Nearly Zero Energy Building Standard for Existing Buildings: Case Study of Residential Units

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ABSTRACT

Energy Performance of Building Directive (EPBD) 2010/31/EU introduced nearly zero energy building (NZEB) standard for new buildings. But existing energy-inefficient buildings will consume great amount of energy unless renovated. This issue is revised in EPBD 2018/844/EU which is setting a framework aiming at long term renovation of existing building stock. The main characteristic of existing building stock is irrationally high energy consumption. Furthermore, the largest share in energy consumption as well as in total construction corresponds to residential building sector. Studies have shown that more than 80% of these buildings do not meet energy efficiency requirements of current legislation. Large energy consumption in buildings is mostly related to the construction period. The construction period has an important role in buildings' energy demand since it is related and represents characteristic construction technology, characteristic building materials used and the legislation on thermal protection of buildings. Therefore, buildings are usually classified into several construction periods according to the age and type of construction and depending on the legislative environment. This paper presents evaluation of the renovation potential of existing residential buildings to NZEB in terms of technical possibilities and economic feasibility. Case study was made on three residential units representative for their construction period. Analysed residential units were chosen to correspond to periods of buildings built between 1961 and 1970, between 1971 and 1980, and between 1981 and 1990. All buildings are in Osijek, Croatia. Infrared thermography and field measurements of airtightness were made as well in order to obtain information regarding initial state of residential units. Results presented in this research give information about construction technology possible to apply during renovation, renovation costs, energy (natural gas and electricity) consumption cost reduction and simple payback periods for proposed renovation measures. Sensitivity analysis method was applied to determine influence of energy price change on payback periods of proposed measures. Results are presented and analysed for three different buildings from three different construction periods.

KEYWORDS

Nearly zero energy building, renovation, construction periods, construction technology, costs, natural gas.

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INTRODUCTION

The European Directive on Energy Performance of Buildings (EPBD) 2010/31/EU prescribes that all new public buildings constructed after 2018 shall be almost zero-energy buildings (NZEB) while after 2020 the same should be applied for all new residential buildings [1]. On the other hand, existing residential buildings will continue to waste enormous of energy unless renovated in terms of their energy performance. This issue is revised in Energy Performance of Buildings Directive 2018/844/EU which sets a framework aiming at long term renovation of existing building stock and decarbonisation by 2050 [2]. Energy consumption in buildings is determined by both building use and building design - including choice of location, structure and layout as well as choice of building materials and equipment predetermine to a considerable extent the quantity of energy required later in the operation of the building [3]. Steps of how residential buildings energy use can be reduced can be summarized as follows [3]:

- Designing the building passively taking into consideration the climate parameters in order to minimize the heating, cooling, dehumidification, lighting, equipment and hot water loads. This can be done by passive cooling, indirect solar gain, best orientation, thermal insulation, glazing...etc.
- Improving the used mechanical and electrical equipment efficiency to meet remain loads and
- Supplying the needed primary energy with renewable rather than fuel.

Although those steps are suggested when building new buildings some of them are applicable when renovating existing buildings. But there is also to keep in mind that renovation of existing buildings doesn’t necessarily decrease energy consumption, it’s also improves whole condition of the building: its exploitation, noise insulation conditions, exterior, and comfort; prolongs buildings life cycle, increases value of the buildings, reduces negative impact to environment and guarantees healthy living and working conditions [4]. The main results expected from buildings refurbishment are [4]:

- Energy savings,
- Increase of comfort,
- Healthy working environment assurance,
- Extension of building life cycle,
- Economized exploitation and
- Environmental protection.

Any actions in the building undertaken during its operational stage can be either refurbishment or retrofit, refurbishment implies the necessary modifications in order to return a building to its original state, while retrofit includes the necessary actions that will improve the building’s energy and/or environmental performance [5]. The aim in the buildings’ design or renovation phase usually is [5]:

- Compliance of the building with regulations in the design or in the operational phase,
- Improvement of the building’s energy efficiency in a sector (i.e. heating or cooling) or overall improvement,
- Improvement of the indoor environment (i.e. improvement of indoor thermal comfort, visual comfort, indoor air quality or a combination of these),
- Environmental impact of the building for global warming, etc. and
- Reduction of the energy-related costs.

