Simulated thermal energy demand and actual energy consumption in refurbished and non-refurbished buildings

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Abstract. The EU legal frame imposes the Nearly Zero Energy Buildings (nZEB) status to any new public building starting with January 1st, 2019 and for any other new building starting with 2021. Basically, nZEB represents a Low Energy Building (LEB) that covers more than half of the energy demand by using renewable energy systems installed on or close to it. Thus, two steps have to be followed in developing nZEB: (1) reaching the LEB status through state-of-the-art architectural and construction solutions (for the new buildings) or through refurbishing for the already existent buildings, followed by (2) implementing renewables; in Romania, over 65% of the energy demand in a building is directly linked to heating, domestic hot water (DHW), and – in certain areas – for cooling. Thus, effort should be directed to reduce the thermal energy demand to be further covered by using clean and affordable systems: solar-thermal systems, heat pumps, biomass, etc. or their hybrid combinations. Obviously this demand is influenced by the onsite climatic profile and by the building performance. An almost worst case scenario is approached in the paper, considering a community implemented in a mountain area, with cold and long winters and mild summers (Odoareul Secuiesc city, Harghita county, Romania). Three representative types of buildings are analysed: multi-family households (in blocks of flats), single-family houses and administrative buildings. For the first two types, old and refurbished buildings were comparatively discussed.

1. Introduction

The building stock is responsible in EU for at least 40% of the total energy consumption and for over 24% of the CO₂ emissions [1], [2], out of which a large share (over 60%) is required for heating, cooling and domestic hot water preparation. A new building usually needs about five times less energy than an old, non-refurbished one; however, approximately 35% of the EU buildings are older than 50 years [1], thus tailored solutions are required, both for refurbishing and for the construction of more efficient, more sustainable buildings, to reduce the energy demand and, consequently, the greenhouse gases emissions[3],[4]. Currently, the EU’s building stock is of approximately 24 billion m², out of which about 75% are residential buildings, with an average of 87 m²/unit. The increased energy consumption of the residential environment, the climate changes and the low standard of living were outlined as three major issues [5] that need to be integrated addressed to support the sustainable development in the buildings sector.

A first step has already been taken as the EU representatives defined the framework elements for the design of the low energy buildings, the legal framework being consolidated through the Energy Efficiency Directive (EED) [6]; the Energy Performance of Buildings Directive (EPBD) [4] and the Renewable Energy Directive (RED) [7]. Thus, a set of measures is put into effect that will secure the
appropriate conditions for long-term, significant improvement of the energy performance in Europe’s built environment [8], [9].

According to the EPBD directive, a nearly zero energy building (nZEB) is: “a building that has a very high energy performance...,” where “the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby” [4]; thus, the directive supports three pillars that should guide the buildings’ design: energy efficiency, building performance and the use of the energy demand from renewable sources.

There is a series of European projects and analyses on the improvement of the energy efficiency in buildings and the optimal design of the renewable energy conversion systems; most projects use as input data values obtained by modelling/commercial software [10]. As a pre-design step, this approach is useful; however, the actual energy demand depends on objective, predictable factors (the climatic profile, the building quality) but also on subjective issues, as the inhabitants’ behaviour, personal comfort definition, etc. Therefore, anew challenge is the energy simulations of the “consumption-response” type [10] based on each user’s actual (real) and customized consumption (taken from the energy bills) correlated with the specific features of the building elements; this approach allows to customize the nZEB design and to outline feasible and more affordable solutions both for new or refurbished buildings; the target is an accurate set of input data in designing the renewable energy mix to be implemented on/near the building and reports show that this approach may reduce the size of these systems by 22% to 46% [11].

This paper presents analyses the simulated and actual thermal energy demand of a building stock implemented in a temperate climate, with long and cold winters and warm (but not hot) summers; this climatic profile asks for heating and domestic hot water, while cooling has an insignificant share in the total thermal energy demand. The results are used to further outline recommendations to calculate the specific energy demand (i.e. the energy per surface unit, kWh/m²) in a given built environment, as a reliable input data in the design of renewable based systems (e.g. solar-thermal collectors arrays, heat pumps, biomass burners, etc.).

