was not operated by the users for safety purposes.
Figure 6. Outdoor temperature and relative humidity.
• The PV-panels did not produce any electricity while being covered with snow during winter times. The longer periods with cloudy days than assumed are another reason for less PV long-term performance.
• The Trombe wall did not function properly, neither for heating, nor for cooling.
• The behaviour pattern of people may significantly influence energy use in any house.

![RELATIVE HUMIDITY in living](chart1)

*Figure 7. Indoor relative humidity before and after dehumidification.*

![RELATIVE HUMIDITY in living](chart2)

*Figure 8. Daily energy terms over two years’ period.*
For the Trombe wall, measurements indicated large air infiltration through the inlet throttles and, as a result, a minor contribution to the house heating. Future repairing is expected to fix this drawback and increase the Trombe efficiency.

One last result of the analysis is a comparison between the estimated energy performance and the actual energy performance (Table 3), after scaling the real measurements to the indoor and outdoor conditions considered in the theoretical calculation.

| Table 3. Comparison of the estimated and actual energy performance. |
|---------------------------------------------------------------|
|                | Heating kWh/(m²·y) | Domestic hot water kWh/(m²·y) | Lighting kWh/(m²·y) | Cooling kWh/(m²·y) | PV production kWh/(m²·y) |
| Estimated      | 10.50              | 2.20                           | 2.50                | 2.40               | 31.00                      |
| Measured       | 12.84              | 2.39                           | 2.19                | 4.03               | 18.69                      |
| Difference, %  | 22.3%              | -8.6%                          | -3.1%               | 6.8%               | -39.7%                     |
5. Conclusion
The paper presents the importance of three stages in the proper analysis of the energy performance of any building.

I. Architectural design based on energy performance concepts
II. Theoretical analysis of multiple solutions for associated energy indicators
III. Monitoring of real building under use conditions.

In the particular case of the house analysed here, all stages led to valuable conclusions and decisions for improvements. No matter the differences between estimations and measurements, the real energy performance of the building is outstanding: a total of annual 40.14 kWh/m² final non-renewable energy. As primary non-renewable energy, the indicator becomes 105 kWh/m², which is below the value of 111 kWh/m² stated in the Romanian legal norms for the nZEB level for an individual house.

The project aims to prove that it is possible to have a healthy living in energy-efficient and sustainable buildings made of clay products, that are attractive and affordable at the same time. A low-energy house design according to E4 house concept proved to be at nZEB level with already widely disseminated design concepts and building and materials. It remains the role of the designer to educate the beneficiary, no matter who is, about the advantages in medium and long terms of having a NZEB type of house.

6. References
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