To find the most suitable solutions for reducing energy consumption and improving system efficiency, interaction between building envelope and energy systems must be considered carefully. Conventional energy efficiency measures can be used to reduce energy use by 20–30% on average without any significant alterations to the building design [6]. Measures to improve energy efficiency are defined as group of actions that generally lead to verifiable and measurable or estimable energy efficiency improvement and reduction of energy and water consumption [7]. Energy efficient measures applied to existing buildings during minor/major retrofits in order to reduce their energy consumption can be grouped into four categories [8, 9]:

- Building envelopes – thermal insulation, thermal mass, windows/glazing (including daylighting) and reflective/green roofs,
- Internal conditions/Human factors – indoor design conditions and internal heat loads (due to electric lighting and equipment/appliances),
- Building services systems – HVAC (heating, ventilation and air conditioning), electrical services (including lighting) and vertical transportation (lifts and escalators) and
- The use of renewable energy technologies.

Regarding all above mentioned and the fact that heat losses through walls account for 35% of total losses [10], one of the most effective and common measures, provided in *The Ordinance on energy audits of construction works and energy certification of buildings* [11], is the improvement of thermal performance of the envelope by applying thermal insulation and installation of new windows. Those principles were adopted in case study presented in this paper. In principle, the NZEB can be a traditional building which is equipped with sufficiently large renewable energy systems and where the energy production over a year balances out the energy use [12]. But to achieve NZEB condition of existing buildings that were built between 1961 and 1990 beside improving energy performance of building envelope it’s important to provide renewable energy sources. However, when considering the NZEB concept, a new problem arises, i.e., to what level should the energy use decrease by means of energy efficiency measures before implementation of renewable energy sources [12]?

In presented case study findings from [3] were used where optimum insulation thickness is 13 cm for external walls. In this paper 15 cm of wall insulation was adopted in order to achieve same thermal transmittance (U-value) of external walls in all studied buildings. Further, for analysis purposes, new windows were presumed to be installed in order to calculate consumption cost reduction and simple payback period for proposed renovation measures. Also, installation of photovoltaic solar system is planned. For the purpose of this study, three residential units were analyzed that differ in construction period. Analyzed residential units were chosen to correspond to periods of buildings built between 1961 and 1970, between 1971 and 1980, and between 1981 and 1990. All buildings are in Osijek, Croatia and have already undergone a process of energy certification, in-situ measurement of airtightness and infrared thermography measurements. Presented case study is made based on only one residential unit from each building and intention of this case study is to give insight in possibilities, costs and technology that could be applied during renovation of existing buildings from different periods in order to transform them to NZEB.

IN-SITU MEASUREMENT OF AIRTIGHTNESS AND INFRARED THERMOGRAPHY MEASUREMENTS

Limiting airtightness requirements are often to be found in building regulations. When measuring the airtightness of buildings, a blower door method is used to find the relation between the pressure difference over the building envelope, ΔP [Pa], and the airflow rate through the building envelope, Q [m^3/h] [13]. Each residential unit airtightness was measured by using a Minneapolis Blower Door equipment in accordance with EN ISO 13829 later EN ISO 9972:2015 [14, 15], Figure 1. Measurements were carried out following method A - common building use of EN ISO 13829 while applying a pressure difference of 50 Pa. Airtightness measurements results of studied residential units are presented later in this paper in Table 1 and they were used for calculation of energy demands.

All experiments' results, measurement values, were acceptable as they fulfil EN ISO 13829, later EN ISO 9972:2015 criteria, which requires [16]:

- the wind speed lower than 6 m/s,
- the product of maximum building height (m) and temperature difference between outdoor and indoor dry bulb temperature to be lower than 500 m°K,
- the building's volume lower than 4000 m^3.