1.1. Energy efficiency

The main legal instrument supporting an increased energy efficiency is the 2012/27/EU Directive (EED). At customer’s level, a more efficient use of energy reduces the energy costs, while at society level the greenhouse gases emissions are mitigated and the dependence on the fossil fuels suppliers is expected to decrease [6]. This is why from many points of view, energy efficiency may be seen as Europe’s greatest source of energy [9]. Article 24 of EED stipulates that each member state (MS) should conceive a National Energy Efficiency Action Plan (NEEAP) [1], [6] every 3 years, as of 2014. During the first stage, the MS should set their general goals and each member state’s efforts will be assessed to estimate the likelihood of attaining the global target. A second stage stipulates that, after assessing the global energy efficiency, the EC will set a series of compulsory measures for the MS, thus allowing the target to be attained.

After 2014, large discrepancies were noticed between the yearly specific energy performance goals of the built environment, self-imposed by the MS: from threshold values of 20 kWh/m² in Denmark, to buildings that will be limited to a maximum consumption of 270 kWh/m² in Estonia. Moreover, a “trend marker” could be noticed from the perspective of energy thresholds imposed by the states in Central and Northern Europe, who tended to set thresholds for nearly-zero consumption [12],[13],[14]. These thresholds are related to the climatic profile, to the baseline (thus the current situation) and to affordability (the investment required for meeting the threshold, corroborated with the general wealth indicators), rationally estimated by each MS.

In 2015, Romania submitted the energy efficiency action report (NEEAP) drafted both for the internal energy consumption and the built environment, which set different thresholds of energy performance depending on the type of building and the representative climate region. The maximum yearly specific energy performance thresholds were sized based on the building use classes: new
1.2. Building energy performance
The EPBD provides a series of measures related to the energy performance of buildings, supporting the energy efficiency typical indicators, among which:

- The mandatory use of energy certificates for the sale and rental of buildings;
- The MS must enforce inspection schemes for the heating and air conditioning systems;
- All new buildings shall be nZEB as of December 31, 2020 (public buildings shall be compliant as of December 31, 2018);
- The MS must set minimum energy requirements regarding the energy performance for most of the refurbishment elements of the buildings (heating and air-conditioning systems, roofs, walls, windows etc.);
- The EU states shall contrive different financing schemes aimed to foster and improve the energy efficiency of buildings [9].

2. Method
A conjugated effort should be directed to reduce the thermal energy demand in buildings to be further covered using clean and affordable systems: solar-thermal systems, heat pumps, biomass, etc. Technically speaking, this demand is mainly influenced by the onsite climatic profile and by the building quality.

2.1 Input data
The simulation of the energy consumption patterns in buildings is well-known method (since the ‘70s) for estimating the specific energy performance. Nowadays, items of specialised software can evaluate the temperature and humidity of the indoor air based on input data as the outdoor climate conditions and, based on, different options of improvement of the energy performance of the building are formulated[16]. Thus, the thermal energy demand can be estimated using e.g. TRNSYS, DOSET-PEC. The input data used to predict the energy demand must take into account the outdoor climate parameters, the building classification in relation to the location of the building in the built environment and the characteristics of the building materials that yield the building energy performance parameters.

The specific outdoor climate parameters (the temperature of the outdoor air, the minimum outdoor temperature in winter, the relative humidity of the outdoor air, the intensity of the solar radiation, the reference wind speed) can be obtained using specialized software (e.g.: Meteonorm), or by applying specific national standards (e.g.: MC001/2006 in Romania [17]), but the best way is to determine them by site measurements and data collection from the local weather stations.

When classifying buildings in relation to their position in the built environment, specifics of the implementation location should also be considered: access, vicinities, exposure to the sunlight/shading, exposure to the wind, the conditions imposed by the natural landscape and others, the orientation vs. to the cardinal points and the dominating wind and the position as opposed to the vicinities (buildings, natural obstacles etc.) [2].