Measurements of airtightness were carried out during a time when buildings were unoccupied. Typical air leakage places in residential units were similar to following ones that can be found in literature [17]:

- junction of the ceiling/floor with the external wall,
- unction of the separating walls with the external wall and roof,
- penetrations of the electrical and plumbing installations through the air barrier systems,
- penetrations of the chimney and ventilation ducts through the air barrier systems,
- leakage around and through electrical sockets and switches and
- leakage around and through windows and doors.

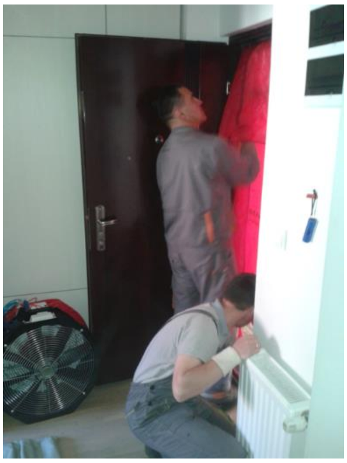

Figure 1. Airtightness measurements by using a Minneapolis Blower Door equipment

Infrared thermography (IRT) can be employed in building diagnostics for the determination of the thermo physical properties of building envelopes. Currently, this application is becoming more important, as the knowledge of the U-Value is a precondition for the classification of the energy performance of existing buildings [18]. Strictly speaking, the investigated object should be in a steady-state condition to be free of disturbing influences. However, as the building envelope is exposed to permanently changing meteorological conditions, such circumstances in reality are seldom if ever met. IRT on external building elements should be performed either at night or during a cloudy day, this was found to be important in order to avoid the problem of temperature increase which occurs as a result of the incident solar radiation, and the impact from the absorbed solar energy, which presents a time lag of a few hours [18]. Additionally measurements should be carried at low wind speeds in order to minimise as much as possible the influence of convective heat losses [18]. The data required to carry out an IR investigation includes the emissivity factor, the reflective temperature, the atmospheric temperature and relative humidity, while temperature difference between the interior and the exterior of the investigated building is expected to be at least 10 °C [19].

IRT measurements results on analysed building i.e. residential units are presented later in this paper, Figures 4, 5 and 6.

Unfortunately, thermal images are often misinterpreted, especially where thermal mass, reflections and moisture might have an impact on readings and thermal performance [20]. Currently, thermography professionals and academics are undertaking work which seeks to develop new methodologies for detecting defects and to measure the thermal performance of existing buildings using building thermography [20]. In general, the main advantages of IRT are the following: [21]

- IRT is a non-contact technology: the devices used are not in contact with the source of heat, i.e., they are non-contact thermometers. In this way, the temperature of extremely hot objects or dangerous products, such as acids, can be measured safely, keeping the user out of danger.
- IRT provides two-dimensional thermal images, which make a comparison between areas of the target possible.
- IRT is in real time, which enables not only high-speed scanning of stationary targets, but also acquisition from fast-moving targets and from fast-changing thermal patterns.
- IRT has none of the harmful radiation effects of technologies, such as X-ray imaging. Thus, it is suitable for prolonged and repeated use.
- IRT is a non-invasive technique. Thus, it does not intrude upon or affect the target in any way.

EXISTING RESIDENTIAL BUILDING STOCK IN CROATIA BY CONSTRUCTION PERIOD

The main characteristic of existing building stock in Croatia is irrationally high energy consumption. According to the annual energy review in 2016 in Croatia, the share of energy consumption in buildings was 43.85% [22]. The largest share in energy consumption as well as in total construction corresponds to residential building sector. Studies have shown that more than 80% of these buildings do not meet energy efficiency requirements of current legislation [22]. The overall quality of existing buildings in Croatia was changed during different construction periods as a result of various climatic, economic, technical-technological and sociological impacts. Impact on quality and thus the energy consumption had construction technology which is related to characteristic building materials used and the legislation on thermal protection of buildings. As general quality of existing buildings was changed by different periods of construction the airtightness of buildings was also changed. Study conducted on a sample of 58 residential units of different years of construction showed a trend of significant improvement in airtightness in the periods of recent construction and that changes in airtightness of residential units throughout different periods of construction are comparable to the changes in average quality of thermal protection of external walls of residential units, Figure 2 [23]. Further on, analysis of the thermal quality of windows installed in residential buildings in the last hundred years reveals a continuous trend of improvement, especially in the last two decades.

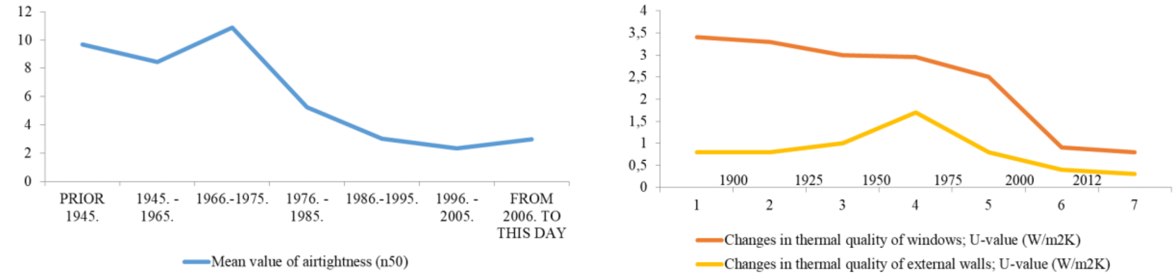

Figure 2. Mean value of airtightness (n_{50}) according to periods of construction and changes in thermal quality of windows and external walls

The left curve on Figure 2 reflects the changes in airtightness of residential units throughout different periods of construction and it is comparable to the right curves on Figure 2 which are approximation of changes in average quality of thermal protection of external walls [24] and approximation of improvements in thermal quality of windows through different construction periods.

In Croatia, depending on the legislative environment, age and type of construction, buildings have been classified into seven construction periods. Construction periods with corresponding share of residential units in the total number of residential units at the level of the Republic of Croatia are presented graphically in Figure 3. It is visible that, most existing residential public buildings have been built between the year 1961 and 1990, Figure 1, approximately 60%. The problem of these buildings is that such buildings have poor energy performance and are characterized by the absence or modest application of thermal insulation and unnecessary heat loss. Considering that the majority of public buildings was built from 1961 till 1990, energy and cost analysis in case study presented in this paper was done for periods of buildings built between 1961 and 1970, between 1971 and 1980, and between 1981 and 1990.