Basically, the characteristics of the building materials are used when assessing the energy performance: i) thermal conductivity; ii) specific heat capacity; and iii) water vapour permeability factor /water vapour resistance [18]. Their assembly in the building’s envelope are further considered: the unidirectional thermal resistance (R), respectively the unidirectional thermal transmittance (U); the thermal resistance (R’), respectively the thermal transmittance (U’) corrected by the effects of the heat bridges; the ratio between the corrected thermal resistance and the unidirectional thermal resistance (r); corrected thermal resistances, environments for each type of marginal element of construction of
the entire building ($R'_m$); corrected, average thermal resistance of the building envelope ($R'_M$), respectively corrected, average, unidirectional thermal transmittance of the building envelope ($U'_\text{building}$);[17]; these properties are correlated as presented in eq. (1) and eq. (2).

\[
U' = \frac{1}{R'} = \frac{l}{R} + \frac{\sum (\psi \cdot l)}{A} + \frac{\sum \chi}{A}
\]  

(1)

where: $U' =$ Corrected thermal transfer coefficient; $R' =$ Corrected specific thermal resistance; $R =$ Unidirectional thermal resistance specific for area $A$; $A =$ the area of the component materials of to the quasi-homogeneous layer; $l =$length of the identical linear bridges within area $A$; $\psi =$specific linear coefficient; $\chi =$ exact coefficient of thermal transfer.

\[
R'_m = \frac{1}{U'_m} = \frac{\sum A_j}{\sum (A_j \cdot U'_j)}
\]  

(2)

where: $R'_m =$ Specific average thermal resistance; $U'_m =$ Average thermal transfer coefficient calculated based on the $U'$ value through temporal mediation; $A_j =$ Areas of component materials of to the quasi-homogeneous layer, measured with the layer in elevation; $U'_j =$ corrected thermal transfer coefficients of the $A_j$ areas.

Other parameters can also be used, e.g.: the thermal inertia index, water vapour diffusion resistance, thermal inertia coefficients (damping, lagging), area absorption coefficient correlated to the colour and status of the surface, optical factor for glazing, glazing ratio etc.

All these values are important; however, an accurate prediction for the hourly/monthly/yearly values should be corrected based on the information received from the users [19] by determining the specific energy consumption related to the equivalent surfaces served by the built environment and depending on their specificity.

Concluding, the thermal demand energy is evaluated: (i) either simulated by identifying the number of building elements and subdivisions, classifying them by their use and by correcting the results through the extrapolation of the level of consumption measured for a minimum set of actual data, or (ii) by collecting the data related to the actual consumption (invoices from the suppliers) and centralizing them based on the specific behaviour of use. Clearly, the second option is the preferred one from a technical and economic point of view, since it enables the design of personalised systems. Nevertheless, for a accurate result, the study should contain data collected for at least one year (but preferably with a longer history).

2.2 Comparative study
The comparison between the results of the simulated calculation and the daily measured amount of energy is studied starting from the identification of the building types that are representative for a given community. As case study the Odorheiul Secuiesc City was subject of analysis. The city is located at 46.3°N and 25.3°E and an altitude of 385m above the sea level and is surrounded by mountains thus the climatic profile is temperate and rather cold. The city has about 34000 inhabitants and the building stock consists of single-family houses, multi-family households (blocks of flats) and administrative buildings. The buildings reported in this study were selected based on the general average level of consumption, from each category. Moreover, one of the most important aspects is the degree of thermal building insulation, since the cases also need to be distinguished apart based on their degree of thermal refurbishment. Thus, five representative buildings were considered:

- Case A1: a non-refurbished collective bricks household with a useful area of 57.0m²;
- Case A2: a refurbished collective bricks household with a useful area of 86.7m²;
- Case B1: a non-refurbished individual bricks house with a useful area of 79.5m²;
- Case B2: a refurbished individual bricks house with a useful area of 172.34m²;
- Case C: a non-refurbished administrative bricks building with a useful area of 1413.78m².
2.3 Analytical calculation

The analytical calculation has been done using the DOSET-PEC software and simulating the energy consumption as it is defined in the energy performance calculation methodologies. The specific thermal energy demand for heating, cooling and domestic hot water over one year, for each type of building was assessed and the results are included in Table 1 and Figure 1(a). Moreover, the software can generate reports regarding both the heating and cooling needs of the building, but in this comparative study there is no need for a cooling system due to the existing climate conditions.