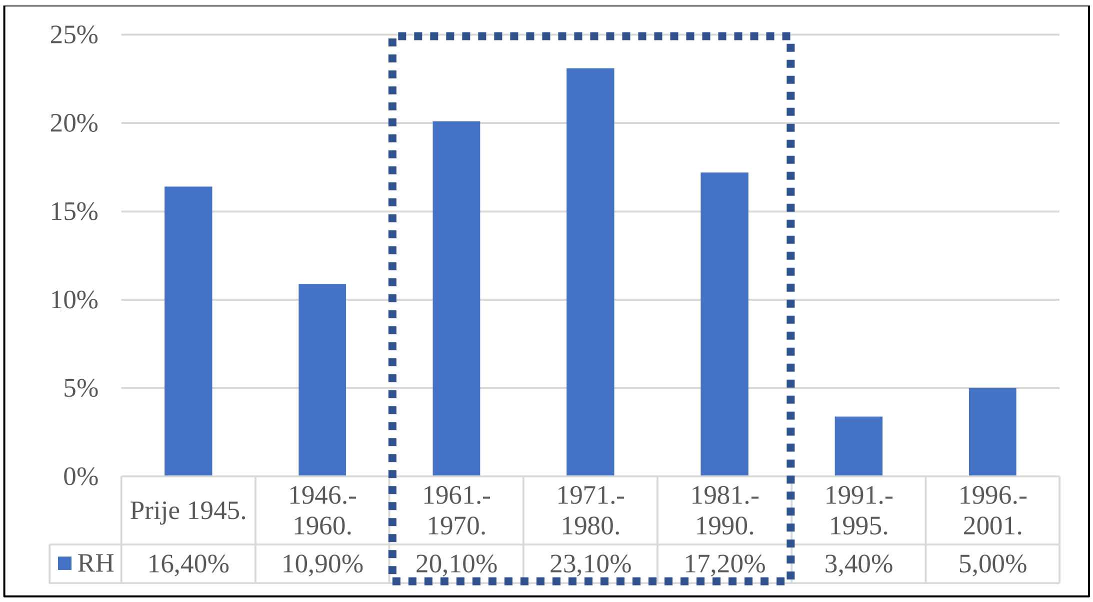

Figure 3. Share of residential units in Croatia according to the year of construction [25]

CASE STUDY

For the purpose of this study, three residential buildings were analyzed that differ in construction period. Analyzed buildings are chosen to correspond to periods of buildings built between 1961 and 1970, between 1971 and 1980, and between 1981 and 1990 as explained in previous chapter. All buildings are in Osijek, Croatia, and have undergone a process of energy certification, in-situ measurement of airtightness and infrared thermography measurements. Main geometry, thermal characteristic and mean values of airtightness of all three residential units i.e. buildings are presented in Table 1. As it can be seen form Table 1, thermal characteristic of three case studies differ according to the construction period and the most commonly used materials for that period. Table 1 contains also basic information regarding type of material used for external walls and type of windows according to specific construction period.

Building energy performance in Table 1 is presented with energy rating based on calculated specific annual energy needs for heating, $Q''_{H,nd}$ [kWh/(m^{2}a)] and specific annual primary energy, Q_{Prim} [kWh/(m^{2}a)] [26] where A+ is the best and G is the worst energy rating.

Furthermore, for all three buildings infrared thermography and field measurements of airtightness were made to obtain information regarding initial state of residential units. IRT measurements results of analysed building are presented on Figures 4, 5 and 6. IRT measurements results presented in this study have qualitative contribution to results. They can help when choosing adequate renovation technology of building envelope.

Table 1. The main characteristics of the residential buildings used in case studies in initial state

CHARACTERISTIC	BUILDING / UNIT A	BUILDING / UNIT B	BUILDING / UNIT C
Construction period	1961-1970 Built in 1965	1971-1980 Built in 1977	1981-1990 Built in 1981
Residential unit floor area, A_k [m^2]	72.78	64.90	43.25
Residential unit volume, V_e [m^3]	188.50	202.80	135.17
No. of floors / Floor	2/1	8/6	4/1
f_0 [m^{-1}]	0.58	0.46	0.34
Percentage of windows in building envelope [%]	11	38	33
External walls type and U-value [Wm^{-2}K^{-1}]	Clay brick 1.89	Reinforced concrete (RC) 3.89	RC and hollow clay brick 3.52
Ceilings and walls bordering unheated attic, U-value [Wm^{-2}K^{-1}]	1.59	2.80	2.16
Windows type and U-value [Wm^{-2}K^{-1}]	Wood frame, single glazing 3.10	Wood frame, single glazing 3.10	Wood frame, double glazing 2.20
Energy rating (from A+ to G)	E/C	E/C	D/C
Airtightness, n_{50} [h^{-1}]	5.77	5.73	4.87

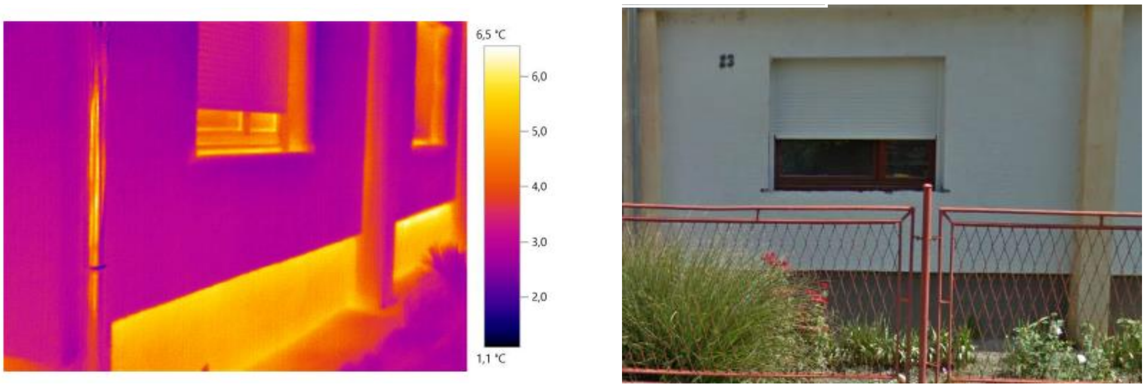

Figure 4. Building envelope thermal image of Building A

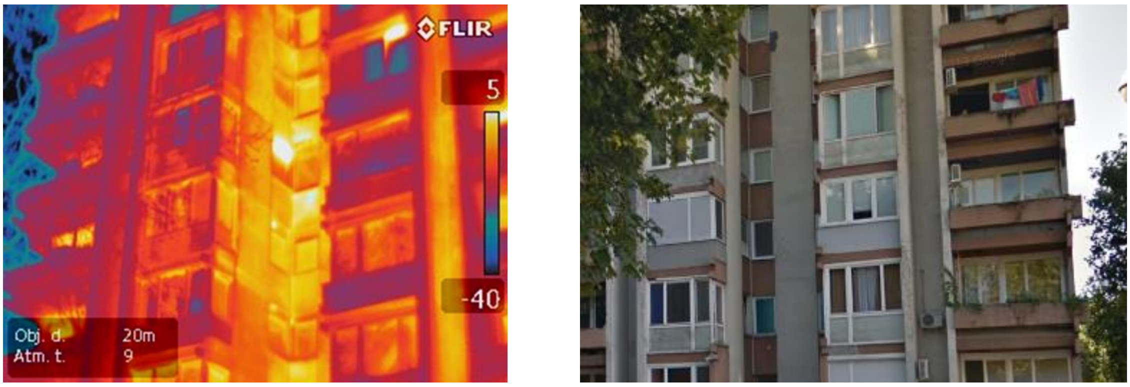

Figure 5. Building envelope thermal image of Building B

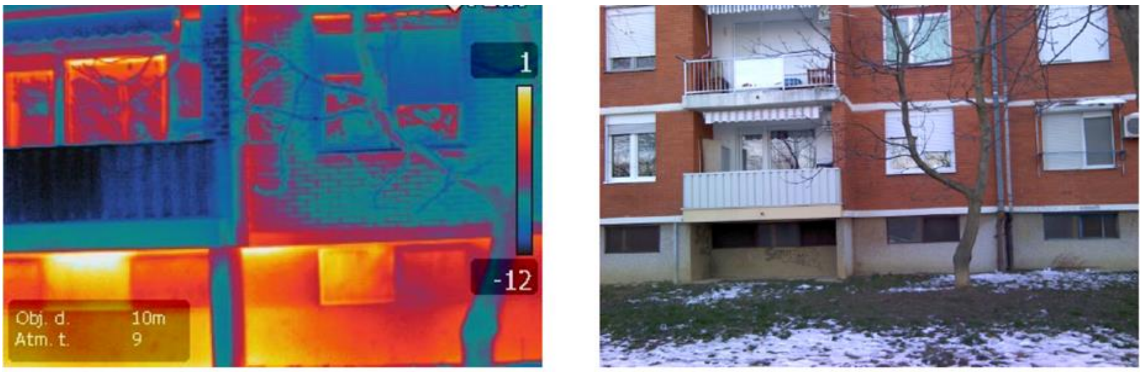

Figure 6. Building envelope thermal image of Building C

In this case study possibilities of changes in the building envelope were examined. These changes include, firstly, the installation of wall insulation of mineral wool 15 cm thick, aiming at the reduction of the thermal transmittance between the internal and the external environments, i.e. the U-value. The next measure, applied, was the replacement of present windows with more energy-efficient ones with lower U-value. All buildings were presumed to have a new and same thermo-technical system and same energy source for heating. In Croatia, minimum energy performance requirements to achieve NZEB refer to consumption of primary energy for heating, cooling, ventilation, hot water supply and lighting, specific annual energy needs for heating and thermal transmittance values of building envelope elements [11].

Regarding renewable energy implementation, minimum 30% integration of renewable energy sources to meet the energy needs of the building is required. In this paper, for case study purposes, all buildings were equipped with photovoltaic solar system but with minimum required module area to achieve NZEB according to above mentioned. Results of case study presented in Table 2 can be divided and observed in 6 sections where for most of observed characteristics, current and proposed (NZEB) value is presented for each building i.e. residential unit.

Table 2. Cases study results

CHARACTERISTIC	BUILDING / UNIT A		BUILDING / UNIT B		BUILDING / UNIT C	
State	Current state	NZEB	Current state	NZEB	Current state	NZEB
External wall U-value [$Wm^{-2}K^{-1}$]	1.89	0.22	3.89	0.21	3.52	0.21
Windows U-value [Wm-2K-1]	3.1	0.8	3.1	0.8	2.2	0.8
CO_2 emission [kgm^{-2} a]	44.55	12.73	48.65	13.11	42.22	12.92
Airtightness, n_{50} [h^{-1}]	5.77	0.86	5.73	0.89	4.87	0.73
Wall insulation area [m^{-2}]	94.99		46.72		25.38	
Wall insulation cost [EUR m^{-2}]	50.00 €		50.00 €		50.00 €	
Windows installation area [m^2]	12.18		28.96		12.78	
Windows installation cost [EUR m^{-2}]	265.00 €		265.00 €		265.00 €	