As expected, the results outline significant differences between the refurbished and non-refurbished buildings, starting from a 20% advantage (in the case of the collective households) and amounting to 280% (in the case of individual houses). This large difference are the result of two different factors: the single-family houses have the ratio of envelope/useful surface much larger than in multi-family households, thus the losses are larger; additionally, many of the single-family houses are rather old, using traditional building materials, subject of erosion in time.

These results highlight, once again, the imminent need for the thermal refurbishment of buildings.

| Table 1. Simulated yearly specific energy performance parameters. |
|---------------------------------------------------------------|
| **Collective house** | **Individual houses** | **Administrative** |
| **Case A1** | **Case A2** | **Case B1** | **Case B2** | **Case C** |
| **I. Input Data (Summary)** |
| Climate region | IV | IV | IV | IV | IV |
| Average indoor temperature [°C] | 20.00 | 20.00 | 20.00 | 20.00 | 20.00 |
| Volume of heated space [m³] | 142.58 | 216.76 | 214.65 | 448.94 | 5,623.57 |
| Heated space area [m²] | 57.00 | 86.70 | 79.50 | 172.34 | 1,413.78 |
| Number of air changes [h⁻¹] | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| Insulating envelope area [m²] | 86.54 | 125.09 | 255.92 | 373.33 | 1,824.14 |
| Compactness index [m⁻¹] | 0.61 | 0.58 | 1.19 | 0.83 | 0.32 |
| Corrected th. resistance, $R'_{th}$ [m²K/W] | 0.98 | 1.08 | 0.85 | 1.70 | 0.71 |
| **II. Simulated thermal energy (Efficiency 78 %)** |
| Yearly specific energy for heating [kWh/m²] | 165.39 | 128.21 | 357.26 | 87.50 | 301.72 |
| Yearly specific energy for cooling [kWh/m²] | - | - | - | - | - |
| Yearly specific energy for DHW [kWh/m²] | 24.67 | 25.46 | 35.37 | 16.32 | 11.69 |
| Total yearly specific energy demand [kWh/m²] | 190.06 | 153.67 | 392.63 | 103.82 | 313.41 |

2.4 Calculation based on the registered consumption

The actual energy consumption was estimated based on the information received from the users (energy costs in the bills emitted by the provider). According to the data and to the Romanian standards, the A2 and B2 buildings qualify as low energy buildings, thus refurbishing was well designed.

| Table 2. Measured yearly specific energy performance parameters. |
|---------------------------------------------------------------|
| **Collective house** | **Individual houses** | **Adm. building** |
| **Case A1** | **Case A2** | **Case B1** | **Case B2** | **Case C** |
| **I. Input Data (Summary)** |
| Climate zone | IV | IV | IV | IV | IV |
| Heated space area [m²] | 57.00 | 86.70 | 79.50 | 172.34 | 1,413.78 |
| Insulating envelope area [m²] | 86.54 | 125.09 | 255.92 | 373.33 | 1,824.14 |
| **II. Actual energy consumption** |
| Yearly specific energy for heating [kWh/m²] | 141.67 | 121.00 | 301.10 | 77.32 | 221.05 |
| Yearly specific energy for cooling [kWh/m²] | - | - | - | - | - |
| Yearly specific energy for DHW [kWh/m²] | 8.57 | 7.52 | 11.21 | 9.51 | 3.24 |
| Total yearly specific energy demand [kWh/m²] | 150.24 | 128.52 | 312.37 | 86.83 | 224.29 |
The data are presented in table 2 and figure 1(b) and show, as expected, differences between the refurbished and non-refurbished buildings; however, the actual gain brought by the thermal refurbishment starts from 15% for the collective households and it reaches 260% for individual houses. Overall, differences were observed between the simulated and the actual data, and these differences were further analysed.