Photovoltaic solar system area [m^2]	20		22		12	
Photovoltaic solar system cost [EUR m^{-2}]	140.00 €		140.00 €		140.00 €	
CO_2 emission reduction [%]	71%		73%		69%	
Energy (natural gas and electricity) consumption cost [EUR a]	735.10 €	234.26 €	706.15 €	192.95 €	410.78 €	131.11 €
Energy savings [EUR a]	500,83 €		513.20 €		279.67 €	
Energy savings [EUR m^{-2}]	6.88 €		7.91 €		6.47 €	
Renovation cost [EUR]	10.777,20 €		13.090,40 €		6.335,70 €	
Renovation cost [EUR m^{-2}]	148.08 €		201.70 €		146.49 €	
Energy rating	E, C	A, A+	E, C	A+, A+	D, C	A+, A+
Simple payback period (SPP)	22		26		23	
Building age at the end of SPP	76		68		60	

Those six sections above mentioned and presented in Table 2 are:

1. Characteristics of thermal performance of building envelope presented with U-value, corresponding CO_2 emissions in kgm^{-2} a and finally airtightness values, n_{50}, where values for current state are measured ones and for NZEB airtightness values were taken

to be 85% of measured ones according to findings in [27]. U-values after renovation are under 0.30 $Wm^{-2}K^{-1}$ and n_{50} above 0.50 h^{-1} and lower than 3.0 h^{-1} as prescribed in [11].

2. Information regarding wall insulation area and insulation cost for 15 cm of mineral wool insulation, amount of replaced windows area and installation cost, and finally photovoltaic solar system area with the accompanying cost.
3. CO_2 emission reduction and energy (natural gas and electricity) consumption cost before and after proposed measures for improving energy efficiency. Energy savings and renovation cost are presented as overall and cost per m^2 of residential building. This way indicative cost for whole building can be easily calculated. It can be noticed how CO_2 emission is reduced for about 70% in all three units. Energy renovation cost are from 150 EUR for units A and C to 200 EUR for unit C.
4. Energy rating of residential units, before and after proposed measures for improving energy efficiency. Where after implementation of measures all building have energy rating A or higher, A+.
5. Simple payback period (SPP) in years which is calculated as ratio of overall renovation cost and yearly energy savings.
6. Building age at the end of SPP as an important factor for further economic and financial viability of investment.

For sensitivity analysis purposes natural gas and electricity prices were increased in four steps for 10%, compared to initial price, in order to observe changes OF SPP for proposed measures in Table 2. Graphical presentation of sensitivity analysis is given in Figure 7.

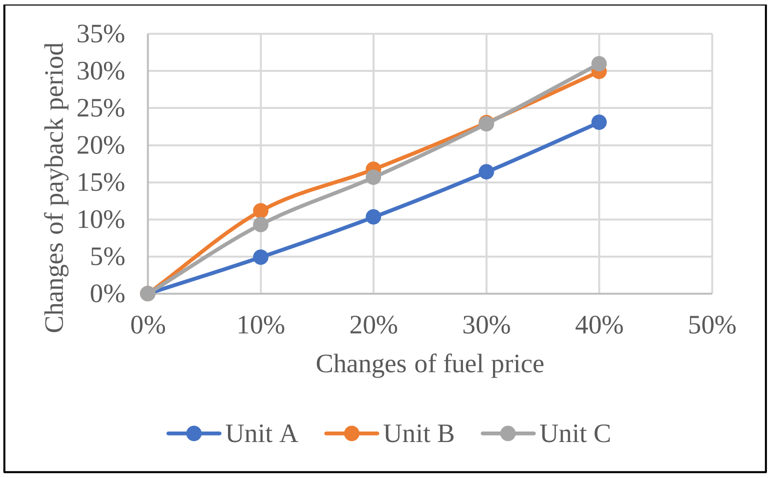

Figure 7. Sensitivity analysis graph

For price changes of 10% in four steps SPP increases from 22 to 26 years for Unit A, from 26 to 33 years for Unit B and from 23 to 30 years for Unit C. In this case study most resilient to fuel prices growth was the SPP of oldest residential unit, Unit A. For Units B and C changes of fuel prices caused almost same amount of changes of SPP.

CONCLUSION

Sensitivity analysis presented in previous chapter proved once again how fuel price changes can influence economic and financial viability of investment and decision making when it comes to implementation of energy efficiency measures. Therefore, current methodology where only SPP is used when decision making is insufficient especially when it comes to large investments. This is even more obvious when building age at the end of SPP is considered together with predicted service life of building or building components. In this case study building age at the end of SPP will be 76, 68 and 60 for Units A, B and C, respectively. Predicted service life of buildings can be observed as a predicted service life of components or building parts that can't be renovated or easily replaced in terms of cost. In this case study that would be predicted service life of external bearing walls made of full clay brick (90 years) and reinforced concrete (70 years) [28]. Further, photovoltaic solar systems are producing less power compared to original power after 20 years. There is also concern on how large amount of photovoltaic solar systems are going to be recycled in the future. Beside all this there is also a problem of finding adequate space for installation of photovoltaic solar system and space large enough (on roof or near building) to ensure required photovoltaic solar system area for all residential units in building. If all stated is considered, then renovation of Unit B and C in terms of making them NZEB is of questionable decision if only based on economic and financial viability of investment. But if other benefits are considered like increase of indoor air quality and comfort and possibility of building life cycle extension this could be reasonable decision which must be made by the investor based on information presented from experts. Since in existing buildings this type of renovation presents a long-term investment it can be questionable investment when it comes to constant migration of population. Investor should be an owner of building long enough in order to investment pays off. Nevertheless, this case study showed great potential in CO_2 emission reduction potential, around 70%, and energy (natural gas and electricity) consumption cost reduction after implementing proposed measures, from 213% to 266%.

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