![Figure 1](image)

**Figure 1.** Building yearly specific energy performance (a) simulated; (b) measured.

### 3. Results and discussion

The results indicate that thermal refurbishment is very efficient for the individual households, as they bring benefits of up to 260%, whereas these benefits are only limited to maximum 15% in the case of the flats in collective households. These results are indicative of the quality of the insulation (material and thickness) used for refurbishment, which, obviously, needs to be done more thoroughly in the case of the individual households. Moreover, the area exposed to weather manifestations is larger in individual dwellings. That is why the lowering of the energy loss has a significant impact as compared to the flats in the collective households.

In the comparative analysis, figure 2 it is also to observe that large differences are observed mainly for buildings with a rather larger specific thermal energy demand and deviations are typical for the month with large energy consumption (December and January). The (larger) “back up margin” approach of the standards ranges between 15% and 22% in the case of households, whereas in the case of administrative buildings it exceeds 25%. Following these values, the initial investment for renewables will be larger than actually needed and the feasibility and affordability of the proposed measures is rather poor. Thus, the design data for the thermal refurbishment and for buildings optimization, as well as the design of the renewable energy conversion systems must rely on actual information collected “on site” and adapted to the users’ real needs, to get feasible and affordable investments. Buildings with higher energy efficiency (as those refurbished, of A2 and B2 type) are better modelled by software, but the cumulative errors in the monthly estimation lead eventually to significant differences even for these types of buildings, as table 3 and figure 3 show.

|                          | Simulated yearly specific energy demand [kWh/m²] | Actual yearly specific energy consumption [kWh/m²] |
|--------------------------|-----------------------------------------------|-----------------------------------------------|
| **Collective households**|                                               |                                               |
| Non-refurbished (A1)     | 190.06                                        | 150.24                                        |
| Refurbished (A2)         | 153.67                                        | 128.52                                        |
| **Individual households**|                                               |                                               |
| Non-refurbished (B1)     | 392.63                                        | 312.37                                        |
| Refurbished (B2)         | 103.82                                        | 86.83                                         |
| **Administrative buildings**|                                           |                                               |
| Non-refurbished (C)      | 313.41                                        | 224.29                                        |
Figure 2. Monthly simulated specific energy demand and the actual consumption for heating
(a) Case A1, (b) Case A2, (c) Case B1, (d) Case B2, (e) Case C.

The monthly analysis also outlines that there is a set of features that give a specific profile of the thermal energy demand of a building; among these features there has to be considered the overall useful area, the ratio envelope area/useful area, the operation regime (household, public building, etc.). All these recommend the use of actual energy consumption data. Future work will concentrate on identifying indicators that might allow to group buildings, according to their yearly and monthly specific energy demand.
4. Conclusions
The design, sizing and implementation of a system based on the use of renewable resources requires an evaluation of the conditions existing in the implementation area, both in terms of climate and in terms of actual energy consumption. The analysis shows that, for the refurbished buildings, the energy assessment by using specialized software has a higher reliability degree, while for thermally non-refurbished buildings, deviations depend on the quality of the building (energy efficiency), the building area and the season. The specialized software usually tends to overestimate the consumption, with deviations ranging between 15% and 25%, its use leading to an overestimation of the implementation costs. Therefore, the recommendation is that the design should use the actual (real) energy demand and consumption data, with immediate effect in decreasing the initial investment for the equipment used for thermal energy production. This recommendation is valid for any type of equipment, but becomes utterly important when renewable energy systems are targeted, because, apart from the investment cost, one also needs to identify the surfaces (space) that should be made available for the project for energy production purposes.

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